Geological Society, London, Memoirs

A review of Palaeozoic palaeomagnetic data from Europe and their palaeogeographical implications

Trond H. Torsvik, Mark A. Smethurst, James C. Briden, et al.

Geological Society, London, Memoirs 1990; v. 12; p. 25-41
doi: 10.1144/GSL.MEM.1990.012.01.02

Email alerting service click here to receive free e-mail alerts when new articles cite this article

Permission request click here to seek permission to re-use all or part of this article

Subscribe click here to subscribe to Geological Society, London, Memoirs or the Lyell Collection

Notes

Downloaded by on January 24, 2012

© The Geological Society 1990. All rights reserved.

A review of Palaeozoic palaeomagnetic data from Europe and their palaeogeographical implications

TROND H. TORSVIK,[1] MARK A. SMETHURST,[1] JAMES C. BRIDEN[1] & BRYAN A. STURT[2]

[1] *Department of Earth Sciences, University of Oxford, Oxford OX1 3PR, UK*

[2] *Norwegian Geological Survey, P.B. 3006 Lade N-7002 Trondheim, Norway*

Abstract: Recent palaeomagnetic studies on Devonian and Carboniferous rocks have resulted in a time re-calibration of the Apparent Polar Wander Path (APWP) for Europe, and revision of the shape of the APWP for North America. Differences between previously published versions of these paths are now much reduced. The APWP for southern Britain is different from those for North America and Armorica, thus southern Britain is believed to have been an isolated block within the pre-Hercynian ocean. New continental reconstructions are presented to take account of these conclusions. A lack of sufficient reliable palaeomagnetic data from Baltica make its position on the map uncertain, and hence the significance of the Tornquist Sea between Baltica and Palaeo-Europe remains incompletely understood.

Given the assumption of a geocentric dipole field, a plate's apparent polar wander path (APWP) forms a reference system with respect to the earth's spin axis and to other plates, thus providing important palaeogeographic information. APWPs, however, should not be considered as permanent frames of reference (Van der Voo 1988), and in particular better constraints on magnetic age by means of detailed field-tests have led to substantial changes in the time-calibration of APWPs.

A large number of Ordovician to Permian palaeomagnetic pole positions have been reported from Europe (North of the Alpine Orogenic Belt), and in order to overcome subjective data-selection various grading schemes have been proposed (e.g. McElhinny 1973; Briden & Duff 1981; Van der Voo 1988). The most important attributes include tectonic and magnetic age control by means of field-tests, and the application of stepwise demagnetization and modern analytical techniques. Nevertheless, it is still necessary to make some subjective judgments in data-selection. In this compilation we have attempted to include all 'reliable' Ordovician to Permian palaeomagnetic data from Northern Europe (cf. geographic locations in Fig. 1). The selected palaeomagnetic data (Tables 1–6) essentially follows compilations given in Briden *et al.* (1984, 1988), Torsvik *et al.* (1989*b*); Perroud *et al.* (1984*a*, *b*) and Kramhov *et al.* (1981), with the inclusion of some new data.

In orogenic zones, rotations on both vertical and horizontal axes occur, and terrane rotations have been demonstrated within the British/Norwegian Caledonides (Smethurst & Briden 1988; Robertson 1988; Abrahamsen *et al.* 1979; Torsvik *et al.* 1989*a*), and the European Hercynides (e.g. McClelland Brown 1983; Bachtadse & Van der Voo 1986). In this review, however, we will address ourselves primarily to assumed 'non-rotated' palaeomagnetic poles.

To aid the definition of APW trends within each tectonic unit, and compare trends between tectonic units we have fitted a smooth path to the data. One advantage of path fitting is that it also constitutes *provisional* data extrapolation. A number of numerical methods for fitting smooth paths to palaeomagnetic poles have been offered in the literature (Gould 1969; Parker & Denham 1979; Thompson & Clark 1981, 1982; Clark & Thompson, 1984; Jupp & Kent 1987). In the present account we have used the method of Jupp & Kent (1987) because most of the previously proposed methods can produce distortion if the data are spread over a large portion of the sphere, and moreover some of the solutions are not invariant to changes in co-ordinate system. The method of Jupp & Kent (1987) aims to fit 'spherical smoothed splines' to a given data-set on the sphere with known ages. The palaeomagnetic pole ages listed in Tables 1–6 represent either approximate magnetic ages quoted in the original studies, or re-interpreted ages by the authors. Magnetic age reinterpretation has been made in cases where there are no independent magnetic age constraints and the palaeomagnetic pole falls on a younger part of the APWP, between well-dated poles. The method we have applied allows various levels of smoothing, as well as weighting of individual data points. We have weighted the data according to their α_{95}, but in the case of some well-dated key poles (e.g. the well-established Upper Silurian/Lower Devonian and Permian poles from Britain) these have been assigned a low α_{95}, value (= 1) to anchor the path. Smoothing methods have certain limitations especially when there are abrupt trend changes in the data, and in such instances it is then necessary to use low smoothing parameters.

Apparent polar wander paths

The British Isles is a key area for palaeomagnetic study of the Lower–Middle Palaeozoic rocks of Europe, and the Ordovician to Permian Apparent Polar Wandering (APW) path from the SE margin of the Laurentian plate, i.e. Northern Ireland and Scotland, is known with some confidence (see e.g. Briden *et al.* 1984, 1988). The Middle–Upper Devonian pole position, however, is not well known, and a number of proposed Devonian poles lie between well-dated Lower Carboniferous and Permian results (Torsvik *et al.*, 1988*b*). Therefore we regard the majority of reported mid–late Devonian poles (mostly derived from sediments) for which there is no magnetic age control as Carboniferous overprints (*c.* 320 Ma; see Tables 1–3). Conversely tectonic models based on the existing 'Devonian' data-base should be considered with great caution.

For convenience we have divided the British Caledonides into three major units (Fig. 1b): (1) the area north of the Great Glen Fault (GGF); (2) the area between the GGF and the Iapetus Suture; (3) the area south of the Iapetus Suture.

Ordovician to Permian palaeomagnetic south pole positions from these units are listed in Tables 1–3 (Fig. 2). The hallmark of the British APW paths is one of pronounced westerly movement through Ordovician and Silurian times. The Upper Silurian/Lower Devonian 'corner' (Fig. 3) in the path is widely accepted, but the apparent backtracking of the APW path during the Siluro-Devonian poses serious problems in discriminating Siluro-Devonian and Lower Carboniferous poles.

Models have been proposed involving major transcurrent motion along the GGF (e.g. Van der Voo & Scotese 1981; Storetvedt 1987), and as such it has been utilized in certain plate models as a prima-facie candidate for a major crustal megashear. The APW paths for the two northerly structural units, i.e. those on either side of the GGF, are virtually identical (Fig. 3), thus precluding large-scale movements (>500 km) along the GGF (and/or the Highland Boundary/Southern Upland Faults). Conse-

From McKerrow, W. S. & Scotese, C. R. (eds), 1990, *Palaeozoic Palaeogeography and Biogeography*, Geological Society Memoir No. 12, pp. 25–41.

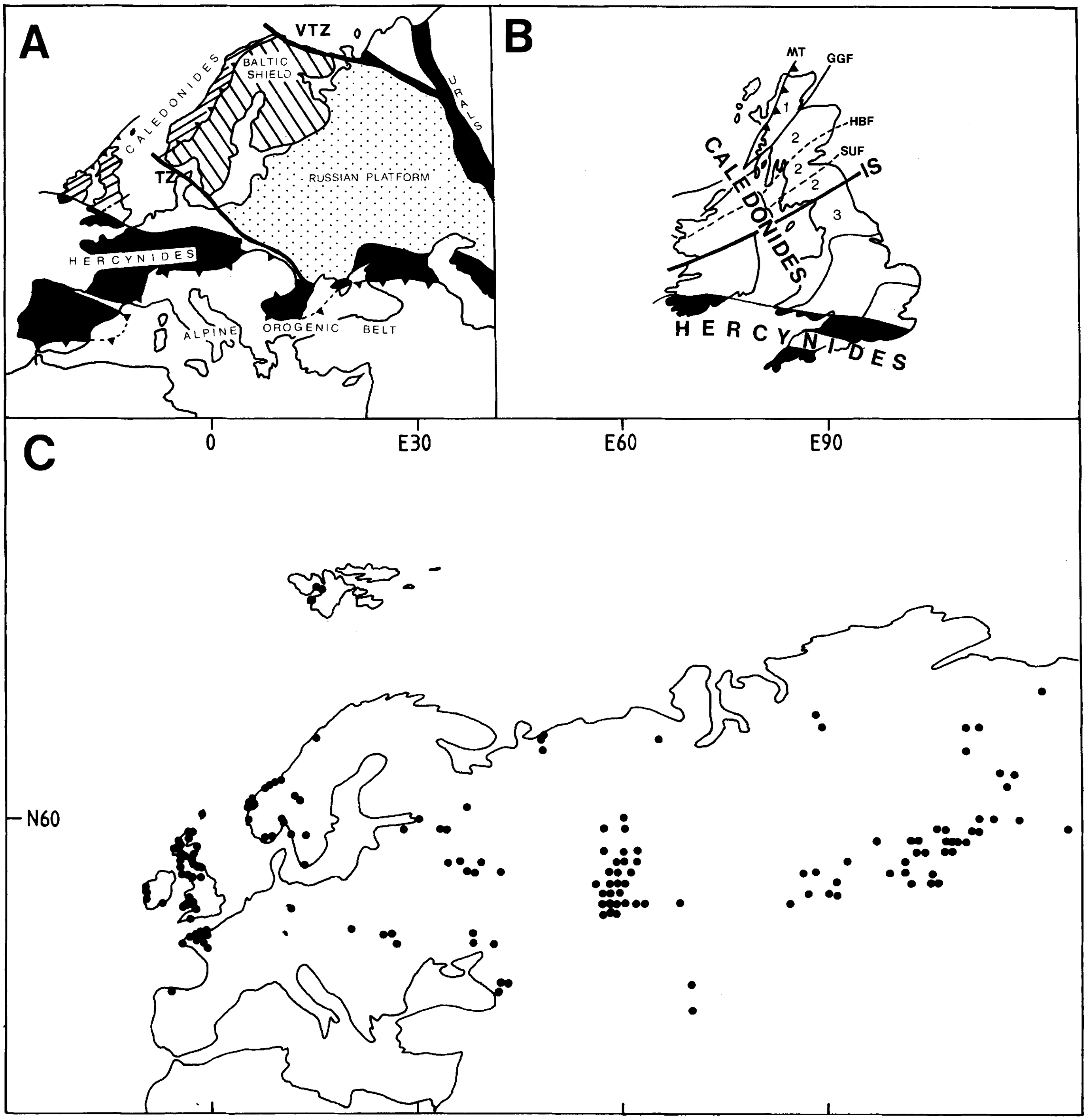


Fig. 1. Principal tectonic units (**a**) of Europe and (**b**) of the British Isles; TZ, Tornquist Zone; VTZ, Varanger Timian Zone; MT, Moine Thrust Zone; GGF, Great Glen Fault; HBF, Highland Boundary Fault; SUF, Southern Upland Fault; IS, Iapetus Suture: 1–3 denote tectonic units discussed in the text. (**c**) the geographical sampling locations for palaeomagnetic poles listed in Tables 1–6.

quently we have combined the palaeomagnetic data from these two units to produce a single APWP for Northern Britain (Fig. 4).

Few new palaeomagnetic data have been reported from southern Britain in recent years, but as previously pointed out by Briden *et al.* (1984, 1988), the majority of Ordovician palaeomagnetic data from southern Britain define an APWP with a more northerly (equatorial) polar trend compared with that recorded north of the suture. This is clearly shown by our fitted paths (Figs 3 & 4) for Ordovician to Middle Silurian times. The post-Lower Devonian paths for northern and southern Britain are essentially similar.

In Northern/Central Europe, overprinting related to Hercynian deformation conceals the original Palaeozoic magnetic signatures. Large discrepancies in declination or azimuth, but fairly coherent inclinations, also point to considerable tectonic/palaeomagnetic rotations of Hercynian age (Bachtadse & Van der Voo 1986). Palaeomagnetic data from the Armorican Massif, however, have shed some interesting light on Palaeozoic reconstructions (Perroud *et al.* 1984*a*). Palaeozoic palaeomagnetic data from the Armorican Massif consist almost entirely of Ordovician and Carboniferous (Hercynian) poles (Fig. 5a). The Silurian and Devonian section of the fitted path is essentially extrapolated between the two comparatively well-defined end-points. The APWP from the

Table 1. *Britain north of GGF.*

Rock-unit	Code	Age	Lat	Long	Reference
Rackwick lavas	(RL)	320 M*	−23	326	Storetvedt & Meland (1985)
Esha Ness ignimbrites	(EN)	320 M*	−20	315	Storetvedt & Torsvik (1985)
Caithness sandstone	(CS)	320 M*	−27	329	Storetvedt & Torsvik (1983)
Argyllshire dykes	(AD)	320 R	−35	355	Esang & Piper (1984*a*)
John O'Groats Sandstone	(JG)	320 M*	−24	325	Storetvedt & Carmichael (1979)
Shetland Sst. & Lavas	(SL2)	320 M	−24	340	Torsvik *et al.* (1989*d*)
Hoy lavas	(HL)	370 R	−14	334	Storetvedt & Meland (1985)
Shetland lavas	(SL1)	370 M	−2	340	Torsvik *et al.* (1989*d*)
Eday Sandstone	(ED)	375 R	−8	346	Robinson (1985)
Kishorn-Moine metased.	(KM2)	400 M	−14	320	Torsvik & Sturt (1988)
Sarclet L.ORS	(SA)	400 R	−9	326	Storhaug & Storetvedt (1985)
Borrolan Syenite, Loch Ailsh & dykes[1]	(BS)	408 M	−17	326	Turnell & Briden (1983)
Moine metased. (Ratagen)	(MR)	408 M	1	324	Turnell (1985)
Moine metasediments (IB)[1]	(MMI)	408 M	−1	309	Watts (1982)
Moine metasediments (HB)[1]	(MMH)	408 M	−6	313	Watts (1982)
Ratagen Complex	(RC)	415 R	−15	347	Turnell (1985)
Helmsdale granite	(HG)	420 R	−31	355	Torsvik *et al.* (1983)
Strontian granite	(SG)	430 R	−21	344	Torsvik (1984)
Borrolan Ledmorite, Pseudo-leucite, Loch Loyal[1]	(BL)	430 R	−13	2	Turnell & Briden (1983)
Caledonian dolerites	(CD)	435 M	−14	347	Esang & Piper (1984*b*)
Caledonian microdiorites	(CM)	435 M	−16	346	Esang & Piper (1984*b*)
Kishorn−Moine metased.	(KM1)	450 M	−14	42	Torsvik & Sturt (1988)
Caledonian Dolerites	(CA)	450 M	−5	56	Esang & Piper (1984*b*)

Palaeomagnetic South Poles are given; LAT, Latitude in degrees;
LONG, Longitude in degrees east;
R, Rock-age; M, magnetic age if not rock-age (*revised age)
[1] Combined pole for reasons of clarity (IB, Intermediate blocking; HB, High blocking)

Table 2. *Britain south of GGF, north of Iapetus*

Rock-unit	Code	Age	Lat	Long	Reference
Peterhead dyke	(PD)	260 R	−41	342	Torsvik (1985*b*)
Dykes & remag. ORS	(DR)	270 RM	−43	343	Torsvik *et al.* (1989*b*)
Queensferry Sill	(QF)	280 R	−38	354	Torsvik *et al.* (1989*b*)
Salrock Fm. overprint	(SFO)	320 M*	−28	331	Smethurst & Briden (1988)
Claire Island overprint	(CO)	320 M*	−35	331	Smethurst & Briden (1988)
Tourmakeady & Glensaul	(TG)	320 M*	−31	349	Deutsch & Storetvedt (1988)
Foyers sandstone	(FS)	320 M*	−30	326	Kneen (1974)
Jedburgh Upper ORS	(JB)	320 M*	−32	338	Nairn (1960)
Burntisland & Kinghorn	(BK)	350 R	−14	332	Torsvik *et al.* (1989*b*)
Clyde Lava & remag. ORS	(CL)	350 RM	−14	322	Torsvik *et al.* (1989*b*)
Cheviot[1]	(CV)	398 R	4	323	Thorning (1974)
Garabal Hill−Glen Fyne	(GH)	404 R	−5	326	Briden (1970)
Lorne Plateau lavas	(LP)	405 R	2	321	Latham & Briden (1975)
ORS lavas & sediments	(MV)	408 R	−4	320	Sallomy & Piper (1973)
Strathmore lavas	(SL)	408 R	2	318	Torsvik (1985*a*)
Lower ORS	(LW)	408 R	−11	307	Douglass (1987)
Comrie complex	(CM)	408 R	−6	287	Turnell (1985)
Peterhead granite	(PG)	415 R	−20	357	Torsvik (1985*b*)
Arrochar complex	(AC)	418 R	−8	324	Briden (1970)
Salrock Formation	(SF)	420 R	−2	288	Smethurst & Briden (1988)
Foyers granite	(FG)	420 R	−27	346	Torsvik (1984)
Aberdeenshire gabbros 3[1]	(AG3)	428 M	−6	331	Watts & Briden (1984)
Aberdeenshire gabbros 2[1]	(AG2)	448 M	−5	360	Watts & Briden (1984)
Ballantrae gabbros	(BG)	450 M	−10	26	Piper (1978*a*)
Ballantrae serpentinites	(BS)	450 M	−12	27	Piper (1978*a*)
Barrovian zone	(BZ)	450 M	−3	22	Watts (1985*a*)
Aberdeenshire gabbros 1[1]	(AG1)	468 M	−14	28	Watts & Briden (1984)
Mweelrea Ignimbrites	(MW)	470 R	−11	38	Morris *et al.* (1973)

Legend as Table 1
ORS = Old Red Sandstone

Table 3. *Britain south of Iapetus*

Rock-unit	Code	Age	Lat	Long	Reference
Exeter lavas	(EL)	280 R	−46	345	Cornwell (1967)
Whin sill	(WS)	281 R	−44	339	Storetvedt & Gidskehaug (1969)
Wackerfield dyke	(WD)	303 R	−49	349	Tarling & Mitchell (1973)
Bristol Upper ORS	(BS)	320 M*	−32	338	Morris *et al.* (1973)
Hendre & Blodwell intrusive rocks	(HB)	320 M*	−32	346	Piper (1978*b*)
Lower ORS Wales	(ORS)	398 R	3	298	Chamalaun & Creer (1964)
Lavas Somerset & Gloucester	(SG)	400 R	8	309	Piper (1975)
Shelve volcanic rocks	(SH)	440 R	−5	78	Piper (1978*b*)
Builth intrusive rocks	(BI)	446 R	2	2	Piper & Briden (1973)
Carrock Fell gabbro	(CA)	448 R	−19	4	Briden & Morris (1973)
Builth volcanic rocks	(BU)	450 R	−3	5	Briden & Mullan (1984)
Breidden Hills	(BR)	453 R	1	17	Piper & Stearn (1975)
Eycott Group	(EG)	460 R	−7	357	Briden & Morris (1973)
Tramore volcanic rocks	(TV)	460 R	11	342	Deutsch (1980)
Borrowdale Volcanic Group	(BV)	460 R	0	23	Faller *et al.* (1977)

Legend as Table 1

Table 4. *Baltic Shield (Scandinavia)*

Rock-unit	Code	Age	Lat	Long	Reference
Ny−Hellesund dykes		255 R	−38	340	Halvorsen (1970)
Arendal (1)		255 R	−44	341	Halvorsen (1972)
Arendal (2)		255 R	−39	333	Halvorsen (1972)
Ytterøy lamprophyre		256 R*	−43	324	Torsvik *et al.* (1989*c*)
Bohuslan dykes (mean)		260 R	−46	345	Abrahamsen *et al.* (1979)
Oslo Igneous rocks (B)		270 R	−40	340	Storetvedt *et al.* (1978)
Oslo Graben Lavas		270 R	−45	338	Douglass (1988)
Sunnhordaland dykes		275 R	−43	342	Løvlie (1981)
Sarna body		287 R	−38	347	Bylund & Patchett (1977)
E−Vastergotland sill		287 R	−31	354	Mulder (1971)
Stabben sill (HB)		297 R	−32	354	Sturt & Torsvik (1987)
Scania dolerites		300 R	−37	354	Mulder (1971)
Scania dolerites		300 R	−39	349	Bylund (1974)
Kvamshesten Sandstone	(KH)	360 M	−21	324	Torsvik *et al.* (1986)
Hornelen Sandstone (A)	(HO)	360 M	−12	327	Torsvik *et al.* (1988)
Håsteinen (A)	(HA)	360 M	−16	335	Torsvik *et al.* (1987)
Hitra Sandstone	(HS)	360 M	−8	350	Bøe *et al.* (1989)
Fongen−Hyllingen P2	(FH)	360 M*	−11	312	Abrahamsen *et al.* (1979)
Røragen Sandstone	(RO)	360 M*	−19	340	Storetvedt & Gjellestad (1966)
Askøy Pluton (B1)	(AP1)	360 M	−16	340	Rother *et al.* (1987)
Smøla ORS/substrate	(SM)	365 M	−13	346	Torsvik *et al.* (1989*a*)
Ringerike Sandstone	(RS)	415 R	−19	344	Douglass (1988)
Gotland Follingbo limest.	(GF)	425 R	−21	344	Claeson (1979)
Gotland limestone	(GL)	425 R	−19	349	Claeson (1979)
Gotland Medby Limestone	(GM)	425 R	−23	351	Claeson (1979)
Skaane limestone	(SL)	425 R	−22	341	Claeson (1979)
Sulitjelma gabbro	(SG)	443 R	−14	0	Piper (1974)
Askøy Pluton (A1)†	(AP2)	474 ?	−25	53	Rother *et al.* (1987)

Legend as Table 1
† The Askøy Pluton (A1) could be rotated since it is situated within a Scandian (Late Silurian) allochthonous unit.

Armorican Massif is in this account considered as representative for the Armorican plate, defined by Van der Voo (1979) to embrace the Armorican and Bohemian Massifs, the Avalon block and southern Britain. The fitted path for Armorica, however, shows a clear discordance with the fitted path for southern Britain from Ordovician to Silurian times (Fig. 4), thus favouring the view that Southern Britain was marginal to Baltica rather than Armorica (Livermore *et al.* 1985; Briden *et al.* 1988). It should be noted, however, that a subordinate number of Ordovician palaeomagnetic poles from southern Britain (cf. Thomas & Briden 1976; McCabe 1988) have been argued as having better correspondence with Armorican palaeomagnetic poles (see later).

Palaeomagnetic data from the Baltic Shield (Scandinavia) indicate inconsiderable APW through Middle Palaeozoic time (Fig. 5b). The majority of poles of published pre-Devonian age, for which there is poor or no magnetic age control, plot close to Upper Devonian/Lower Carboniferous poles. Accruing evidence suggests that the latest Caledonian tectonism, including terrane

Table 5. *Northern Europe (Armorican Massif)*

Rock-unit	Code	Age	Lat	Long	Reference
Rozel B		300 M	−37	341	Perroud *et al.* (1982)
Tregastel−Ploumanac'h		300 M	−34	332	Duff (1979)
Jersey dolerite (A)		300 M	−31	336	Duff (1980)
Crozon dolerites remag.		300 M	−23	322	Perroud *et al.* (1983)
Montmartin Red Beds		300 M	−38	325	Perroud *et al.* (1984*b*)
Laval syncline		300 M	−33	309	Edel & Coulon (1984)
Cambro−Ord. Red beds		300 M	−33	325	Duff (1979)
Cap Frehel		300 M	−39	338	Jones *et al.* (1979)
Zone Bocaine		300 M	−33	332	Jones *et al.* (1979)
Paimpol−Brehec		300 M	−26	320	Jones *et al.* (1979)
San Pedro red beds[2]		320 M*	−23	324	Perroud & Bonhommet (1984)
Carteret (B)		320 M	−18	322	Perroud *et al.* (1982)
Flamanville		320 M	−30	332	Van der Voo & Klootwijk (1972)
Thouars Massif remag.		320 M	−23	316	Perroud & Van der Voo (1985)
Moulin de Chat remag.		320 M	−21	320	Perroud *et al.* (1986*a*)
St Malo dykes		330 M	−30	328	Perroud *et al.* (1986*b*)
Jersey dolerite (B)	(JD)	408 M	−1	339	Duff (1980)
Jersey lampr. dykes	(JL)	408 M	16	322	Duff (1980)
Crozon dolerites	(CD)	440 R	3	358	Perroud *et al.* (1983)
Thouars Massif	(TM)	444 R	34	5	Perroud & Van der Voo (1985)
Cabo de Penas[2]	(CP)	450 R	30	330	Perroud (1983)
Moulin de Chat Fm.	(MC)	480 R	34	343	Perroud *et al.* (1986*a*)
Erquy Spilite series	(ES)	493 M	35	344	Duff (1979)

[2] Corrected for the opening of Bay of Biscay
Legend as Table 1

Table 6. *Spitsbergen*

Rock-unit	Code	Age	Lat	Long	Reference
Permo−Carboniferous sst	(PC)	280 R	−36	321	Vincenz & Jelenska (1985)
Billefjorden sandstone	(BF)	350 R	−23	332	Watts (1985*b*)
Mimer Valley Sandstone	(MV)	360 M	−24	325	Torsvik *et al.* (1985)
Wood Bay Sst. Combined	(WB)	408 R	−3	322	Torsvik et al. (1985), Jelenska & Lewandowski (1986) and Douglass (1987)

Legend as Table 1

docking (Torsvik *et al.* 1986, 1987, 1988, 1989*a*; Sturt & Roberts 1987), occurred in Late Devonian time. This episode is generally known as the Solundian/Svalbardian orogenic phase (Sturt 1983). The apparent lack of APW for the Baltic Shield during Ordovician and Silurian times could, therefore, be explained by widespread Late Devonian remagnetization associated with the Solundian/Svalbardian orogenic phase. The Lower−Middle Palaeozoic APWP for the Baltic Shield should therefore be viewed with considerable caution (see also Pesonen *et al.* 1989). As yet, only the Middle Silurian Ringerike Sandstone for which there is a positive fold-test, and a stratigraphically related polarity pattern (Douglass 1988), can be regarded as a reliable pre-Devonian pole position from the Baltic Shield.

Few Palaeozoic palaeomagnetic results have been reported from Spitsbergen (Table 6, Fig. 5c). The fitted APWP for Spitsbergen is only based on four Lower Devonian to Permian poles, and is therefore weakly constrained (Fig. 6). Although the Lower Devonian pole is uncertain (see Løvlie *et al.* 1985 and Douglass 1987), the fitted path follows a pronounced southerly track which corresponds with the post Lower Devonian path of the two British paths (see also Torsvik *et al.* 1985; Watts 1985*a*, *b*; Douglass 1987). Note the discordance between the Spitsbergen and the Baltic Shield path in Fig. 6.

Ordovician to Permian data from the USSR have been divided into three parts, i.e. those data from the Russian Platform taken to be part of Baltica, those from the Urals region and those from the Siberian Platform. We have used the data compiled by Khramov *et al.* (1981) which are shown in Fig. 7. A number of the Lower−Middle Palaeozoic poles from the Russian Platform plot close to Permian poles from the Platform and Western Europe. Consequently, extensive Late Palaeozoic overprinting may also account for much of the Early to Middle Palaeozoic data from the Urals, and one can hardly distinguish palaeomagnetic poles astride the Urals. Thus, we have combined all data in Fig. 7b, and naturally, a fitted path can not be derived from such an analysis.

Time-calibration of some parts of the paths for the USSR (Russian and Siberian Platforms) is as yet impossible, and our interpretation of these data relies on a trend analysis which is only weakly time constrained. The Ordovician poles from the Siberian Platform, however, are well-grouped around 30° N−310° E (Fig. 7a) and do not conform to Permian poles which fall at intermediate southerly latitudes. The first Palaeozoic palaeomagnetic results from the Russian and Siberian Platforms were obtained at the beginning of the 1960s (see Krahmov & Sholpo 1967). It was shown that the data might be consistent with relative

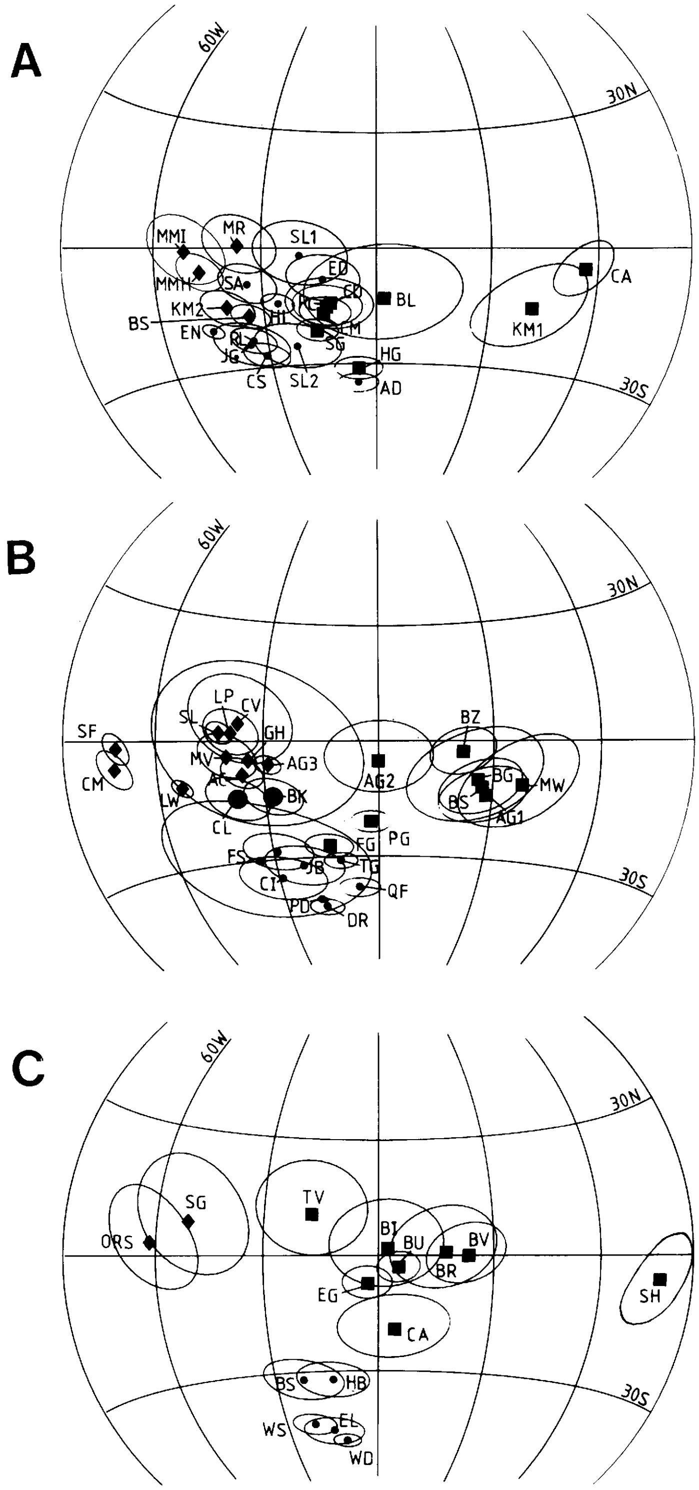


Fig. 2. Ordovician to Permian palaeomagnetic poles from the British Isles (**a**) North of the Great Glen Fault (GGF), (**b**) South of the GGF-North of the Iapetus Suture and (**c**) South of the Iapetus Suture. Cf. Tables 1–3 for pole labels. Square symbols, Ordovician/Silurian poles; Triangles, Upper Silurian/Lower Devonian poles; circles, Devonian to Permian poles. All poles are shown with the oval of 95% confidence around the mean pole (semi-axes dp/dm). Equal-area projection.

rotation of the two platforms, at least during the Early Palaeozoic. An alternative explanation has since been put forward which is that divergence in the Early Palaeozoic poles from the two platforms is due to widespread Upper Palaeozoic remagnetization on the Russian Platform, which is also seen throughout Western Europe. It is now generally accepted that extensive remagnetization of Lower–Middle Palaeozoic rocks of the Russian Platform has occurred, probably in Permo-Carboniferous time. However, this does not preclude significant Lower Palaeozoic relative movements/rotation of the Siberian and Russian platforms.

Palaeogeographic reconstructions

Throughout this study we use spherical splines as fitted APWPs (Table 7) from which we generate palaeo-reconstructions. This enables us to animate a plate-tectonic scenario for any given time. No error confidences have been listed for the APWPs, but it should be noted that the uncertainty is notably high and tentative in the extrapolated section of the paths. We emphasize that the fitted APWPs should not be considered absolute and some of the palaeogeographic enigmas are outlined below. All reconstructions are only quantitative in terms of palaeo-latitude, and palaeo-longitude is unconstrained by the paths. As time-calibration of much of the Russian and Siberian Platform APWPs is at present difficult, Baltica is positioned according to data from the Baltic Shield. Siberia is not included in the reconstructions because its Middle–Late Palaeozoic APWP is poorly constrained, and only Ordovician poles show a consistent grouping which deviates systematically from Late Palaeozoic (Permian) palaeomagnetic poles for Europe. For comparison, the coastline of North America is displayed and positioned according to Northern British data (southern margin of Laurentia) in a Bullard *et al.* (1964) fit.

There are only small differences between the paths in Lower Devonian times, and virtually no difference at all between the Permian part of the paths (Fig. 8). In post Lower Devonian time the paths move southward from near the equator, a feature also indicated in the Russian and Siberian Platform APWPs. The Baltic Shield APWP, however, deviates from this pattern, but the bend in its Middle Palaeozoic part of the path probably has no physical significance.

Ordovician

On the balance of both palaeomagnetic and faunal data it is evident that Armorica was situated in high southerly latitudes (probably together with Gondwana) in Middle Ordovician time (450 Ma; Fig. 9). Similarly, palaeomagnetic results from Siberia suggest high latitudes during Ordovician time. Perroud *et al.* (1984*a*) used the Ordovician palaeomagnetic data from Armorica to confirm the existence of a Medio-European Ocean (Whittington & Hughes 1972) which formed part of an implied triple-junction configuration with the Iapetus Ocean. Such an triple-junction pattern has also been suggested by Cocks & Fortey (1982). Based on faunal evidence Cocks & Fortey (1982) argue for a major oceanic separation between Gondwana and Baltica in Early Ordovician time (Tornquist Sea). The Tornquist Sea probably compares with the Medio-European Ocean of Whittington & Hughes (1972). Cocks & Fortey (1982) contend that the Tornquist Sea was essentially closed in Upper Ordovician time.

If we were to accept some 'anomalous' Ordovician palaeomagnetic poles (McCabe 1988) as being representative for southern Britain, it would carry the implication that southern Britain could have been positioned marginal to Armorica (see also Fig. 3a of Kent & Van der Voo 1990). This has obvious implications concerning the width of the Iapetus Ocean during the Ordovician. This southerly position of Southern Britain is based on a few 'anomalous' directions described in the literature together with a new palaeomagnetic result from the Llanvirn aged (*c.* 470 Ma) Stapeley Volcanic Formation (Welsh Borderlands; McCabe 1988). McCabe reports a pre-folding dual-polarity magnetization which implies high southerly latitudes (*c.* 50–55° S) for southern Britain (along with Armorica) during Ordovician times. However, this argument is not certain, and the best palaeomagnetic data (e.g. Builth volcanic rocks; Briden & Mullan 1984) suggest that

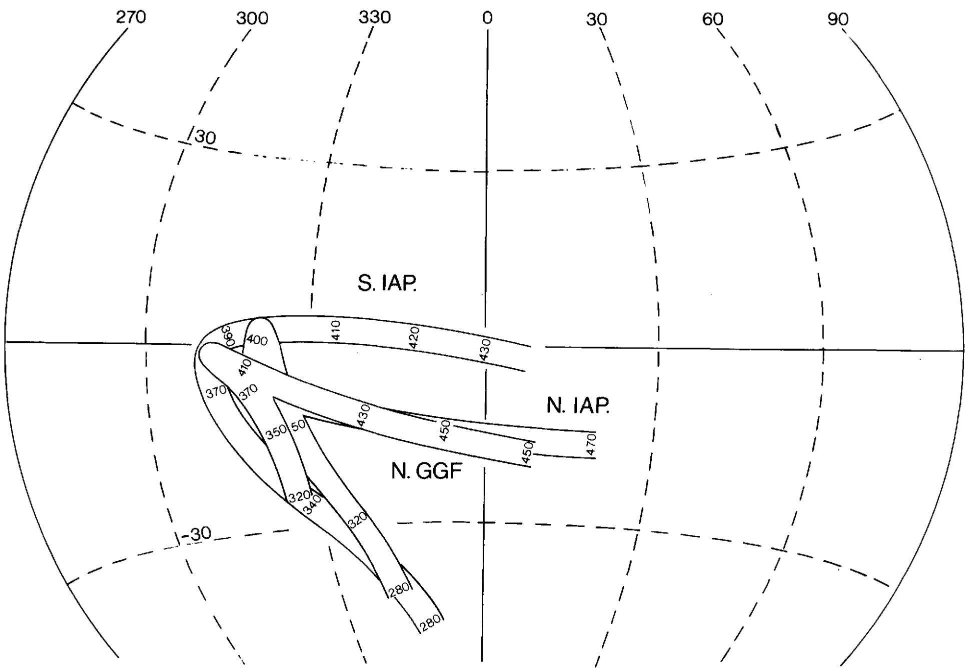


Fig. 3. Spherically smoothed APW paths for the palaeomagnetic poles shown in Fig. 2. S.IAP, South of Iapetus Suture; N.IAP, North of the Iapetus Suture/South of the Great Glen Fault; N.GGF, North of the Great Glen Fault. Numbers along the path represent ages in millions of years. Equal area projection.

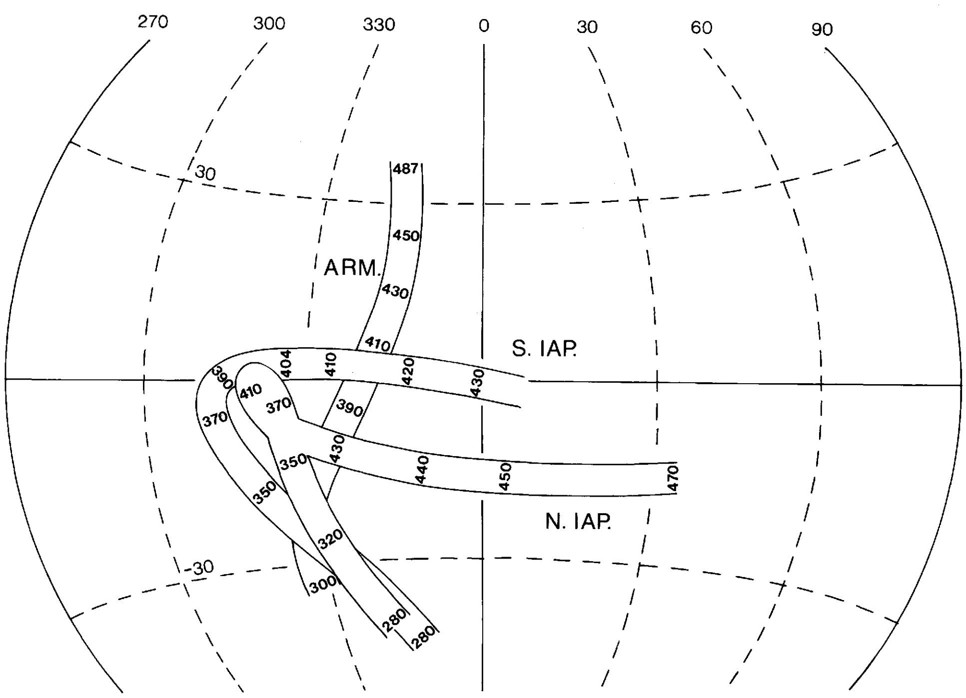


Fig. 4. Spherically smoothed APW paths for Armorica (ARM), South of Iapetus (S.IAP, British Isles) and North of Iapetus (N.IAP). See Table 7 for details. Convention as Fig. 3.

southern Britain was located in mid-latitudes (30–35° S), some 1000–1500 km south of Northern Britain at that time (Figs 9 & 10).

Throughout the Lower–Middle Palaeozoic, Baltica was effectively stationary at low latitudes (see e.g. Fig. 10). This, however, could be an artifact of extensive Devonian/Lower Carboniferous remagnetization. An equatorial position for Baltica is not consistent with faunal evidence which indicates temperate latitudes for Baltica in Ordovician times. This is why a number of published Ordovician reconstructions show Baltica at southerly latitudes around 30–45° (see e.g. Cocks & Fortey 1982; Fortey & Cocks 1988; Livermore *et al.* 1985). The reconstructions based on Ordovician palaeontological evidence, however, make little allowance for oceanic circulation models, and in particular major current patterns.

Silurian

It has commonly been argued that Armorica (and Gondwana) drifted northwards during latest Ordovician and Silurian times. By Middle–Silurian time (Fig. 11) Armorica appears marginal to southern Britain. In an alternative model, however, Edel (1987*b*) postulates that Armorica consisting of Central Europe was situated at high latitudes until Middle–Upper Devonian time. Northern and southern Britain appear to have remained fairly stationary at temperate/tropical palaeo-latitudes during the Early Palaeozoic.

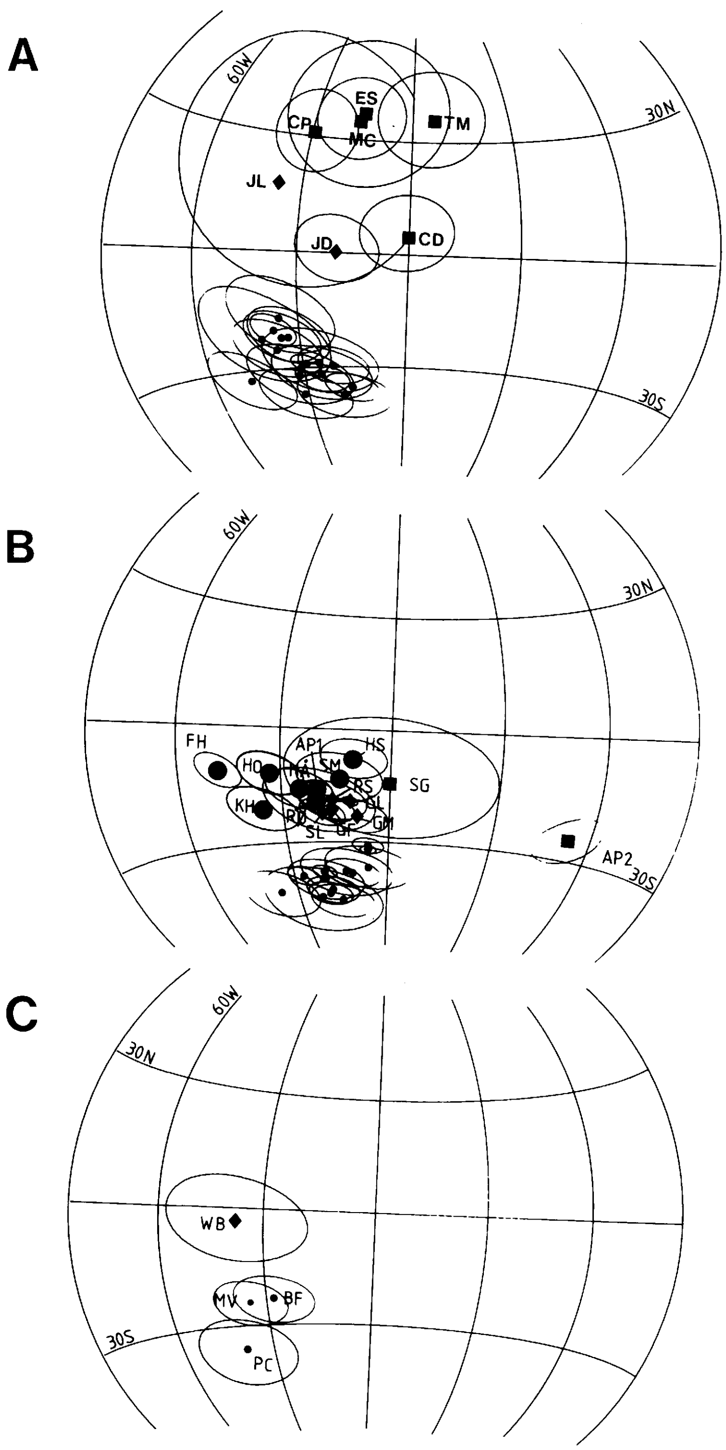


Fig. 5. Ordovician to Permian (Carboniferous) from (a) the Armorican Massif, (b) Baltic Shield and (c) Central Spitsbergen. See Tables 4–6 for details. Permo-Carboniferous poles in (a) and (b) are unlabelled. Symbol code in (a,c) as Fig. 2. In (b) large circular symbols denote poles known to represent secondary Solundian/Svalbardian remagnetization.

Conversely the width of the intervening Iapetus Ocean is probably as wide as in Ordovician time. Considerable anti-clockwise rotation of Northern Britain during Ordovician and Silurian time took place (compare Figs 9 & 11; see also Fig. 10), a feature, also characteristic of the North American craton (Van der Voo 1988). The latitudinal position of northern Britain, during Ordovician and Silurian times, however, is somewhat more southerly than latitudes predicted from the North American data-base. This has recently been amplified by Briden *et al.* (1988) and Van der Voo (1988). New palaeomagnetic data from North America (Miller &

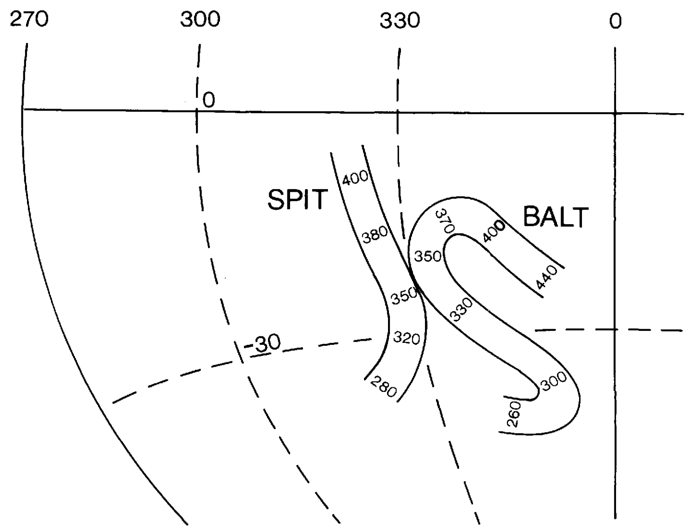


Fig. 6. Spherically smoothed APW paths for Spitsbergen (SPIT) and the Baltic Shield (BALT). Conventions as Fig. 3.

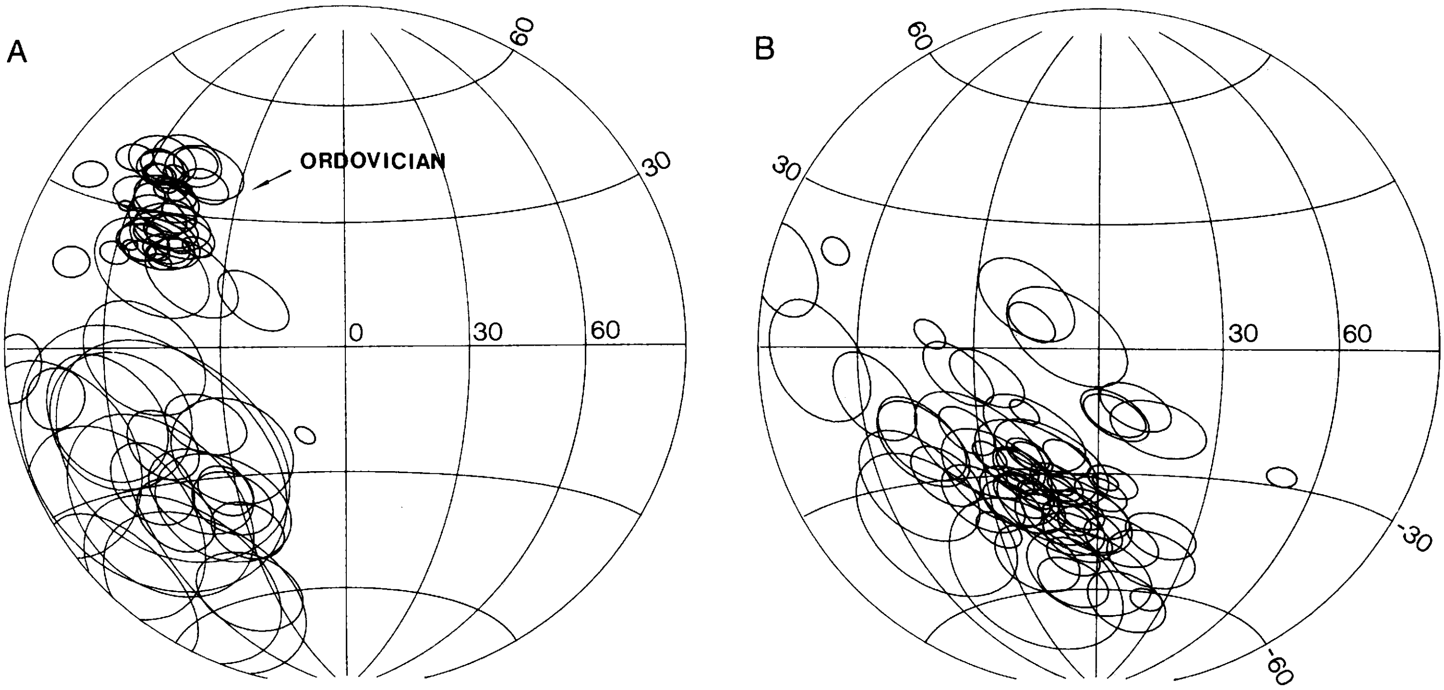
Kent 1988) and Greenland (Stearns *et al.* Pers. Comm.), however, imply a more southerly position of the North American craton in Upper Silurian/Lower Devonian time than had previously been assumed. Thus, taken as a face value, the APWPs from northern Britain and the North American craton (Laurentia) now converge to a common path in a classical Bullard *et al.* (1964) fit.

The most striking difference between recent palaeoreconstructions shown by Livermore *et al.* (1985) and those presented here, is our equatorial positioning of Baltica throughout Ordovician and Silurian time (Figs 9 & 11). Livermore *et al.* (1985) always show Baltica marginal to southern Britain. The relationship between southern Britain and Armorica also differ somewhat in our reconstructions, and for example during the Silurian we suggest a closer relationship between Armorica and southern Britain (Fig. 11) than that presented by Livermore *et al.* (1985; see their fig. 5). Furthermore, Livermore *et al.* (1985) map the Avalon Platform marginal to Southern Britain, whereas we have plotted the Avalon Platform at high southerly latitudes as part of the Armorican plate.

Early–Middle Devonian

By Early Devonian times the APW paths for northern and southern Britain converge (Figs 10 and 12), implying effective closure of the Iapetus Ocean in Britain. Recent studies in the Scandinavian Caledonides, however, have attempted to establish how much Caledonian terrane accretion can be ascribed to a Late Devonian (Solundian) orogenic event rather than Late Silurian (Scandian) crustal imbrication. The metamorphic signature of folded Devonian sediments in Norway and Western Shetland, and the occurrence of Lower–Middle Devonian island-arc type calc-alkaline lavas (Thirlwall 1981, 1988) cut by a calc-alkaline batholith in Western Shetland suggests final closure of parts of the Iapetus Ocean system in as late as Middle–Late Devonian time (Thirlwall 1988; Torsvik *et al.* 1988*a*).

Baltica and Laurentia most likely collided in the earliest Devonian to form Euramerica. In Middle–Upper Silurian time Laurentia was drifting southward, and during the collisional event Laurentia attained its most southerly Palaeozoic latitudinal position. The southerly latitudinal shift of Laurentia during Silurian times, previously only evident from palaeomagnetic data from northern Britain, is confirmed by (1) new Upper Silurian/Lower Devonian palaeomagnetic data from North America/Greenland (see Kent & Van der Voo 1990) and (2) Late Ordovician/Silurian expansion of evaporites across central North America (Witzke 1988).



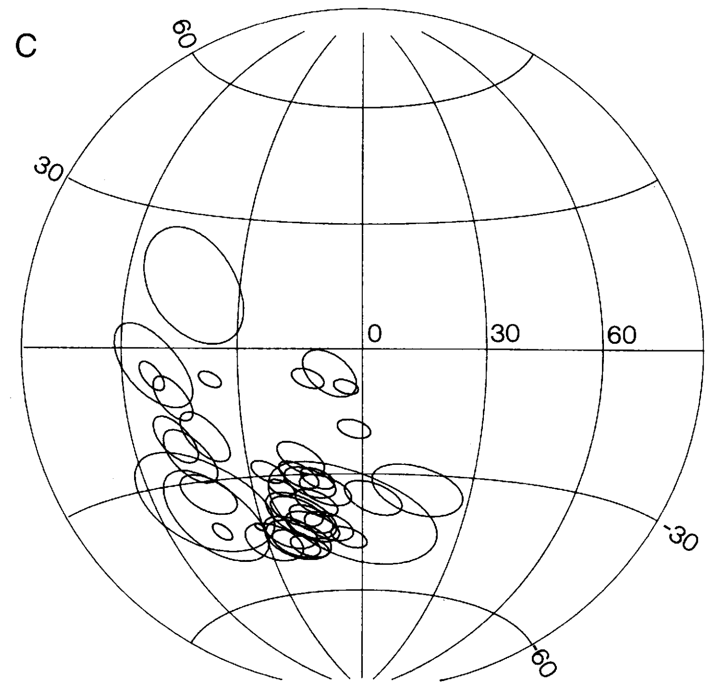


Fig. 7. Ordovician to Permian palaeomagnetic poles (portrayed with oval of 95% confidences) from (**a**) Siberian Platform, (**b**) the 'Urals' and (**c**) Russian Platform. Note in (a) that Ordovician palaeomagnetic poles cluster around N30 & E 310.

The precise timing of the docking of Armorica against Laurentia/Baltica is uncertain. Van der Voo (1979) originally suggested that collision was related to the Taconian Orogeny. This view was later revised, and Perroud *et al.* (1984*a*, *b*) and Van der Voo & Johnson (1987) proposed collision in the Early–Middle Devonian, marked by the Acadian Orogeny, to form the Old Red Sandstone Continent. This issue is still not clear due to the sparsity of Siluro-Devonian palaeomagnetic data, and the only Late Silurian–Lower Devonian poles claimed in the literature as being representative for Armorica are from the Jersey dolerite and lamprophyre dykes, for which there is no magnetic age control. The fitted paths for southern Britain and Armorica, however, suggest that the two were at similar latitudes during Early Devonian time.

Late Devonian/Early Carboniferous

The Ordovician–Devonian APWP discordance between Baltica, and Britain and Armorica is eliminated in Carboniferous times (cf. Figs 13 & 14). If the relatively large pre-Carboniferous discordance in the paths between Baltica and southern/northern Britain is real, Baltica and Britain can be assumed to have moved into their present juxtaposition in Late Devonian to Lower Carboniferous time through megashearing along the Tornquist

Table 7. *Palaeozoic Apparent Polar Wander Paths for N. Europe in 10 million year intervals*

	N Britain		S Britain		Armorica		'Baltica'		Spitsbergen	
Age	lat	long	lat	long	lat	long	lat	long	lat	long
260	−42	343					−42	344		
270	−42	342					−42	348		
280	−41	341	−46	342			−41	351	−36	322
290	−39	340	−48	345			−38	352	−35	323
300	−35	337	−48	347	−33	328	−37	351	−34	325
310	−31	333	−45	346	−31	328	−34	347	−32	326
320	−28	332	−38	341	−28	327	−31	342	−30	328
330	−24	330	−32	335	−26	327	−27	337	−28	328
340	−18	328	−25	327	−23	328	−23	333	−27	328
350	−14	327	−20	322	−20	330	−19	331	−25	328
360	−9	326	−12	315	−17	331	−16	333	−22	328
370	−5	325	−8	313	−12	333	−14	337	−20	326
380	−2	324	−3	312	−8	336	−14	339	−16	325
390	+1	322	+1	315	−4	337	−14	341	−13	324
400	0	320	+2	322	0	339	−16	342	−9	323
410	−3	320	+3	334	+6	341	−18	344	−5	322
420	−8	325	+2	348	+10	343	−19	346		
430	−12	335	0	359	+15	345	−21	348		
440	−15	352	−2	006	+20	346	−23	350		
450	−16	004	−3	007	+25	346				
460	−16	019	−3	003	+29	346				
470	−15	036			+33	345				
480					+36	345				
490					+39	344				

Legend as Table 1

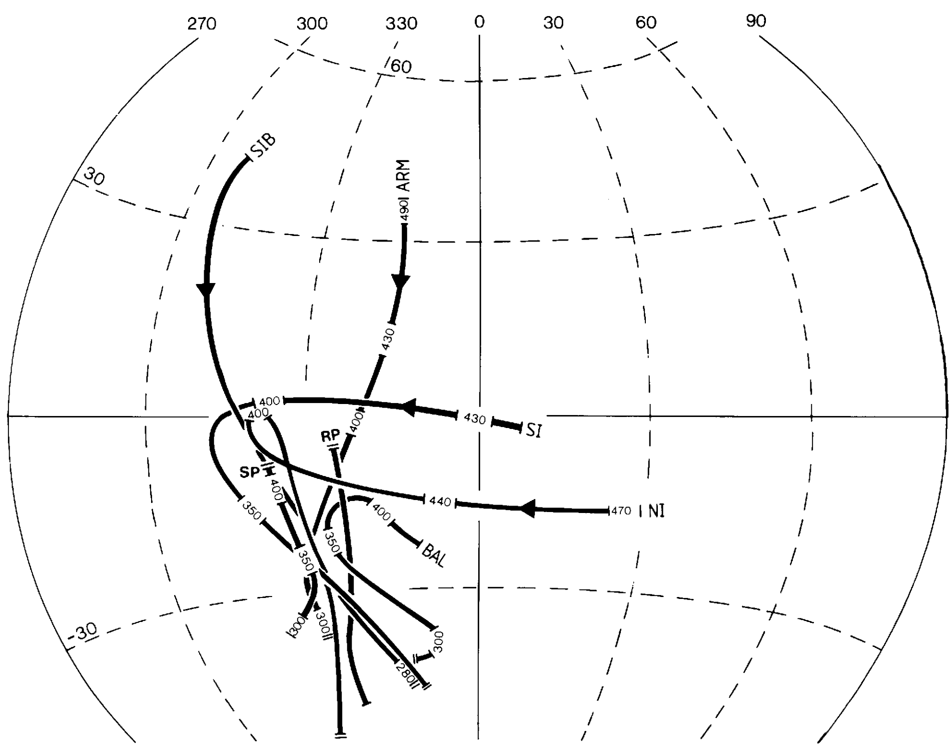


Fig. 8. Compilation of all spherically smoothed paths. SIB, Siberian Platform; ARM, Armorica; SI, South of Iapetus (British Isles); NI, North of Iapetus; BAL, Baltic Shield; SP, Spitsbergen; RP, Russian Platform. Note that SIB and RP are only distributional trend paths.

Zone since there is no evidence for an ocean. Central Spitsbergen is generally considered part of Baltica in Devonian times. However, the palaeo-latitudinal trend for Spitsbergen is consistent with Britain. Consequently, if we were to accept dextral mega-shearing along the Tornquist Zone (Fig. 1a) as for example postulated by Douglass (1988), it would also have been accompanied by sinistral movements along the north-eastern border of Baltica, i.e. the Varanger–Timian Zone (cf. geographic location in Fig. 1a). Devonian or younger movements along the Varanger–Timian Zone, however, are precluded by the continuity of Caledonian Nappes across the zone. We would stress again, however, that the Lower–Middle Palaeozoic data from Scandinavia are of uncertain age and/or tectonic significance (see e.g. Pesonen *et al.* 1989), excepting the Ringerike Sandstone results of Douglass (1988). Therefore reconstructions of the Baltic Shield based on Lower–Middle Palaeozoic palaeomagnetic data are at best speculative. The position of Baltica has therefore traditionally been heavily reliant on the assumption

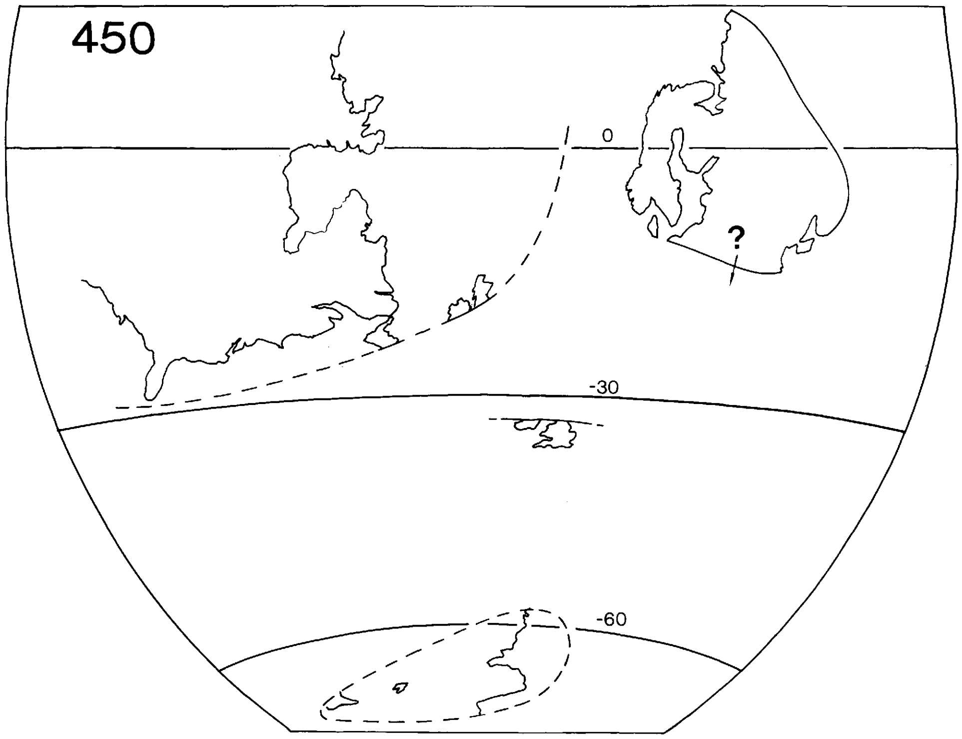


Fig. 9 Ordovician (450 Ma) reconstruction based on palaeomagnetic data. Optional longitude. Laurentia (N. America) positioned according to Northern Britain palaeomagnetic data. Equal-area projection.

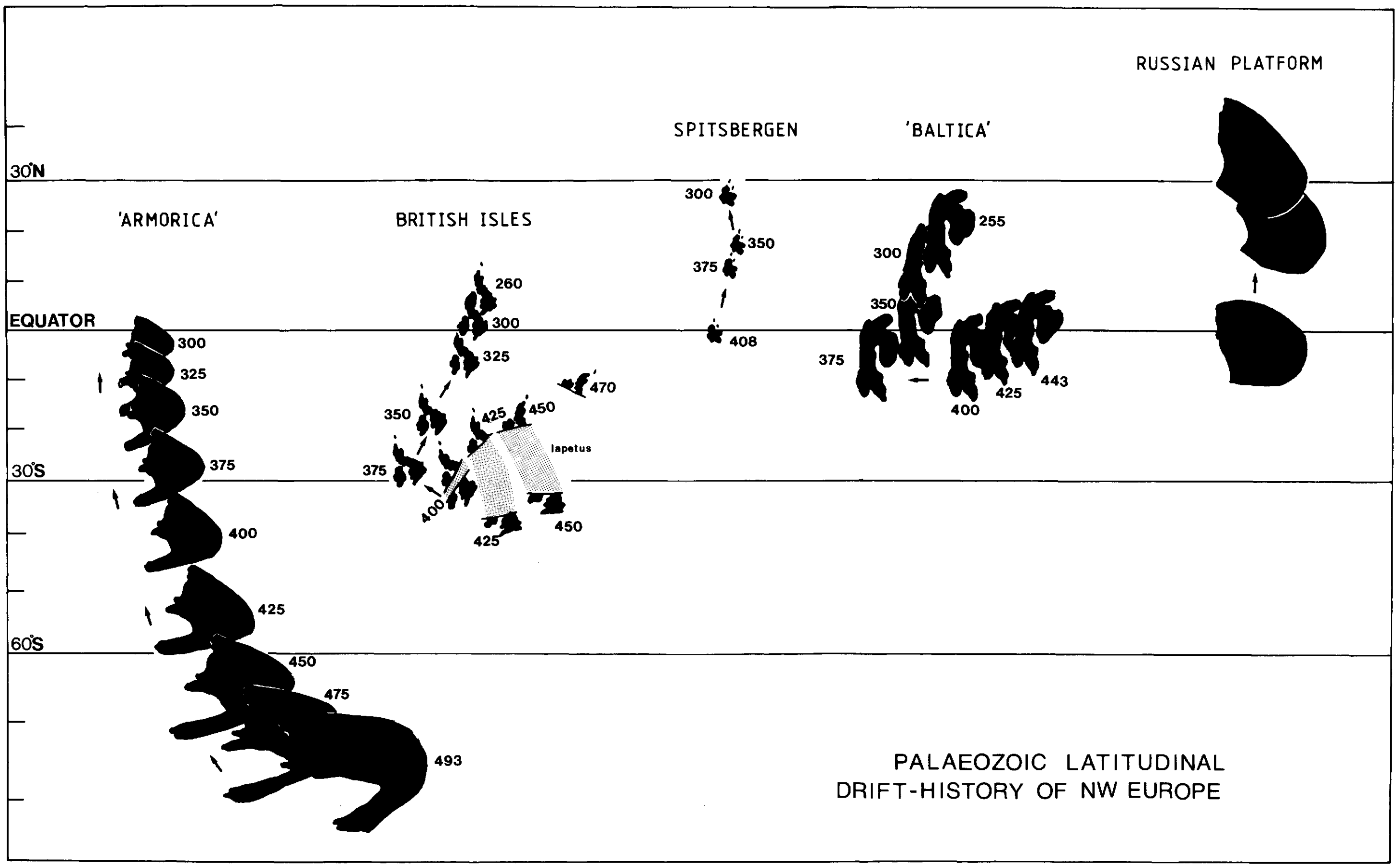


Fig. 10. Palaeozoic latitudinal drift-history of 'Armorica', the British Isles, Spitsbergen, 'Baltica' and the Russian Platform. The latter is a trend plot, i.e. an expression of the latitudinal spread of the palaeo-magnetic data. Numbers represent million years (approximately 25 million years interval). Galls projection.

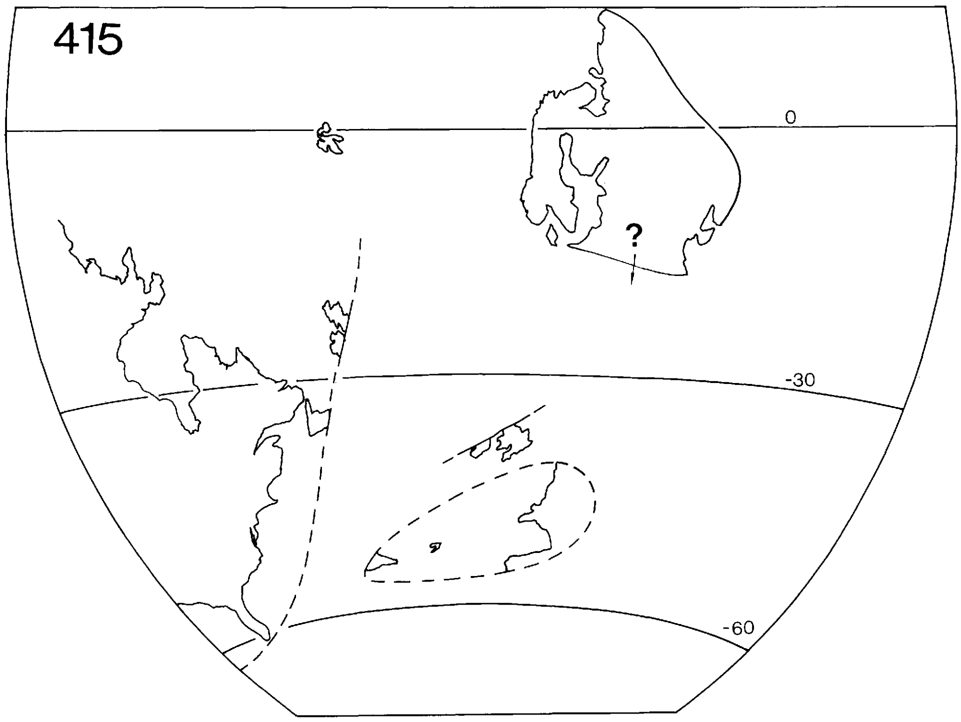


Fig. 11. Silurian (415 Ma) palaeogeographic reconstruction.

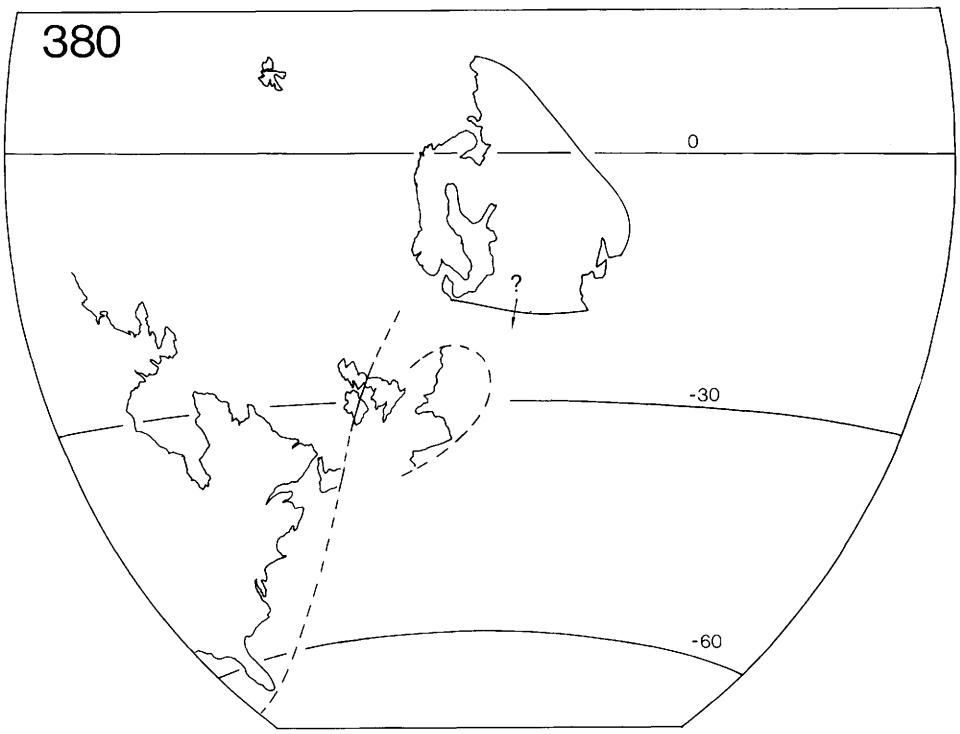


Fig. 12. Early Devonian (380 Ma) palaeogeographic reconstruction.

that southern Britain was marginal to Baltica through Palaeozoic times (e.g. Livermore *et al.* 1987; Briden *et al.* 1988).

Palaeomagnetic arguments for megashearing along the Tornquist Zone (Douglass 1988) are based on a palaeomagnetic discordance between the Ringerike Sandstone pole and Lower Old Red Sandstone poles from Britain. This analysis, however, is of uncertain validity since the Middle Silurian Ringerike Sandstone has been compared with poles of Upper Silurian to Lower Devonian age.

A popular view on the Devonian/Lower Carboniferous tectonic evolution of the Caledonian–Appalachian orogen has been one of megashearing and continental re-arrangement, including the shear zones of Spitsbergen (Billefjorden Fault), northern Britain (Great Glen Fault) and Newfoundland/New England (Cabot Fault). This long-held mobilistic view was is part based on palaeomagnetic data (e.g. Kent & Opdyke 1978, 1979; Van der Voo & Scotese 1981; Storetvedt 1987). New palaeomagnetic and geological information, however, has eliminated the need for such extreme tectonic interpretations (e.g. Irving & Strong 1984, 1985; Kent & Opdyke 1985; Briden *et al.* 1984; Torsvik *et al.* 1985).

Carboniferous–Permian

The Carboniferous is characterized by collisional docking of Gondwana with Euramerica leading to the Hercynian Orogeny. Northward drift of Euroamerica took place during the

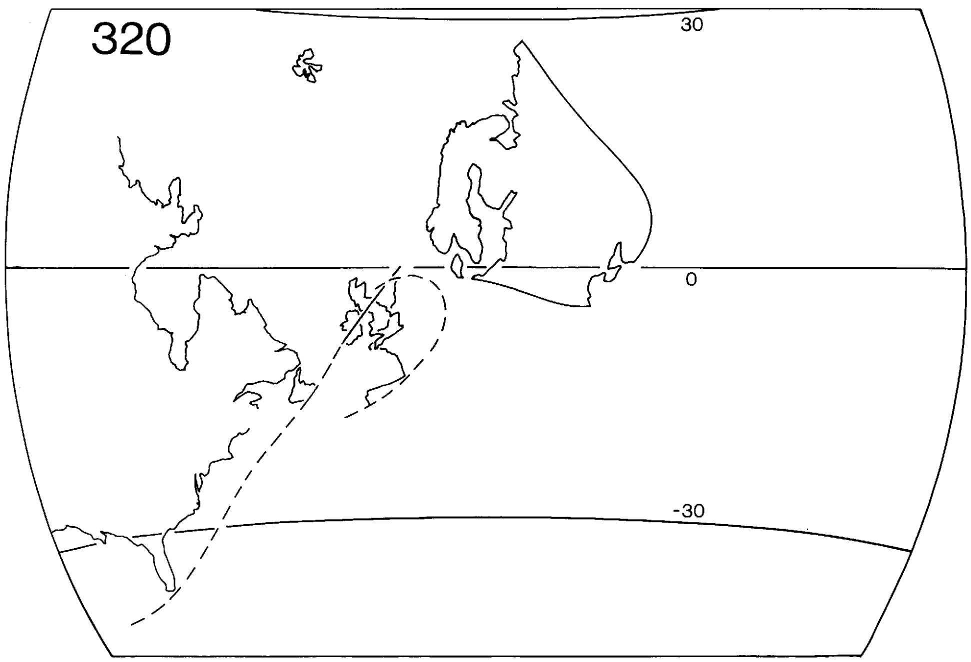


Fig. 13. Carboniferous (320 Ma) palaeogeographic reconstruction.

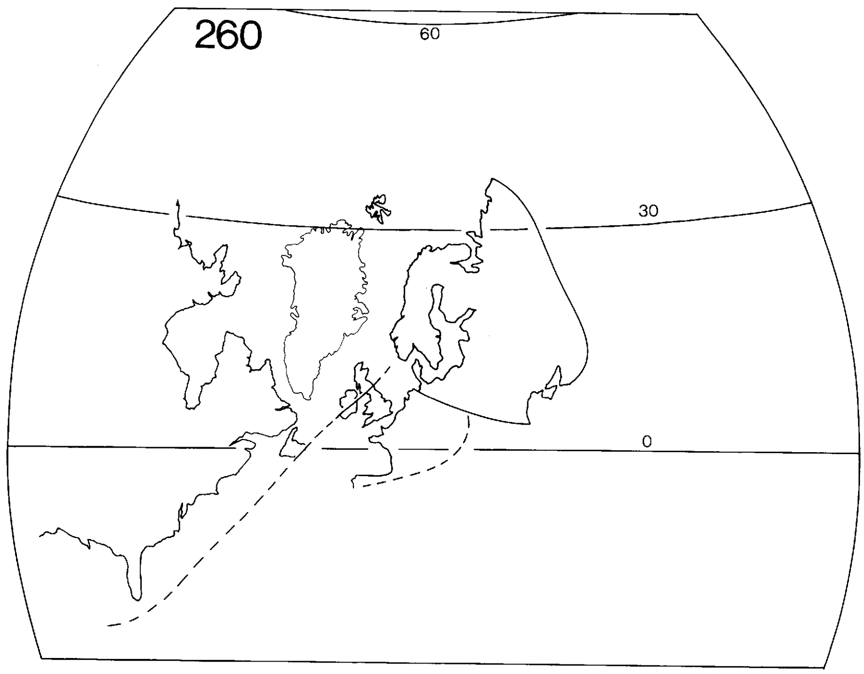


Fig. 14. Permian (260 Ma) palaeogeographic reconstruction. Armorica positioned according to its present position relative to the British Isles. Greenland located according to its present position relative North America after adjusting for opening of the Labrador Sea.

Carboniferous, and the final 'Pangaean' continental assembly was probably achieved in Late Carboniferous/Early Permian time (Fig. 14). Northward-drift of Euroamerica (*c.* 2–4 cm a^{-1}) is also reflected in the rapid changes in palaeoclimatic and lithological patterns (Steel & Worsley 1984; Witzke 1988). A minor overlap between Britain and Armorica is noted in the 320 Ma reconstruction (Fig. 13), but this we relate to minor inaccuracies in the paths. There are, however, indications that Hercynian palaeomagnetic overprints from Armorica (Armorican Massif) differ in polar longitude compared with contemporaneous data from the British Isles and Baltica (compare Figs 5a & b and 2b & c), which may indicate relative rotations during Middle–Upper Carboniferous time. In the Pangaean continent configuration of Fig. 14 Armorica is located according to its current position relative Britain. Similarly, Greenland is located according to its current position relative North America after adjusting for opening of the Labrador Sea.

Conclusions

The Caledonian and Hercynian assembly of Pangaea entails collisional docking of Laurentia, Baltica, Gondwana and Siberia, and destruction of the intervening Iapetus and Tornquist Oceans. Additionally, a number of minor plates or continental fragments such as Armorica, including the Armorican Massif and Avalon Terranes, each having their separate crustal histories during the Palaeozoic have been postulated. In this review we have addressed ourself primarily to palaeomagnetic data from the SE margin of Laurentia, Baltica and Armorica, and some major points are outlined below.

(1) Armorica together with Gondwana was situated in high southerly latitudes (>60) during the Ordovician, at which time Laurentia was situated in equatorial to temperate southerly latitudes. A problem with respect to Armorica, however, concerns the various models as to which elements comprised the Armorican

plate (cf. review in Young 1987). The time at which Armorica rifted off from Gondwana, if it did at all, and when it eventually docked against Euramerica is unclear. However, assuming a uniform northward-drift (*c.* 5 cm a^{-1}) in Siluro-Devonian time (Fig. 10) Armorica would appear to have collided with Euramerica during the Lower Devonian (Acadian) to form the Old Red Sandstone Continent.

(2) There is a clear discordance between the latitudinal position of Northern and Southern Britain in Ordovician and Silurian time, suggesting that the intervening Iapetus Ocean was at least 1000–1500 km wide in Middle Ordovician times (Fig. 10). During collision of Laurentia and Baltica, Laurentia reached its most southerly latitudinal position. The convergence vector for Laurentia was probably near SE (present day co-ordinates). The majority of palaeomagnetic data from Southern Britain suggest temperate southerly latitudes during the Ordovician, although some new data, previously regarded as 'anomalous', imply high southerly latitudes (McCabe 1988).

(3) Palaeomagnetic data from Spitsbergen suggest northerly movement harmonious with drift of the British Isles in post-Lower Devonian time (Fig. 10). This is also indicated by data from the Russian Platform, although time calibration is complicated by extensive late Palaeozoic remagnetization. The palaeolatitudinal position of the Baltic Shield (Baltica) during the Lower–Middle Palaeozoic is highly uncertain. The palaeomagnetic data suggest tropical latitudes in Ordovician to Devonian times (Fig. 10). It is suspected, however, that this apparent equatorial position is an artifact of Late Devonian magnetic resetting. Accordingly, palaeomagnetic data from the Baltic Shield are as yet insufficient to shed any light on postulated oceanic separations (Tornquist Sea) between Baltica and Gondwana/Armorica in Lower Ordovician time.

(4) The northern Britain APWP is broadly similar to the North American APWP (cf. Kent & Van der Voo 1990), but there is still a minor latitudinal difference during Ordovician and Silurian time (on the Bullard *et al.* (1965) reconstruction). A number of tectonic models for the assemblage of Euramerica that have been postulated over the last two decades are now clearly invalid and were due to the failure to recognize extensive Late Palaeozoic magnetic overprinting. These remagnetization features were strongly diachronous. In the Appalachians of North America, Permian or Kiaman overprinting is far-reaching, whereas an Upper Devonian/Lower Carboniferous (Svalbardian) remagnetization episode has been identified on the Baltic Shield in Scandinavia. On the other hand, Carboniferous and Early Mesozoic overprinting are frequently observed in the British Isles. In Central–Northern Europe, Carboniferous or Hercynian magnetic overprinting is widespread. Congruent pre-Devonian palaeomagnetic data have only been derived from rocks of the Armorican Massif. Similarly, a hiatus in the APW for the Russian Platform probably reflects Late Palaeozoic/Early Mesozoic remagnetization.

In conclusion it is proposed that future work should be addressed to carefully designed palaeomagnetic studies from southern Britain and Baltica, including the Russian Platform, in order to establish the position of Baltica during the Early–Middle Palaeozoic, and to determine whether southern Britain was part of Armorica in Ordovician time. We submit that the palaeogeographical position of Laurentia and Armorica is fairly well constrained for parts of the Palaeozoic. The position portrayed for Baltica, however, is speculative at best, and new studies of early–mid Palaeozoic rocks are of vital importance in order to provide more detailed insight into Palaeozoic reconstructions.

The Norwegian Research Council for the Humanities and Science (NAVF), the Natural Environment Research Council (NERC) and the Norwegian Geological Survey are acknowledged for financial support. Valuable discussions with R. Van der Voo, D. V. Kent, N. D. Opdyke and C. Scotese are acknowledged. Norwegian Lithosphere Contribution (46).

References

ABRAHAMSEN, N., WILSON, J. R., THY, P., OLSEN, N. O. & EESBENSEN, K. H. 1979. Palaeomagnetism of the Fongen–Hyllingen gabbro complex, southern Scandinavian Caledonides; plate rotation or polar shift. *Geophysical Journal of the Royal Astronomical Society*, **59**, 231–248.

BACHTADSE, V. & VAN DER VOO, R. 1986. Palaeomagnetic evidence for crustal and thin-skinned rotations in the European Hercynides. *Geophysical Research Letters*, **13**, 1, 161–164.

BRIDEN, J. C. 1970. Palaeomagnetic results from the Arrochar and Garabal Hill-Glen Fyne igneous complexes, Scotland. *Geophysical Journal of the Royal Astronomical Society*, **21**, 457–470.

—— & DUFF, B. A. 1981. Pre-Carboniferous palaeomagnetism of Europe north of the Alpine Orogenic Belt. *In*: MCELHINNY, M. W. & VALENCIO, D. A. (eds) *Palaeoreconstruction of the Continents*. Geo-dynamic Series, **2**, American Geophysical Union, 137–149.

—— & MORRIS, W. A. 1973. Palaeomagnetic studies in the British Caledonides-III. Igneous rocks of the Northern Lake District, England. *Geophysical Journal of the Royal Astronomical Society*, **34**, 27–46.

—— & MULLAN, A. J. 1984. Superimposed Recent, Permo-Carboniferous and Ordovician palaeomagnetic remanence in the Builth Volcanic Series, Wales. *Earth Planetary Science Letters*, **69**, 413–421.

——, TURNELL, H. B. & WATTS, D. 1984. British paleo-magnetism, Iapetus Ocean, and the Great Glen fault. *Geology*, **12**, 428–431.

——, KENT, D. V., LAPOINTE, P. L., LIVERMORE, R. A., ROY, J. L., SEGUIN, M. K., SMITH, A. G., VAN DER VOO, R. & WATTS, D. 1988. Palaeomagnetic constraints on the evolution of the Caledonian–Appalachian orogen. *In*: HARRIS A. L. & FETTES, D. J. (eds) *The Caledonian–Appalachian Orogen*. Geological Society, London, Special Publication, **38**, 35–48.

BULLARD, E. C., EVERETT, J. E. & SMITH, A. G. 1965. The fit of the continents around the Atlantic. *Royal Society of London, Philosophical Transections Series A*, **258**, 41–51.

BYLUND, G. 1974. Palaeomagnetism of dykes along the southern margin of the Baltic Shield. *Geologiske Foreningen Stockholm Forhandlinger*, **96**, 231–235.

—— & PATCHETT, P. J., 1977. Palaeomagnetic and Rb-Sr isotopic evidence for the age of the Sarna alkaline complex, western central Sweden. *Lithos*, **10**, 73–59.

BØE, R., ATAKAN, K. & STURT, B. A. 1989. The style of deformation of the Devonian rocks of Hitra and Smøla. *Norsk Geologisk Tidskrift* (in press).

CHAMALAUN, F. H. & CREER, K. M. 1964. Thermal demagnetization studies on the Old Red Sandstone of the Anglo–Welsh Cuvette. *Journal of Geophysical Research*, **68**, 8, 1607–1616.

CLAESSON, C. 1979. Early Palaeozoic geomagnetism of Gotland. *Geologisk Forening Stocholm Forhandlinger*, **101**, 149–155.

CLARK, R. M. & THOMPSON, R. 1984. Statistical comparison of palaeomagnetic directional records from lake sediments. *Geophysical Journal of the Royal Astronomical Society*, **76**, 337–368.

COCKS, L. R. M. & FORTEY, R. A. 1982. Faunal evidence for oceanic separations in the Palaeozoic of Britain. *Journal of the Geological Society, London*, **139**, 465–478.

CORNWELL, J. D. 1967. Palaeomagnetism of the Exeter Lavas, Devonshire. *Geophysical Journal of the Royal Astronomical Society*, **12**, 181–196.

DEUTSCH, E. R. 1980. Magnetism of the mid-Ordovician Tramore volcanics, SE Ireland, and the question of a wide Proto–Atlantic Ocean. *Journal of Geomagnetism and Geoelectricity*, **32**, 77–98.

—— & STORETVEDT, K. M. 1988. Magnetism of igneous rocks from the Tourmakeady and Glensaul inliers, W. Ireland: mode of emplacement and aspects of the Ordovician field pattern. *Geophysical Journal*, **92**, 223–234.

DOUGLASS, D. N. 1987. *Geology and palaeomagnetics of three Old Red Sandstone Basins: Spitsbergen, Norway and Scotland*. PhD thesis, Dartmouth College, Hanover, New Hampshire, USA.

—— 1988. Palaeomagnetics of Ringerike Old Red Sandstone and related rocks, southern Norway: implications for pre-Carboniferous separation of Baltica and British terranes. *Tectonophysics*, **148**, 11–27.

DUFF, B. A. 1979. The palaeomagnetism of Cambro-Ordovician red beds, the Erquy spilite series, and the Tregastel–Ploumanach granite

complex, Armorican Massif (France and the Channel Islands). *Geophysical Journal of the Royal Astronomical Society*, **59**, 345–365.
—— 1980. The palaeomagnetism of Jersey volcanics and dykes and the lower Palaeozoic apparent polar wander path for Europe. *Geophysical Journal of the Royal Astronomical Society*, **60**, 355–375.

EDEL, J. B. 1987*b*. Palaeopositions of the western European hercynides during the Late Carboniferous deduced from palaeomagnetic data: consequences for "stable Europe". *Tectonophysics*, **139**, 31–41.
—— & COULON, M. 1984. Late Hercynian remagnetization of Tournaisian Series from the Laval Syncline, Armorican Massif, France. *Earth and Planetary Science Letters*, **68**, 343–350.

ESANG, C. B. & PIPER, J. D. A. 1984*a*. Palaeomagnetism of the Carboniferous E-W dyke swarm in Argyllshire. *Scottish Journal of Geology*, **20**, 3, 309–314.
—— & —— 1984*b*. 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. & MORRIS, W. A. 1977. Palaeomagnetic results from the Borrowdale Volcanic Group, English Lake District. *Geophysical Journal of the Royal Astronomical Society*, **48**, 111–121.

FORTEY, R. A. & COCKS, L. R. M. 1988. Arenig to Llandovery faunal distribution in the Caledonides. *In*: HARRIS, A. L. & FETTES, D. J. (eds) *The Caledonian-Appalachian Orogen*. Geological Society, London, Special Publication, **38**, 233–246.

GOULD, A. L. 1969. A regression technique for angular variates. *Biometrics*, **25**, 683–700.

HALVORSEN, E. 1970. Palaeomagnetism and the age of the younger diabases in the Ny-Hellesund areas, S. Norway. *Norsk Geologisk Tidskrift*, **50**, 2, 157–166.
—— 1972. On the palaeomagnetism of the Arendal diabases. *Norsk Geologisk Tidskrift*, **52**, 3, 217–228.

IRVING, E & STRONG, D. F. 1984. Evidence against large-scale Carboniferous strike-slip faulting in the Appalachian–Caledonian orogen. *Nature*, **310**, 762–764.
—— & —— 1985. Palaeomagnetism of rocks from Burin Peninsula, Newfoundland: Hypothesis of Late Palaeozoic displacement of Acadia criticized. *Journal of Geophysical Research*, **90**, B2, 1949–1962.

JELENSKA, M. & LEWANDOWSKI, M. 1986. A paleomagnetic study of Devonian sandstone from Central Spitsbergen. *Geophysical Journal of the Royal Astronomical Society*, **87**, 617–632.

JONES, M., VAN DER VOO, R. & BONHOMMET, N. 1979. Late Devonian to early Carboniferous palaeomagnetic poles from the Armorican Massif (France). *Geophysical Journal of the Royal Astronomical Society*, **58**, 287–308.

JUPP, P. E. & KENT, J. T. 1987. Fitting smooth paths to spherical data. *Applied Statistics*, **36**, 1, 34–46.

KENT, D. V. & Opdyke, N. 1978. Palaeomagnetism of the Devonian Catskill Red Beds: evidence for motion of the coastal New England relative to Cratonic North America. *Journal of Geophysical Research*, **83**, 4441–4450.
—— & —— 1979. The early Carboniferous palaeo-magnetic field of North America and its bearing on tectonics of the Northern Appalachians. *Earth and Planetary Science Letters*, **44**, 365–372.
—— & —— 1985. Multicomponent magnetizations from the Mississippian Mauch Chunk Formation of the Central Appalachians and their tectonic implications. *Journal of Geophysical Research*, **90**, B7, 5371–5383.
—— & VAN DER VOO, R. 1990. Palaeozoic palaeogeography from the palaeomagnetism of the Atlantic-bordering continents. *In*: MCKERROW, W. S. & SCOTESE, C. R. (eds) *Palaeozoic Palaeogeography and Biogeography*. Geological Society, London, Memoir, **12**, 49–56.

KNEEN, S. 1973. The palaeomagnetism of the Foyers Plutonic Complex, Inverness-shire. *Geophysical Journal of the Royal Astronomical Society*, **32**, 53–63.

KHRAMOV, A. N. & SHOLPO, L. E. 1967. *Palaeomagnetism. Principles, methods and geological applications of palaeomagnetology*. Nedra, Leningrad.
——, PETROVA, G. N. & PECHERSKY, D. M. 1981. Palaeomagnetism of the Soviet Union. *In*: MCELHINNY, A. W. & VALENCIO, D. A. (eds) *Palaeoreconstruction of the Continents*. Goedynamic Series, **2**, American Geophysical Union, 177–194.

LATHAM, A. G. & BRIDEN, J. C. 1975. Palaeomagnetic field directions in Siluro-Devonian lavas of the Lorne Plateau, Scotland, and their regional significance. *Geophysical Journal of the Royal Astronomical Society*, **43**, 243–252.

LIVERMORE, R. A., SMITH, A. G. & BRIDEN, J. C. 1985. Palaeomagnetic constraints on the distribution of continents in the late Silurian and early Devonian. *Philosophical Transactions of the Royal Society London*, B **309**, 29–56.

LØVLIE, R. 1981. Palaeomagnetism of coast-parallel alkaline dykes from western Norway; ages of magmatism and evidence for crustal uplift and collapse. *Geophysical Journal of the Royal Astronomical Society*, **66**, 417–426.

MCCABE, C. 1988. *Palaeomagnetism of the Ordovician Stapeley Volcanic Formation, Welsh Borderlands*. Palaeozoic Biogeography and Palaeogeographic symposium, Oxford (abstract).

MCCLELLAND BROWN, E. 1983. Palaeomagnetic studies of fold development in the Pembrokshire Old Red Sandstone. Tectonophysics, **98**, 131–139.

MCELHINNY, M. W., 1973. *Palaeomagnetism and Plate Tectonics*. Cambride University Press, Cambridge.

MILLER, J. D. & KENT, D. V. 1988. Palaeomagnetism of the Silurian–Devonian Andreas redbeds: Evidence for an Early Devonian supercontinent? *Geology*, **16**, 195–198.

MORRIS, W. A., BRIDEN, J. C., PIPER, J. D. A. & SALLOMY, J. T. 1973. Palaeomagnetic studies in the British Caledonides- V. Miscellaneous new Data. *Geophysical Journal of the Royal Astronomical Society*, **34**, 69–106.

MULDER, F. G. 1971. Palaeomagnetic research in some parts of Central and Southern Sweden. *Sveriges Geologiske Undersokelse*, **64**, 10, 1–56.

NAIRN, A. E. M. 1960. Palaeomagnetic results from Europe. *Journal of Geology*, **68**, 285–306.

PARKER, R. L. & DENHAM, C. R. 1979. Interpolation of unit vectors. *Geophysical Journal of the Royal Astronomical Society*, **58**, 685–687.

PERROUD, H. 1983. Palaeomagnetism of Palaeozoic rocks from the Cabo de Penas, Asturia, Spain. *Geophysical Journal of the Royal Astronomical Society*, **75**, 201–215.
—— & —— 1984. A Devonian palaeomagnetic pole for Armorica. *Geophysical Journal of the Royal Astronomical Society*, **77**, 839–845.
—— & VAN DER VOO, R. 1985. Palaeomagnetism of the late Ordovician Thouars Massif, Vendee Province, France. *Journal of Geophysical Research*, **90**, B6, 4611–4625.
——, BONHOMMET, N. and ROBARDET, M. 1982. Comment on "A palaeomagnetic study of Cambrian volcanics and intrusives from the Armorican Massif, France" by W. A. MORRIS. *Geophysical Journal of the Royal Astronomical Society*, **69**, 573–578.
——, —— & VAN DER VOO, R. 1983. Palaeomagnetism of Crozon peninsula (France). *Geophysical Journal of the Royal Astronomical Society*, **72**, 307–319.
——, —— & THEBAULT, J. P. 1986*a*. Palaeomagnetism of the Ordovician Moulin de Chateaupanne formation, Vendee, western France. *Geophysical Journal of the Royal Astronomical Society*, **85**, 573–582.
——, Van der Voo, R. & BONHOMMET, N. 1984*a*. Palaeozoic evolution of the Armorica plate on the basis of palaeomagnetic data. *Geology*, **12**, 579–582.
——, AUVRAY, B., BONHOMMET, N., MACE, J. & VAN DER VOO, R. 1986*b*. Palaeomagnetism and K-Ar dating of Lower Carboniferous dolerite dykes from northern Brittany. *Geophysical Journal of the Royal Astronomical Society*, **87**, 143–154.
——, ROBARDET, M., VAN DER VOO, R., BONHOMMET, N. & PARIS, F. 1984*b*. Revision of the age of magnetization of the Montmartin red beds, Normandy, France. *Geophysical Journal of the Royal Astronomical Society*, **80**, 541–549.

PESONEN, L. J., TORSVIK, T. H., BYLUND, G. & ELMING, S. A. 1989. Crustal evolution of Fennoscandia — Palaeomagnetic constraints. *Tectonophysics* (in press).

PIPER, J. D. A. 1974. Sulitjelma Gabbro, Northern Norway: A palaeomagnetic result. *Earth and Planetary Science Letters*, **21**, 383–388.
—— 1975. Palaeomagnetism of Silurian lavas, of Somerset and Gloucestershire, England. *Earth and Planetary Science Letters*, **25**, 355–360.

—— 1978*a*. Palaeomagnetism and palaeogeography of the Southern Uplands in Ordovician times. *Scottish Journal of Geology*, **14**, 93–107.

—— 1978*b*. Palaeomagnetic survey of the (Palaeozoic) Shelve inlier and Berwyn Hills, Welsh Borderland. *Geophysical Journal of the Royal Astronomical Society*, **53**, 355–371.

—— & Briden, J. C. 1973. Palaeomagnetic studies in the British Caledonides-I. Igneous rocks of the Builth Wells–Llandrindod Wells Ordovician inlier, Radnorshire, Wales. *Geophysical Journal of the Royal Astronomical Society*, **34**, 1–12.

—— —— & Stearn, J. E. F. 1975. Palaeomagnetism of the Breidden Hill (Palaeozoic) inlier, Welsh Borderlands. *Geophysical Journal*, **43**, 1013–1016.

Robertson, D. J. 1988. Palaeomagnetism of the Connemara Gabbro, Western Ireland. *Geophysical Journal of the Royal Astronomical Society*, **94**, 1, 51–64.

Robinson, M. A. 1985. Palaeomagnetism of volcanics and sediments of the Eday Group, Southern Orkney. *Scottish Journal of Geology*, **21**, 285–300.

Rother, K., Fluge, P. R. & Storetvedt, K. M. 1987. Palaeomagnetism of the Askøy mafic pluton (late Precambrian), West Norway; events of Caledonian metamorphic remagnetization. *Physics of the Earth and Planetary Interiors*, **45**, 85–96.

Sallomy, J. T. and Piper, J. D. A. 1973. Palaeomagnetic studies in the British Caledonides IV. Lower Devonian lavas of the Strathmore Region, Scotland. *Geophysical Journal of the Royal Astronomical Society*, **34**, 47–68.

Smethurst, M. A. & Briden, J. C. 1988. Palaeomagnetism of Silurian sediments in W. Ireland: evidence for block-rotation in the Caledonides. *Geophysical Journal*, **95**, 327–346.

Steel, R. J. & Worsley, D. 1984. Svalbard's post-Caledonian Strata — an atlas of sedimentological patterns and palaeogeographic evolution. *Journal of petroleum geology of the North European Margin*, Graham Trotman, 59–69.

Storetvedt, K. M. 1987. Major late Caledonian and Hercynian shear movements on the Great Glen Fault. *Tectonophysics*, **143**, 253–267.

—— & Carmichael, C. M. 1979. Resolution of superimposed magnetizations in the Devonian John O'Groats Sandstone, N. Scotland. *Geophysical Journal of the Royal Astronomical Society*, **58**, 769–784.

—— & Gidskehaug, A. 1969. The magnetization of the Great Whin Sill, Northern England. *Physics of the Earth and Planetary Interiors*, **2**, 105–111.

—— & Gjellestad, G. 1966. Palaeomagnetic investigation of an Old Red Sandstone formation of Southern Norway. *Nature*, **212**, 59–61.

Storetvedt, K. M. & Meland, A. H. 1985. Geological interpretation of palaeomagnetic results from Devonian rocks of Hoy, Scotland. *Scottish Journal of Geology*, **21**, 337–352.

—— & Torsvik, T. H. 1983. Palaeomagnetic re-examination of the basal Caithness Old Red Sandstone; aspects of local and regional tectonics. *Tectonophysics*, **98**, 151–164.

—— & —— 1985. Palaeomagnetism of the Middle–Upper Devonian Esha Ness ignimbrite, W. Shetland. *Physics of the Earth ands Planetary Interiors*, **37**, 169–173.

——, Pedersen, S., Løvlie, R. & Halvorsen, E. 1978. Palaeomagnetism in the Oslo rift. *In*: Ramberg, J. B. & Neumann, E. R. (eds) *Tectonics and Geophysics of Continental Rifts*, D. Reidel Publishing Company, Holland, 289–296.

Storhaug, K. & Storetvedt, K. M. 1985. Palaeomagnetism of the Sarchlet Sandstone (Orcadian Basin); age perspectives. *Scottish Journal of Geology*, **20**, 3, 275–284.

Sturt, B. A. 1983. *Late Caledonian and possible Variscan stages in the Orogenic evolution of the Scandinavian Caledonides*. The Caledonide Orogen-IGCP Project 27, symposium de Rabat, Morocco (abstract).

—— & Roberts, D. 1987. *Terrane linkage in the final stages of the Caledonian orogeny in Scandinavia*. Extended abstract IGCP Project 233 symposium, Nouakchott, Mauritania, 193–196.

—— & Torsvik, T. H. 1987. A late Carboniferous palaeomagnetic pole recorded from a syenite sill, Stabben, Central Norway. *Physics of the Earth and Planetary Interiors*, **49**, 350–359.

Tarling, D. H. 1985. Palaeomagnetic studies of the Orcadian Basin. *Scottish Journal of Geology*, **21**, (3), 261–273.

—— & Mitchell, J. G. 1973. A palaeomagnetic and isotopic age for the Wackerfield dyke of Northern England. *Earth and Planetary Science Letters*, **18**, 427–432.

Thirlwall, M. F. 1981. Implications for Caledonian plate tectonic models of chemical data from volcanic rocks of the British Old Red Sandstone. *Journal Geological Society, London*, **138**, 123–138.

—— 1988. Wenlock to mid-Devonian volcanism of the Caledonian–Appalachian orogen. *In*: Harris, A. L. & Fettes, D. J. (eds) *The Caledonian–Appalachian Orogen*. Geological Society, London, Special Publication, **38**, 415–428.

Thorning, L. 1974. Palaeomagnetic results from Lower Devonian rocks of the Cheviot Hills, Northern England. *Geophysical Journal of the Royal Astronomical Society*, **36**, 487–496.

Thomas, C. & Briden, J. C. 1976. Anomalous geomagnetic field during the late Ordovician. *Nature*, **259**, 5542, 380–382.

Thompson, R. & Clark, R. M. 1981. Fitted polar wander paths. *Physics of the Earth and Planetary Interiors*, **27**, 1–7.

—— & —— 1982. A robust least-square Gondwanan apparent polar wander path and the question of palaeomagnetic assessment of Gondwanan reconstructions. *Earth and Planetary Science Letters*, **57**, 152–158.

Torsvik, T. H. 1984. Palaeomagnetism of the Foyers and Strontian granites, Scotland. *Physics of the Earth and Planetary Interiors*, **36**, 163–177.

—— 1985*a*. Magnetic properties of the Lower Old Red Sandstone Lavas in the Midland Valley, Scotland; palaeomagnetic and tectonic considerations. *Physics of the Earth and Planetary Interiors*, **39**, 194–207.

—— 1985*b*. Palaeomagnetic results from the Peterhead granite, Scotland; implication for regional late Caledonian magnetic overprinting. Physics of the Earth and Planetary Interiors, **39**, 108–117.

—— & Sturt, B. A. 1988. Multiphase magnetic overprints in the Moine Thrust Zone. *Geological Magazine*, **125**, 1, 63–82.

——, Løvlie, R. & Storetvedt, K. M. 1983. Multicomponent magnetization in the Helmsdale granite, N. Scotland; geotectonic implications. *In*: McClelland, B. & Vandenberg, J. (eds) *Palaeomagnetism of orogenic belts*. Tectonophysics, **98**, 111–129.

——, —— & Sturt, B. A. 1985. Palaeomagnetic argument for a stationary Spitsbergen relative to the British Isles (Western Europe) since late Devonian and its bearing on North Atlantic reconstruction. *Earth and Planetary Science Letters*, **75**, 278–288.

——, Sturt, B. A. & Ramsay, D. M. 1989*d*. On the origin and the tectonic implications of magnetic overprinting of the Old Red Sandstone, Shetland. *Geophysical Journal International*, (in press).

——, Lyse, O., Atterås, G. & Bluck, B. 1989*b*. Palaeozoic palaeomagnetic results from Scotland and their bearing on the British Apparent polar wander path. *Physics of the Earth and Planetary Interiors*, **55**, 93–105.

——, Sturt, B. A., Ramsay, D. M. & Vetti, V. 1987. The tectonomagnetic signature of the Old Red Sandstone and pre-Devonian strata in the Håsteinen area, Western Norway, and implications for the later stages of the Caledonian Orogeny. *Tectonics*, **6**, 3, 305–322.

——, ——, Grønlie, A. & Ramsay, D. M. 1989*c*. Palaeomagnetic data bearing on the age of the Ytterøy Dyke, Central Norway. *Physics of the Earth and Planetary Interiors*, **54**, 156–162.

——, ——, Ramsay, D. M., Kisch, H. J. & Bering, D. 1986. The tectonic implications of Solundian (Upper Devonian) magnetization of Devonian rocks of Kvamshesten, western Norway. *Earth and Planetary Science Letters*, **80**, 337–347.

——, ——, ——, Bering, D. & Fluge, P. R. 1988. Palaeomagnetism, magnetic fabrics and the structural style of the Hornelen Old Red Sandstone, Western Norway. *Journal Geological Society, London*, **145**, 413–430.

——, ——, ——, Grønlie, A., Roberts, D., Smethurst, M., Atakan, K., Bøe, R. & Walderhaug, H. J. 1989*a*. Palaeomagnetic constraints on the early history of the Møre–Trøndelag Fault Zone, Central Norway: *In*: Kissel, C. & Laj, C. (eds) *Palaeomagnetic rotations and continental deformation*. Kluwer Academic Publishers, 431–457.

Turnell, H. B. 1985. Palaeomagnetism and Rb-Sr ages of the Ratagen and Comrie intrusions. *Geophysical Journal of the Royal Astronomical Society*, **83**, 363–378.

—— & Briden, J. C. 1983. Palaeomagnetism of NW Scotland syenites in relation to local and regional tectonics. *Geophysical Journal of the Royal Astronomical Society*, **75**, 217–234.

Van der Voo, R. 1979. Palaeozoic assembly of Pangea: a new plate tectonic model for the Taconic, Caledonian and Hercynian orogenies. *Eos Transactions AGU*, **60**, 241.

—— 1988. Palaeozoic paleogeography of North America, Gondwana, and intervening displaced terranes: Comparison of palaeomagnetism with paleoclimatology and biogeographical patterns. *Geological Society of America Bulletin*, **100**, 311–234.

—— & Johnson, R. J. E. 1985. Palaeomagnetism of the Dunn Point Formation (Nova Scotia): High palaeolatitudes for the Avalon terrane in the late Ordovician. *Geophysical Research Letters*, **12**, 6, 337–340.

—— & Klootwijk, C. T. 1972. Palaeomagnetic reconnaissance study of the Flamanville granite, with special reference to the anisotropy of its susceptibility. *Geological Mijnbouw*, **51**, 609–617.

—— & Scotese, C. 1981. Palaeomagnetic evidence for a large (ca. 2000 km) sinistral offset along the Great Glen Fault during Carboniferous time. *Geology*, **9**, 583–589.

Vincenz, S. A. & Jelenska, M. 1985. Palaeomagnetic investigations of Mesozoic and Palaeozoic rocks from Svalbard. *In*: Huseby, E. S. & Kristoffersen, Y. (eds) *Geophysics of the Polar Regions*. Tectonophysics, **114**, 163–180.

Whittington, H. B. & Hughes, C. P. 1972. Ordovician geography and faunal provinces deduced from Trilobite distribution. *Philosophical Transactions of the Royal Society of London*, B **263**, 235–278.

Watts, D. 1982. A multicomponent, dual-polarity palaeomagnetic regional overprint from the Moine of northwest Scotland. *Earth and Planetary Science Letters*, **61**, 190–198.

—— 1985*a*. Palaeomagnetic resetting in the Barrovian Zones of Scotland and its relationship to the late structural history. *Earth and Planetary Science Letters*, **75**, 258–264.

—— 1985*b*. Palaeomagnetism of the Lower Carboniferous Billefjorden Group, Spitsbergen. *Geological Magazine*, **4**, 383–388.

—— & Briden, J. C. 1984. Palaeomagnetic signature of slow post-orogenic cooling of the north-east Highlands of Scotland recorded in the Newer Gabbros of Aberdeenshire. *Geophysical Journal of the Royal Astronomical Society*, **77**, 775–788.

Witzke, B. J. 1988. *Constraints for Palaeozoic Palaeolatitudes of Euramerica*. Palaeozoic Biogeography and Palaeogeographic symposium, Oxford (abstract).

Young, G. C. 1987. Devonian palaeontological data and the Armorica problem. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **60**, 283–304.