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Baltica. A synopsis of Vendian–Permian palaeomagnetic data and their palaeotectonic implications

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ABSTRACT

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In light of recent additions to the Palaeozoic palaeo-magnetic data-base, particularly for the Ordovician era, a revised apparent polar wander (APW) path for Baltica has been constructed following a rigorous synthesis of all Late Precambrian–Permian data. The APW path is characterized by two prominent loops. Firstly, a Late Precambrian–Cambrian loop probably relating to a rifting event and secondly, a younger loop relating to a Mid-Silurian (Scandian) collision event. These features imply major change in plate-tectonic reconfiguration.

Baltica probably represented an individual continental unit in Early Palaeozoic times and was positioned in high southerly latitudes in an "inverted" geographic orientation. In such a reconstruction Baltica was separated from the northern margin of Gondwana by the Tornquist Sea and from Laurentia by the Iapetus Ocean. The Tornquist Zone is thus interpreted as a passive or dextral transform margin during the early Palaeozoic.

While undergoing counter-clockwise rotations (up to 1.6°/Ma), Baltica drifted northward through most of the Palaeozoic, except for a short period of southerly movement in Late Silurian–Early Devonian times after collision with Laurentia. Rapid movements in latitude (up to 9 cm/yr) are noted in Late Precambrian/early Palaeozoic times and significant decrease in velocities throughout Palaeozoic time probably reflect the progressive amalgamation of a larger continent by Early-Devonian (Euramerica) and Permian (Pangea) times.

The Tornquist Sea had a principal component of palaeo-east–west orientation. Hence it is difficult to be precise in the timing of when micro-continents such as Eastern Avalonia and the European Massifs ultimately collided along the southwestern margin of Baltica. These micro-continents are considered to have been peripheral to Gondwana (in high southerly latitudes) during the Early Ordovician. Eastern Avalonia clearly had rifted off Gondwana by Llanvirn–Llandeilo times and may have collided with Baltica during Late Ordovician times, although the present available Silurian palaeomagnetic data from Eastern Avalonia may suggest collision in Late Silurian times.

Across the Iapetus facing margin of Baltica, Laurentia was situated in equatorial to southerly latitudes during most of the Lower Palaeozoic. These continents collided in Mid-Silurian times, i.e. a first collision between southwestern Norway and Greenland/Scotland which gave rise to the early Scandian Orogeny (425 Ma) in southwestern Norway possible followed by a later, but less dramatic, Scandian event in northern Norway at around 410 Ma. Since Baltica was geographically inverted in early Palaeozoic times, the collisional margin could not have been a margin that once rifted off Laurentia as assumed in a number of plate-tectonic models.

INTRODUCTION

The Palaeozoic palaeocontinent of Baltica is bounded to the west by the Iapetus suture, to the north by the Trollfjord–Komagelv Fault Zone (Fig. 1), to the east by the Ural mountains, to the south by the Variscan–Hercynian suture, and to the southwest by the Tornquist Zone (Pegrum, 1984). As such, Baltica includes parts or all of Norway, Sweden, Finland, Denmark, Poland, Russia, Es-

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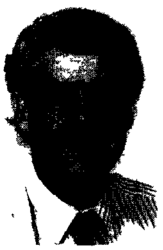

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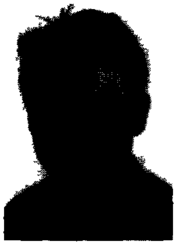

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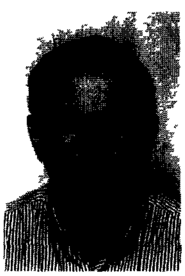

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tonia, Latvia, Lithuania and Ukraine. During Palaeozoic time, a number of orogenic events occurred along the margins of Baltica, ultimately leading to the incorporation of Baltica into the supercontinent Pangea.

In this paper, we quantify the Palaeozoic drift history of Baltica using a rigorous synthesis of presently available palaeomagnetic data. In so doing, we attempt to further constrain the geotectonic history of the continent's margins. A newly-determined apparent polar wander (APW) path for Baltica will be described in detail. The generation of that APW path followed thorough re-evaluation of all published poles for Baltica made during the European Geotraverse Palaeomagnetic workshop in Luleå, Sweden (Pesonen and Van der Voo, 1991).

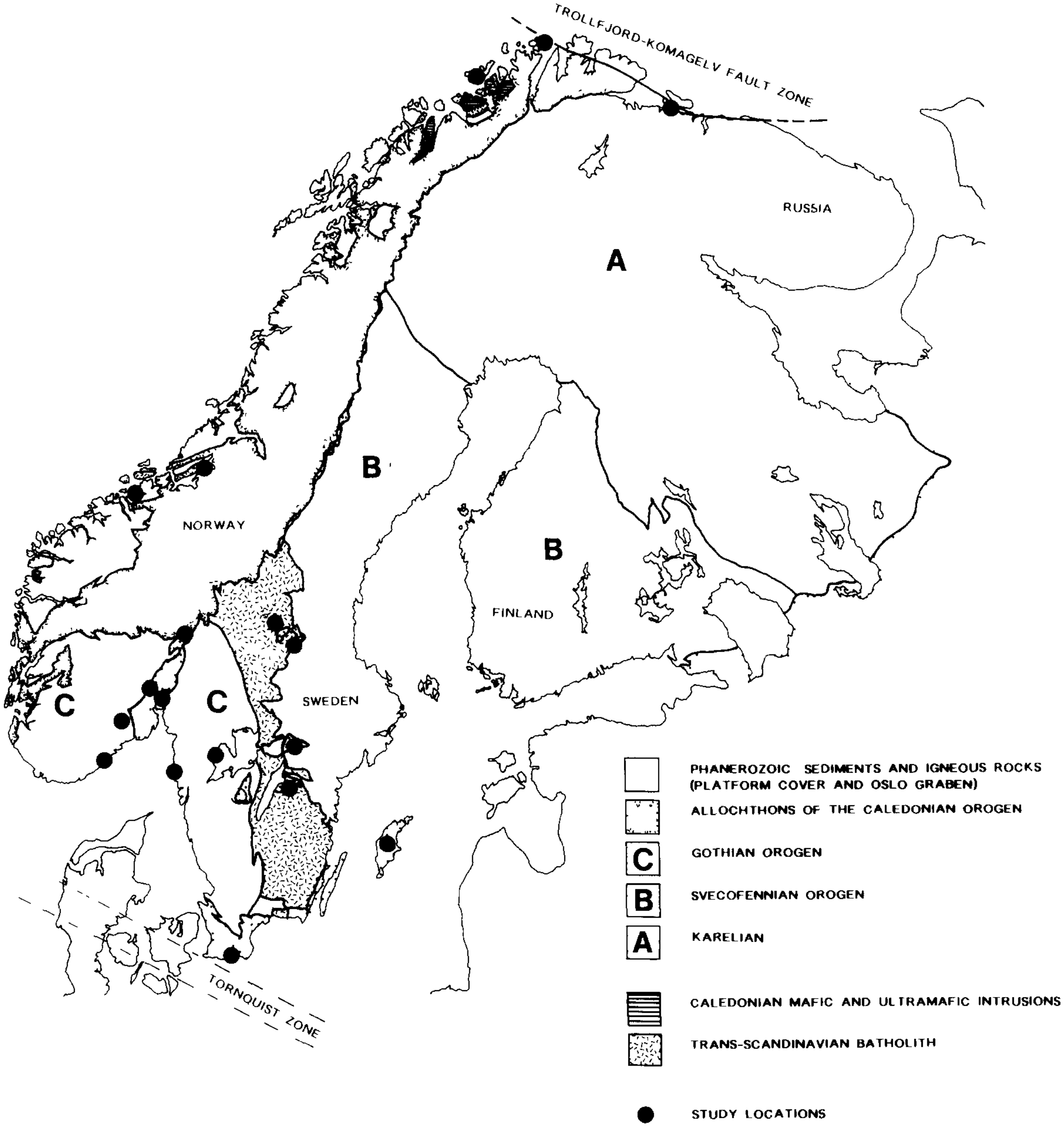

Fig. 1 Simplified geological map of Western Baltica (Baltic Shield) and palaeomagnetic sampling areas listed in Table 1

TABLE 1

Permian to Vendian Palaeomagnetic data from Scandinavia, Spitsbergen (entries 5-24, 5-25 and 5-28), Ukraine (5-27) and Russia (2-11)

Code Formation	α_{95}	P	Age	Ma	Lat	Long	Grading	Q
							1234567	
Permian								
7-19 Ytterøy dyke (HB)	8.0	R	256 ± 10	256	−44.0	323.0	1010101	4
7-03 Arendal diabases (A)	5.2	R	M-Permian	260	−43.6	341.3	1010101	4
7-05 Arendal diabases (C)	3.7	R	M-Permian	260	−38.5	332.9	1110101	5
7-04 Arendal diabases (B)	8.9	R	M-Permian	260	−46.6	320.2	1110101	5
7-07 Arendal diabases (D1 + D2)	5.7	R	M-Permian	260	−47.8	317.6	1110101	5
7-15 Bohuslan dolerite dykes (D)	29.1	R	M-Permian	260	−55.6	341.9	1110101	5
7-11 Bohuslan dykes (RPM)	8.8	R	M-Permian	260	−44.7	349.2	1010101	4
7-12 Bohuslan dykes (RPC)	3.6	R	M-Permian	260	−47.2	345.6	1110101	5
7-14 Bohuslan porphyry dykes (PD)	20.8	R	M-Permian	260	−57.1	354.6	1110101	5
7-09 Ny-Hellesund dykes	2.9	R	273–255	265	−38.7	340.7	1110101	5
6-11 Oslo Graben lavas (HB)	13.4	R	280–260	270	−44.6	337.1	1110101	5
6-01 Oslo Igneous rocks (B)	8.8	R	280–260	270	−39.9	339.9	1110101	5
7-08 Oslo Igneous rocks (I)	3.0	R	280–260	270	−47.7	337.0	1110101	5
7-01 Scania melaphyres	11.0	R	278–260	270	−54.0	351.5	1100101	4
6-03 Sarna body (1)	11.0	R	281 ± 14	281	−38.0	348.0	1010101	4
6-02 Sarna body (2)	8.8	R	281 ± 14	281	−38.5	345.0	1010101	4
7-17 W-Vastergotland sill	6.3	R	284 ± 8	284	−38.0	346.0	1110101	5
Carboniferous								
6-06 Scania dolerites (A)	11.0	R	U-Carbon.	290	−39.0	360.0	1110101	5
6-07 Scania dolerites (B)	6.5	R	U-Carbon	290	−38.5	348.5	1110101	5
6-09 Stabben sill (hb)	2.4	R	291 ± 8	291	−32.1	354.4	1110101	5
6-05 E-Vastergotland sill	4.0	R	293 ± 15	293	−31.0	354.0	1110101	5
5-25 Billefjorden Group (R)	24.9	R	Tourn–Nam.	350	−26.0	344.0	1010111	5
5-24 Billefjorden Group (N)	12.6	R	Tourn–Nam	350	−22.0	327.0	1010111	5
Devonian								
5-27 ORS W. Ukraine	7.1	M	Ged.-Sieg.	400	2.6	325.4	1110111	6
5-28 Dicksonfjorden ORS	10.0	M	L-Devonian	400	−10.0	315.0	1010111	5
Silurian								
4-13 Seiland Igneous Complex (A)	7.7	N	430–290	410	5.0	335.0	0111001	4
4-15 Honningsvåg Igneous Complex	8.4	M	411 ± 7	411	7.0	344.0	1110011	5
4-07 Ringerike sandstone (HB)	9.1	M	L-Ludlow	420	−19.0	344.0	1111111	7
4-10 Gotland Medby Limestone	8.0	N	L-Ludlow	420	−23.0	351.0	1000101	3
4-09 Gotland Dacker limestone	2.0	N	M-Wenlock	425	−19.0	349.0	1010101	4
4-08 Gotland Follingbo limestone	6.0	N	M-Wenlock	425	−21.0	344.0	1000101	3
4-14 Gotland Visby Limestone (HB)	5.1	N	L-Wenlock	428	−19.0	352.0	1110101	5
Ordovician								
3-17 Mjøsa Limestone	5.4	M	U-Ashgill	440	−5.3	6.5	1011011	5
3-08 Swedish Limestone I(N)	13.4	N	464–447	455	3.0	35.0	1010111	5
3-11 Vestergotland (N3)	4.8	N	464–447	455	5.0	34.0	1110111	6
3-10 Vestergotland (N1, N2 & R1-R3)	4.4	M	466–464	465	14.0	49.0	1110111	6
3-12 Swedish Limestones	9.0	R	493–469	481	30.0	55.0	1110101	5
3-09 Swedish Limestones I(R)	5.1	R	493–469	481	18.0	46.0	1110111	6
3-01 Swedish Limestones	2.2	R	493–469	481	30.0	46.0	1110101	5
Vendian–Cambrian								
2-02 Nexø sandstone	11.5	R	570–536	553	38.0	134.0	1110000	3
2-03 Fen carbonate complex	3.0	M	600–530	565	63.0	142.0	0010110	3
2-09 Fen tinguaites	6.4	M	600–530	565	50.9	143.9	0110110	4
2-11 Sredny diabase dyke	5.0	R	600	600	70.0	078.5	0100101	3

We believe this re-evaluation to be timely in the light of recent additions to the Palaeozoic palaeomagnetic data-set for Baltica. Furthermore, during the last five years, palaeomagnetic reliability criteria have become better formalised (Van der Voo, 1988), and more sophisticated numerical methods for modelling APW paths are now available (Silverman, 1985; Jupp and Kent, 1987). We take advantage of these recent developments in the present study.

ASSESSMENT OF RELIABILITY AND DATA SELECTION

In our assessment of the reliability of palaeomagnetic data from Baltica, we have classified published data according to the reliability criteria proposed by Van der Voo (1988). Van der Voo recognises seven fundamental reliability criteria for palaeomagnetic results which we briefly reiterate below.

(1) Well-determined age. (In our analysis magnetisation age should be equal to rock age and stratigraphic ages are according to the time-scale of Harland et al., 1989).

(2) Result based on more than 25 samples, with Fisher (1953) precision k greater than 10 and α_{95} less than 16°.

(3) Demagnetisation results reported in sufficient detail

(4) Positive field (fold-, conglomerate-, contact-) tests

(5) Tectonic coherence with continent, good structural control

(6) Antipodal reversals identified

(7) Lack of similarity with younger poles

In general, palaeomagnetic results will either satisfy, or not, each of the seven criteria. The total criteria satisfied (0 to 7) can be used as a measure of a result's overall reliability. This is referred to as the "quality factor" or "Q" by Van der Voo (1988).

Our selection of Late Precambrian to Permian palaeomagnetic data for Baltica (Table 1) satisfy at least three of the reliability criteria listed above. In the making of our selection, however, we recognise that failure to endure just one of the seven tests might invalidate the result for palaeogeographic work.

We attribute comparatively little weight to criterion 7. Firstly, the reliability of the poles with which the result (under scrutiny) is being compared must themselves be assessed, making the procedure somewhat subjective. Secondly, success or failure to meet criterion 7 depends on the completeness of the apparent polar wander record since the reported age of the result in question. Thirdly, the usefulness of the criterion diminishes with increasing magnetisation age, in accordance

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Notes to Table 1

α_{95} = 95% confidence circle, P = Palaeomagnetic polarity (N = normal, R = Reverse; M = Mixed); Age = rock age in million years (= magnetic age used to construct the smooth APW path listed in Table 2); L, M and U = Lower, Middle & Upper; Lat/Long = Latitude/Longitude for palaeomagnetic south poles; Q = quality factor (cf. text for explanations for criterion 1–7).

References:

Permian 7-19 Torsvik et al, 1978; 7-03 to 7-05 and 7-07 Halvorsen, 1972; 7-11, 7-12, 7-14 and 7-15 Thorning and Abrahamsen, 1980; 7-09 Halvorsen 1970; 6-11 Douglass, 1988; 6-01 Storetvedt et al., 1978, 7-08 Van Everdingen 1960; 7-01 Bylund 1974, 6-03 Bylund and Patchett, 1977, 6-02 Smith and Piper, 1979, 7-17 Mulder, 1970.

Carboniferous 6-06 Mulder, 1970; 6-07 Bylund, 1974, 6-09 Sturt and Torsvik, 1987; 6-05 Mulder, 1970; 5-25 and 5-24 Watts, 1985

Devonian 5-27 Smethurst and Khramov, 1992; 5-28 Jelenska and Lewandowski, 1986

Silurian 4-13 Torsvik et al., 1990b; 4-15 Torsvik et al., 1992; 4-08 to 4-10 Claesson, 1979, 4-07 Douglass, 1988; 4-14 Trench and Torsvik, 1991a

Ordovician 3-17 Bøhm 1989; 3-08 and 3-09 Torsvik and Trench, 1991a; 3-10 and 3-11 Torsvik and Trench, 1991b; 3-12 Claesson, 1978; 3-01 Perroud et al, 1992

Vendian–Cambrian 2-02 Prasad and Sharma 1978; 2-03 Poorter, 1972; 2-09 Piper, 1988, 2-11 Shipunov, 1988.

Pole codes are according to the list of Pesonen et al (1991) with the increasing extent and complexity of the reference APW curve with which the result should be compared.

We have experienced difficulty in assessing the reliability of magnetic overprints. Their ages are often based on accordance with reference APW interpretations which are, themselves, of finite reliability. With a view to establishing the best possible time calibration (criterion 1) of our new apparent polar wander curve we have excluded all overprints from our data compilation.

PALAEOMAGNETIC POLES

For the sake of consistency we refer to the geographic positions of palaeomagnetic poles as south poles only. The actual polarities of the palaeomagnetic data are given in Table 1.

Late Precambrian-Cambrian (610-510 Ma)

Approximately 15 palaeomagnetic poles of possible Late Precambrian (Vendian) and Cambrian age are reported in the literature, a number of which are only available in summary tables (Khramov, 1987), thereby failing criterion 3, and few, if any, of these are of high palaeomagnetic reliability.

For Vendian times we have selected a palaeomagnetic result from the 600 Ma Sredny Diabase dyke (Shipunov, 1988; K/Ar whole rock age). The dyke is located to the

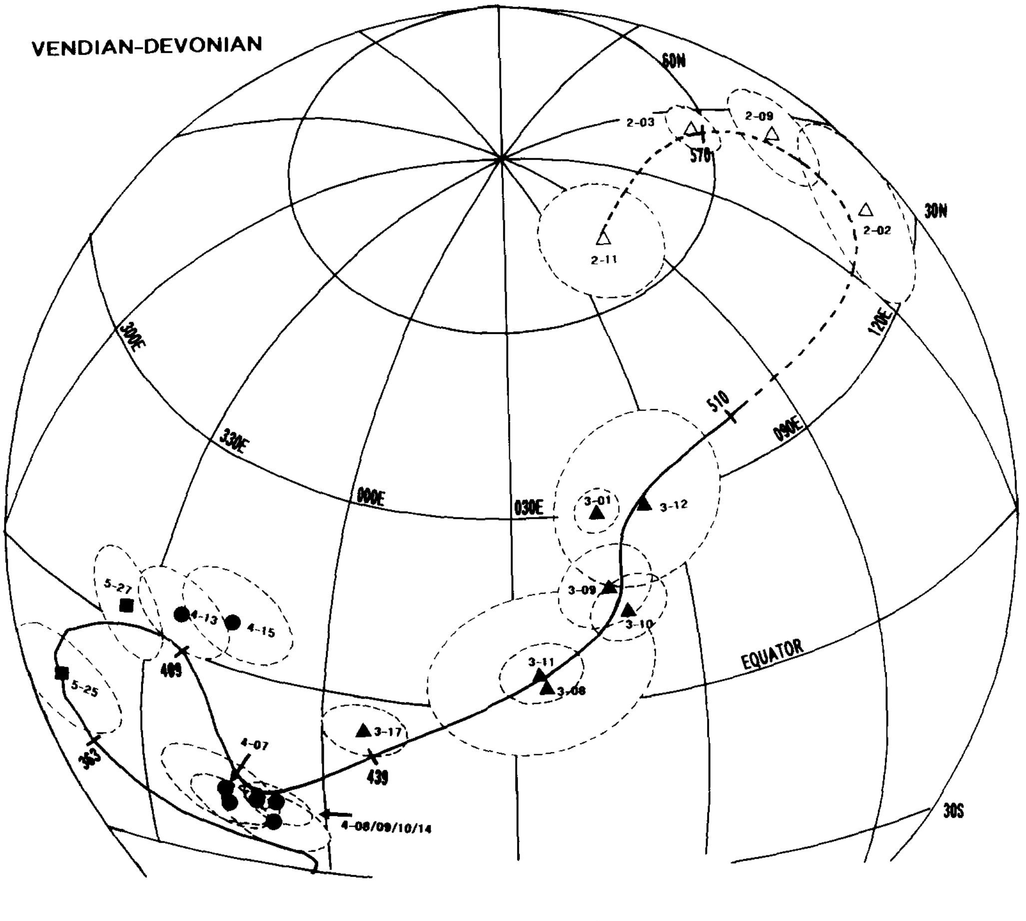

Fig 2. Vendian to Devonian palaeomagnetic poles from Baltica (Table 1) portrayed with ovals of 95% confidence. See Table 1 for pole codes A smooth APW path has been fitted to the data (cf. text and Figs. 3 and 5) Pole symbols are as follows: Open Triangles = Vendian–Cambrian, Closed Triangles = Ordovician; Dots = Silurian; Closed squares = Devonian. Equal-area projection

south of the Trollford–Komagelv Fault Zone, Kola Peninsula (Russia; Fig. 1). Some other poles of reported Late Precambrian age from the same region (Sredny and Kildin Islands) were excluded from our selection due to negative fold-tests (Shiponov, 1988). The well-referenced Late Precambrian (640 Ma —K/Ar Biotite age) Båtsfjord pole of Kjøde et al. (1978), northern Norway, has also been excluded because this pole was obtained from dykes north of the Trollfjord–Komagelv Fault Zone, so failing criterion 5.

Three Early Cambrian (c. 560 Ma) poles qualify for inclusion in our data compilation (Table 1 and Fig. 2). These poles are derived from intrusive and sedimentary rocks in southern Norway and Denmark (Bornholm island). Dual-polarity remanence was observed, and the Early Cambrian south poles cluster around 51°N, 139°E. These poles resemble Triassic poles for Europe, hence they do not meet criterion 7.

Ordovician (510–439 Ma)

Extensive re-sampling of the Swedish Ordovician Limestones (Torsvik and Trench, 1991a, b; Perroud et al., 1992) have shed important light on the Ordovician palaeofield for Baltica, and these new Ordovician palaeo-poles (Fig. 2) now form a key element in the APW path for Baltica. The age of these reliable Ordovician palaeo-poles is Arenig to Caradoc (481–455 Ma), supported by a stratigraphically-linked reversal pattern (Torsvik and Trench, 1991b). The Ordovician south-poles show systematic westerly directed APW (Fig. 2).

Silurian (439–409 Ma)

A number of palaeo-poles of possible Silurian age are reported in the literature, but most of their magnetic ages are at best uncertain, and many of them were obtained from rocks within the scandinavian part of the Caledonian orogenic belt where structural control is poor.

The Ringerike pole of Douglass (1988; Ludlow—ca. 420 Ma), from the Caledonian foreland, southeast Norway, constitutes the most reliable Silurian palaeo-pole for Baltica; a pole constrained in age by a positive fold-test and a stratigraphically linked reversal pattern. Other mid to late Silurian poles (i.e. Wenlock to Ludlow, ca. 418–428 Ma; Claesson, 1979; Trench and Torsvik, 1991a) with lower quality-factors (Table 1) fall close to the Ringerike pole position.

Six poles have been used to constrain the Silurian segment of the APW path for Baltica (Fig. 2). Four of these cluster around the Ringerike pole (mean pole 20°S, 348°E, $A_{95} = 3.8$; average age 425 Ma), and the remaining around 6°N, 339°E. The latter poles were derived from Scandian (ca. 410 Ma) intrusives from northern Norway. The collective data suggest northwesterly south APW from mid to Upper Silurian/Lower Devonian times; a feature also recognized in the APW path for Laurentia (Kent and Van der Voo, 1990; Torsvik et al., 1990a; Van der Voo, 1990).

Devonian (409–363 Ma)

Few primary Devonian palaeomagnetic directions have been identified within Baltica as many palaeo-poles from Devonian rocks of western and central Norway are recognized to be magnetic overprints (Torsvik et al., 1988, 1990a; Smethurst, 1990). Therefore we have been able to select only two poles for Devonian times (Table 1 and Fig. 2), i.e. Lower Old Red Sandstone (ORS) poles from western Ukraine and central Spitsbergen (Jelenska and Lewandowski, 1986; Smethurst and Khramov, 1992; mean pole: 4°S, 320°E; age ca. 400 Ma). In the former case, a stratigraphically linked polarity pattern suggests a primary origin of remanence. In the latter case we assume that central Spitsbergen was tectonically coherent with Baltica from Devonian times within the limits of palaeomagnetic resolution (Torsvik et al., 1985).

Carboniferous (363–290 Ma)

Carboniferous poles (Table 1) are derived from Upper Carboniferous sills in southern Sweden and central Norway and Lower Carboniferous sediments from central Spitsbergen. The Lower Carboniferous palaeomagnetic data have dual-polarity (mean pole 24°S, 336°E; age ca. 350 Ma). Upper Carboniferous poles are exclusively of reverse polarity and cluster around 35°S, 354°E ($A_{95} = 6.4$, $N = 4$). A south-easterly course for the Carboniferous south-APW path is indicated by these data (Fig. 3).

Permian (290–245 Ma)

Seventeen Permo-Carboniferous poles are listed in Table 1. The majority of these poles (Fig. 3) are derived from intrusive and extrusive rocks within the Oslo rift (250–280 Ma) and rift-related dykes and sills in southern Sweden, southwest Norway and central Norway. All of the Permian poles are of reverse polarity and yield a mean pole of 45°S, 339°E ($A_{95} = 4.3$, $N = 17$).

DIGITAL CONSTRUCTION OF THE APPARENT POLAR WANDER PATH

A smooth path has been fitted to the selected palaeomagnetic pole positions (Table 1; Figs. 2 and 3) using the "spherical spline" algorithm of Jupp and Kent (1987). The smooth path, with locus and time progression, is analogous to the familiar apparent polar wander path.

It is possible to generate a number of paths with different smoothing from a single

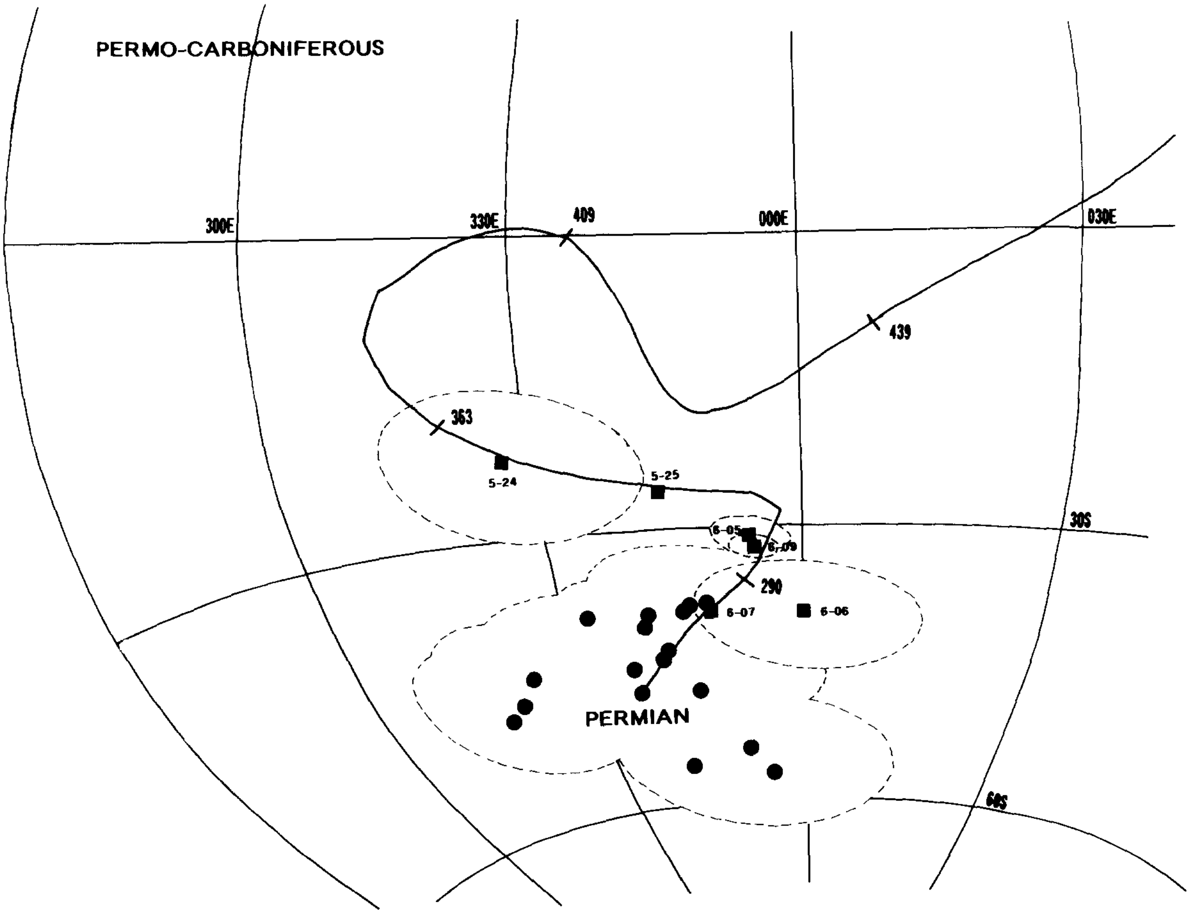

Fig. 3 Permian (Dots) and Carboniferous (closed squares) palaeomagnetic poles from Baltica plotted with dp/dm semi-axes Conventions as in Fig. 2.

data set. This is done by adjusting a smoothing parameter used by the computer program (Torsvik et al., 1990c). The route taken by the "spherical spline" through the data set also depends on the standard error for each of the palaeopole positions. The lower the reported angular error for a pole position, the closer the curve will pass by it.

It is clear that the angular error associated with a particular palaeomagnetic pole position is far from an adequate description of the quality or reliability of that pole. For example, uncertainty in the age of the result has a direct bearing on the angular uncertainty which should be associated with it, since apparent polar wander might be continuing within the time period of uncertainty. Instead of weighting pole positions solely on the basis of criterion 2 in Van der Voo's reliability scheme (α_{95}), we chose to weight the data in proportion to their "Quality factors". This causes the smooth path to pass close to the data which score "7", full-marks, and be only gently guided by those data with lower reliabilities.

We ran the algorithm with various smoothing parameters and obtained smooth paths which were very similar to each other; all paths showed the same major features. We also attempted to derive some indication of the relative reliability of the smooth path along its length (i.e. through time). This was achieved using an adaptation of the BATHSPLINE program of Silverman and Waters (1984). The BATHSPLINE program produces an estimate of the accuracy of the fitted path at each time for which there are palaeo-poles. Because we have adjusted the sizes of the error ovals on each original palaeopole to take account of our reliability criteria (e.g. uncertainty in age) we can only interpret the accuracy of our path in relative terms. The accuracies obtained for the various parts of our fitted path, at times for

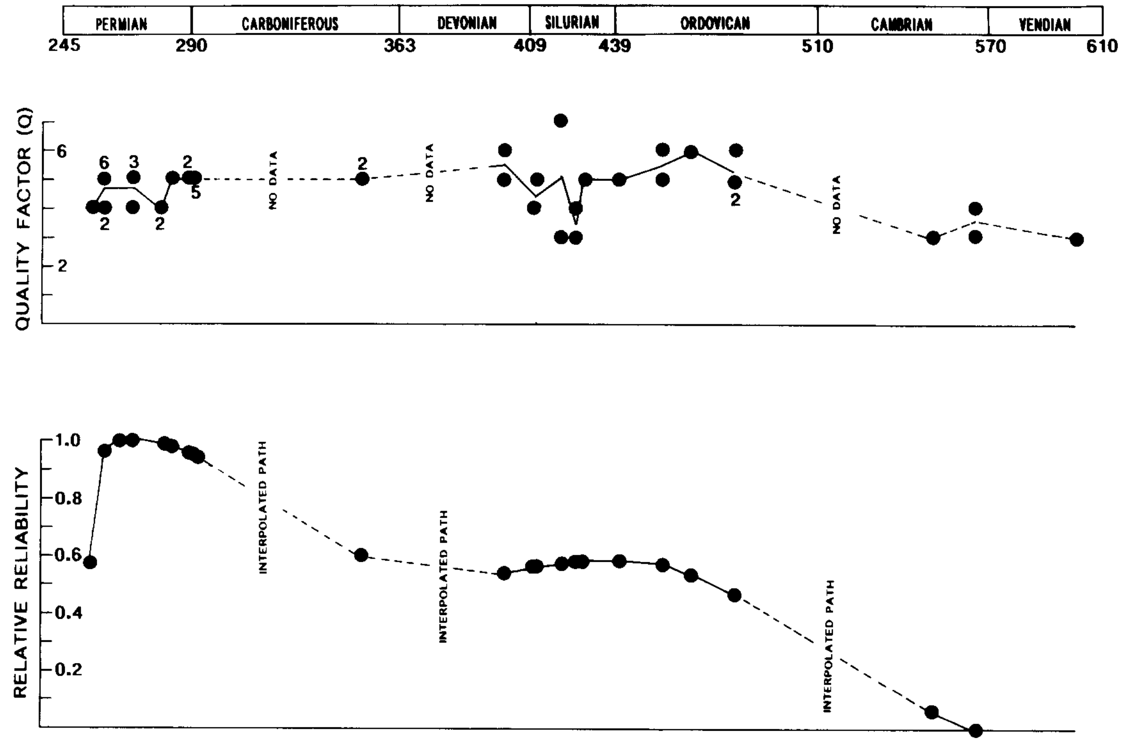

Fig. 4 Palaeomagnetic quality factor's (Top diagram–Van der Voo 1988) and relative reliability diagrams for the new APW path from Vendian to Permian times (see text). Numbers associated with points in the quality factor diagram denote number of poles with that quality factor. Relative reliability is indicated between 1 (best) and 0 (worst). Time-scale/ages after Harland et al. 1989.

TABLE 2

South Apparent Polar Wander Path for Baltica (Vendian–Permian times)

Age	Lat.	Long.	Age	Lat	Long.	Age	Lat.	Long.
256	-48.6	330.9	415	-7.2	341.0	514	38.3	84.9
257	-48.4	332.1	416	-8.6	341.7	517	38.5	89.6
258	-48.3	333.3	417	-11.4	343.1	520	38.5	94.4
259	-48.0	334.5	418	-12.8	343.8	523	38.4	99.2
260	-47.7	335.5	419	-14.0	344.5	526	38.2	103.8
261	-47.3	336.6	420	-15.2	345.1	529	38.0	108.2
263	-46.8	337.6	425	-18.5	349.2	532	37.8	112.4
264	-46.3	338.4	427	-18.7	350.6	535	37.7	116.4
265	-45.9	339.0	428	-18.4	352.2	538	37.8	120.1
267	-45.4	339.8	430	-17.8	354.1	541	38.1	124.0
268	-44.9	340.4	431	-16.7	356.1	544	38.7	126.7
270	-44.4	341.0	433	-15.4	358.3	547	39.6	129.6
273	-43.4	342.1	435	-13.9	0.6	550	41.0	132.3
276	-42.2	343.4	437	-12.2	3.0	553	42.9	134.8
278	-40.9	344.9	438	-10.5	5.6	555	44.2	136.1
281	-39.7	346.6	440	-8.8	8.3	556	45.6	137.4
284	-38.3	348.6	442	-7.3	10.8	558	47.1	138.5
286	-37.4	350.1	443	-5.9	13.4	560	48.8	139.6
288	-36.6	351.6	445	-4.5	16.0	562	50.4	140.5
290	-35.4	353.2	446	-3.2	18.7	563	52.1	141.3
291	-35.0	353.6	448	-1.8	21.4	565	53.8	141.9
293	-33.9	354.7	449	-0.5	24.1	569	57.0	142.3
303	29.8	357.5	450	0.8	26.7	572	60.1	141.6
312	27.6	357.4	452	2.1	29.3	576	63.0	139.5
322	26.7	354.8	454	3.4	31.9	579	65.7	135.9
331	26.3	350.0	455	4.7	34.3	583	68.1	130.4
341	25.8	343.3	456	6.2	36.9	586	70.0	122.9
350	24.1	335.2	458	7.7	39.3	590	71.4	113.3
356	22.5	330.1	460	9.2	41.5	593	72.0	102.2
361	20.2	325.1	462	10.7	43.4	597	71.9	90.4
367	17.6	320.6	463	12.1	45.1	600	71.0	79.2
372	14.7	317.0	465	13.5	46.4			
378	11.7	314.6	468	16.1	48.1			
383	8.7	313.7	471	18.5	48.8			
389	5.9	314.5	475	20.8	49.0			
394	3.2	317.4	478	23.0	49.1			
400	0.9	322.7	481	25.0	49.4			
402	0.3	324.8	484	26.9	50.2			
403	0.1	327.1	487	28.7	51.6			
405	0.3	329.4	490	30.3	53.6			
407	0.2	331.8	493	31.9	56.2			
408	0.3	334.1	496	33.3	59.2			
410	1.4	336.3	499	34.6	62.6			
411	2.3	337.4	502	35.7	66.5			
412	3.4	338.4	505	36.7	70.7			
413	4.5	339.3	508	37.4	75.2			
414	5.8	340.2	511	38.0	79.9			

Lat./Long. = Latitude/Longitude for palaeomagnetic south poles.

Age in million years. Poles older than ca. 500 Ma should be treated with caution due to low palaeomagnetic reliability.

which there are data, are interpreted as indications of the reliability of the path at those times. We find, almost invariably, that the algorithm assigns low accuracies to the end-parts of paths. This is because the algorithm has no way of knowing where the path is "coming from" or "going to" at the oldest and youngest ends of the path respectively.

To avoid misinterpretation of the path accuracy or relative reliability parameter, we report values which are normalised to the most reliable, well constrained part of the path (with value 1). Figure 4 illustrates the fluctuation in relative reliability of the fitted path through time. We also indicate, alongside this curve, the reliabilities of the original data set in terms of Van der Voo's Q-factor.

Examination of Fig. 4 indicates that the locus of our fitted path is most reliably constrained for Permian times. The Silurian and Ordovician parts of the path have a somewhat lower relative reliability, despite the fact that some of the latter poles have high Q-factors. The lowest reliability is noticed for the Late Precambrian and Cambrian segments of the path. The high reliability of the Permian part of the path can be explained by the large number of palaeomagnetic poles available for Permian times, and their tight grouping, whereas the lower reliability segments of Fig. 4 are clearly caused by the relatively low density of individual results along the path. Note that the Middle Carboniferous, most of the Devonian and the Middle-Cambrian to Lower-Ordovician parts of the APW path are essentially interpolated due to the sparsity of data. No relative errors have been assigned to these segments of the path.

The new south APW (SAPW, Table 2) path (Fig. 5) has the following characteristics:

(1) A Vendian–Cambrian loop or cusp.

(2) Steady south-west directed APW through Ordovician times.

(3) A tight loop from Silurian to Middle-Carboniferous times.

Compared with earlier published APW

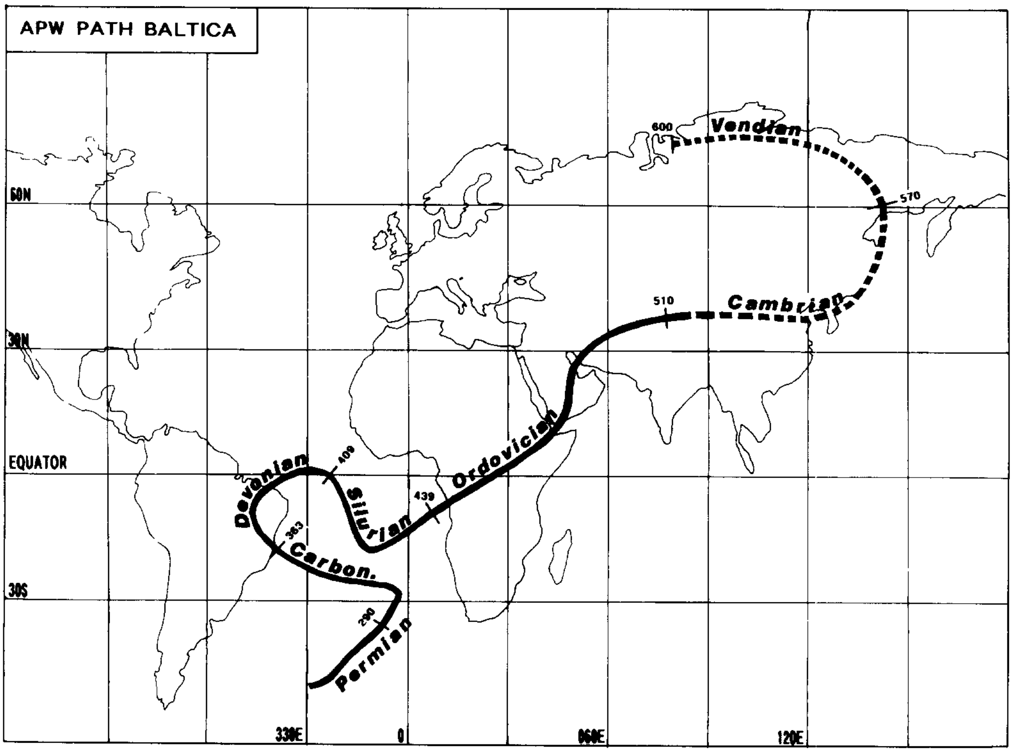

Fig. 5. A smooth APW path for Baltica derived from the Vendian to Permian palaeomagnetic data. The Vendian–Cambrian part of the path should be treated with caution due to the sparsity of avaiable data and consequent low path reliability (cf. Fig. 4) Galls Projection

paths for Baltica, our new path closely resembles path "Y" of Torsvik et al. (1990b) in the Cambrian to Devonian time range. The Ordovician part of path "Y" was based on early Ordovician uplift magnetizations carried by basic intrusive rocks in northern Norway (Torsvik et al., 1990b, 1991; Trench and Torsvik, 1991a) and a pole reported by Claesson (1978) from the Swedish Ordovician limestones. Ironically, the former result were not considered to be reliable enough for our present analysis.

DRIFT-HISTORY FOR BALTICA

The Late Precambrian to Permian palaeolatitudinal drift-history for Baltica, based on our new APW path, is portrayed in Fig. 6. Rotational velocities and latitudinal driftrates calculated for Oslo (60°N, 10°E) are shown in Fig. 7. From these figures we observe the following:

(1) Baltica was situated in high to intermediate southerly latitudes from Late-Precambrian to Early-Palaeozoic times.

(2) Baltica drifted northwards through most of Palaeozoic times, except for Cambrian and Late-Silurian/Early-Devonian times, occuping equatorial latitudes by mid-Silurian times.

(3) Latitudinal drift velocities vary from ca. 9 cm/yr in Vendian times to less than 2 cm/yr in Permo-Carboniferous times (Figs. 6 and 7).

(4) Baltica was geographically inverted in Late-Precambrian and Early-Palaeozoic times. A marked anticlockwise rotation of Baltica is recognized throughout the Palaeozoic and angular velocities ranged between 0.02°/Ma and 1.6°/Ma (Figs. 6 and 7).

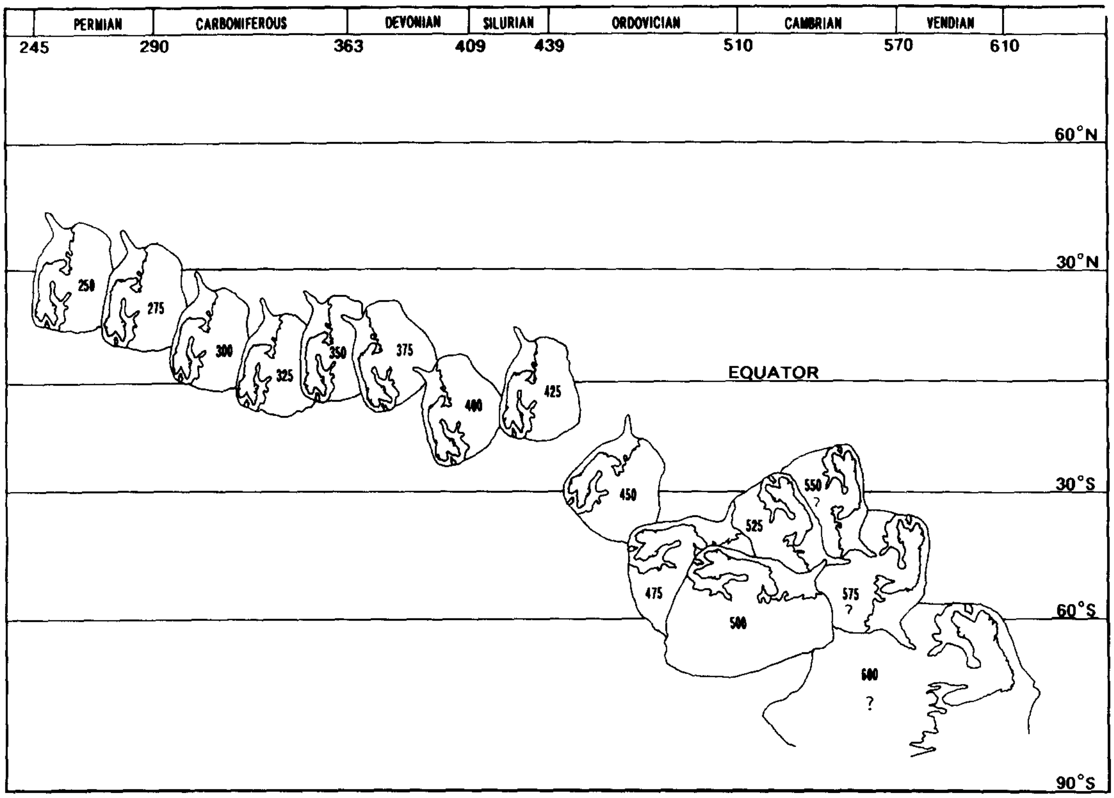

Fig 6. The drift-history for Baltica from Vendian to Permian times. Geological time is on the horizontal axis. The reconstructions are positioned in the horizontal time scale according to the position of city of Oslo (60°N, 10°E). Vendian and Cambrian palaeo-positions are of low reliability. Palaeo-poles used in the reconstruction (25 Ma intervals) are based on Table 2

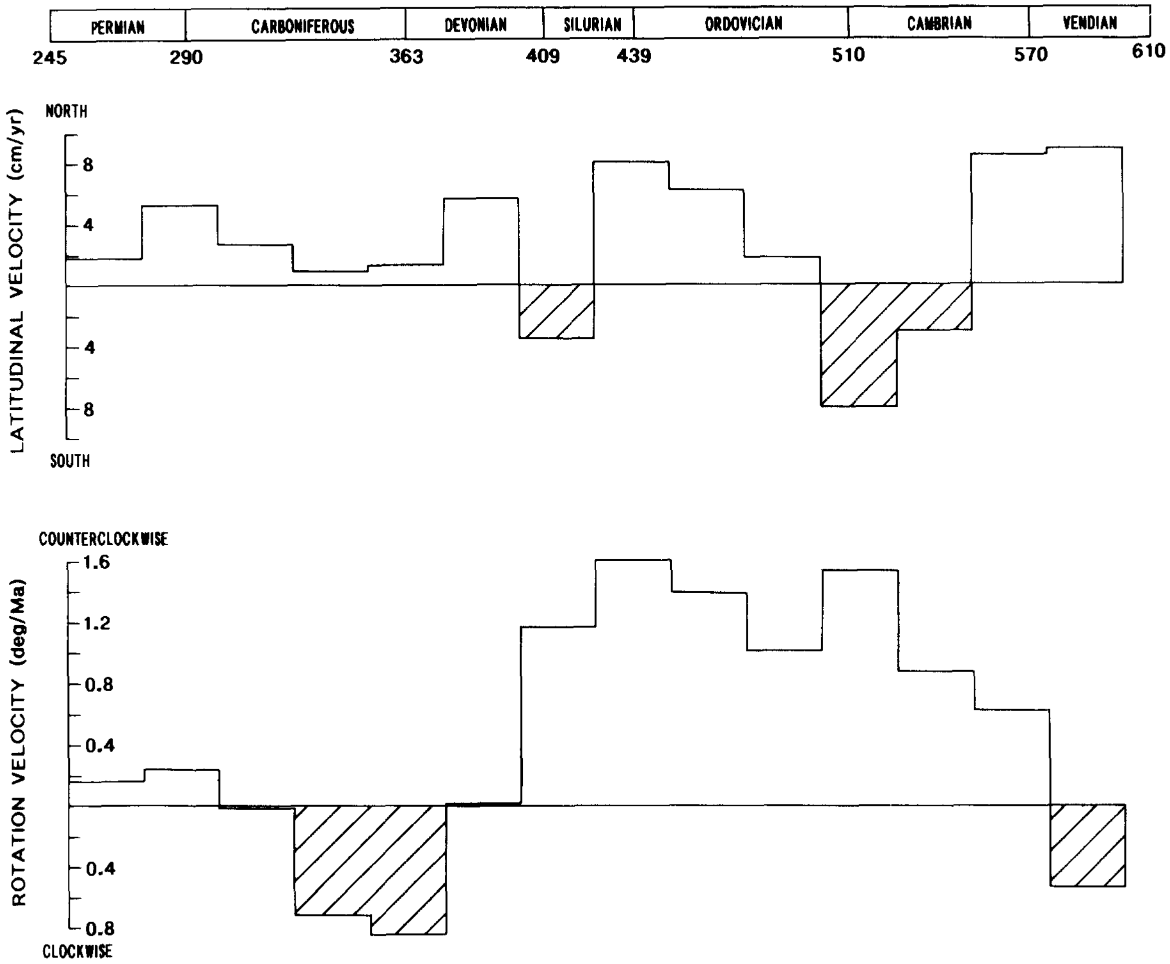

Fig. 7 The latitudinal and angular velocity of Baltica as a function of geological time. Southward movements and clockwise rotations are shaded. Vendian–Cambrian estimates poorly constrained by data.

The high- to intermediate southerly latitudes in Late-Precambrian/Early-Palaeozoic times for Baltica is supported by the presence of Vendian tillites in the stratigraphic record and Early–mid-Ordovician cold-water carbonates in southeast Norway and southern Sweden. We also observe a notable decrease in the latitudinal velocity of Baltica through the Palaeozoic (Fig. 7), which may reflect the accretion of continents during Palaeozoic times to form Euramerica and ultimately the supercontinent Pangea by Permian times.

Notably high anticlockwise rotations of Baltica occured in Late-Cambrian/Early-Ordovician and Late-Ordovician–mid-Silurian times. Anticlockwise rotation of Baltica has important implications for the development of the Tornquist Sea (Fig. 8) and the continental suturing of Baltica to Gondwana-derived microcontinents during the Palaeozoic; dextral shear along the former line of the Tornquist Sea is expected (Torsvik and Trench, 1991a). The inverted orientation of Baltica in Late-Precambrian–lower-Palaeozoic times has also profound implications for identifying the former margins to the Iapetus Ocean; the ocean that once separated Laurentia and Baltica (Fig. 8). It would now seem that the margin of Baltica which rifted from, we assume, Laurentia in the Late Precambrian was not the same margin that collided with Laurentia, hence bringing into question the true nature of the "Wilson cycles" theory (Wilson, 1966). The initiation of continental-scale anticlockwise rotation during the early Palaeozoic could be linked to a rift event or alternatively tied to the Late-Cambrian–Early-Ordovician Finnmarkian orogeny in northern Norway.

INTERACTION OF BALTICA WITH OTHER PALAEOCONTINENTS

When referring to the Tornquist and Iapetus margins of Baltica we mean the margins of Baltica which currently border the Tornquist Zone and Iapetus suture respectively. We do not intend to imply that those same margins necesserily bordered the former Tornquist Sea and Iapetus Ocean thoughout Palaeozoic times.

Tornquist margin

In Early-Ordovician times Eastern Avalonia and other European Massifs (e.g. the Armorican and Bohemian Massifs) were po-

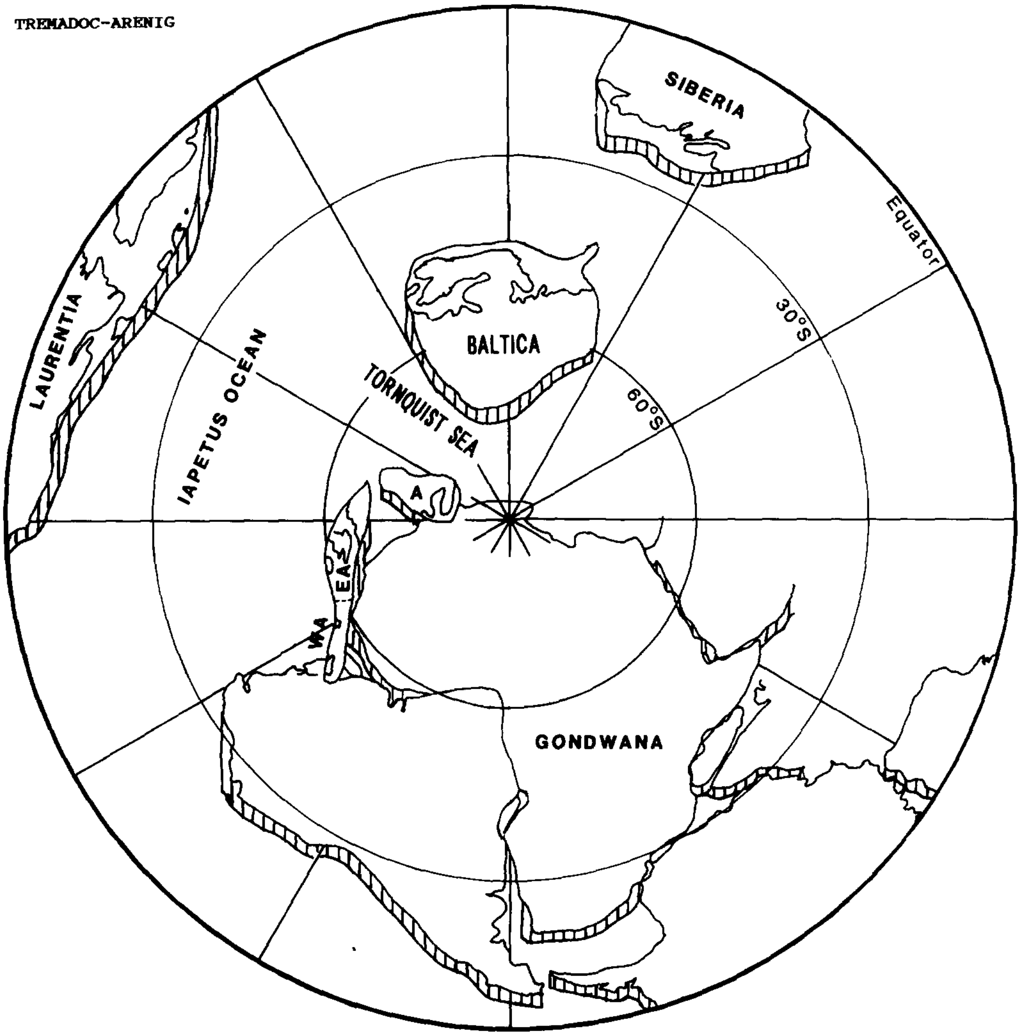

Fig 8. Early Ordovician, Arenig (ca. 490 Ma), reconstruction. Laurentia, Siberia, Gondwana, Armorica (denoted A) and Eastern Avalonia (EA) positioned according to Torsvik and Trench (1991c). Baltica positioned according to a palaeomagnetic pole at 30.3°N, 53.6°E (490 Ma pole in Table 2). The Iapetus Ocean is approximately 5000 kilometres (minimum) across the British sector in this reconstruction. Note that the true width of the Tornquist Sea is not constrained by palaeomagnetic data (see text). Equal area polar projection.

sitioned in high southerly latitudes (Fig. 8) together with Gondwanaland (Cocks and Fortey, 1982, 1990; Van der Voo, 1988; Scotese and McKerrow, 1990; Soper and Woodcock, 1991; Torsvik and Trench, 1991c). Gondwana and Armorica are known to have occupied high southerly latitudes throughout Ordovician times. Their post-Ordovician movements are, however, still poorly constrained by palaeomagnetic data and not depicted in post-Ordovician reconstructions.

The faunas and sedimentary facies of Baltica differed from those of the northern margin of Gondwana in Early-Ordovician times, hence the Tornquist Sea is presumed to constitute a faunal barrier at this time (Cocks and Fortey, 1982; Scotese and McKerrow, 1990). On palaeomagnetic grounds it is difficult to estimate the width of the Tornquist Sea. Palaeolatitude estimates for Baltica are similar to those obtained for the northern margin of Gondwana, and Baltica and the margin of Gondwana must have been offset longitudinally in order to accomodate the Early-Ordovician Tornquist Sea (Fig. 8). This tectonic scenario may suggest that the faunal differences between Baltica and the northern margin of Gondwana were not

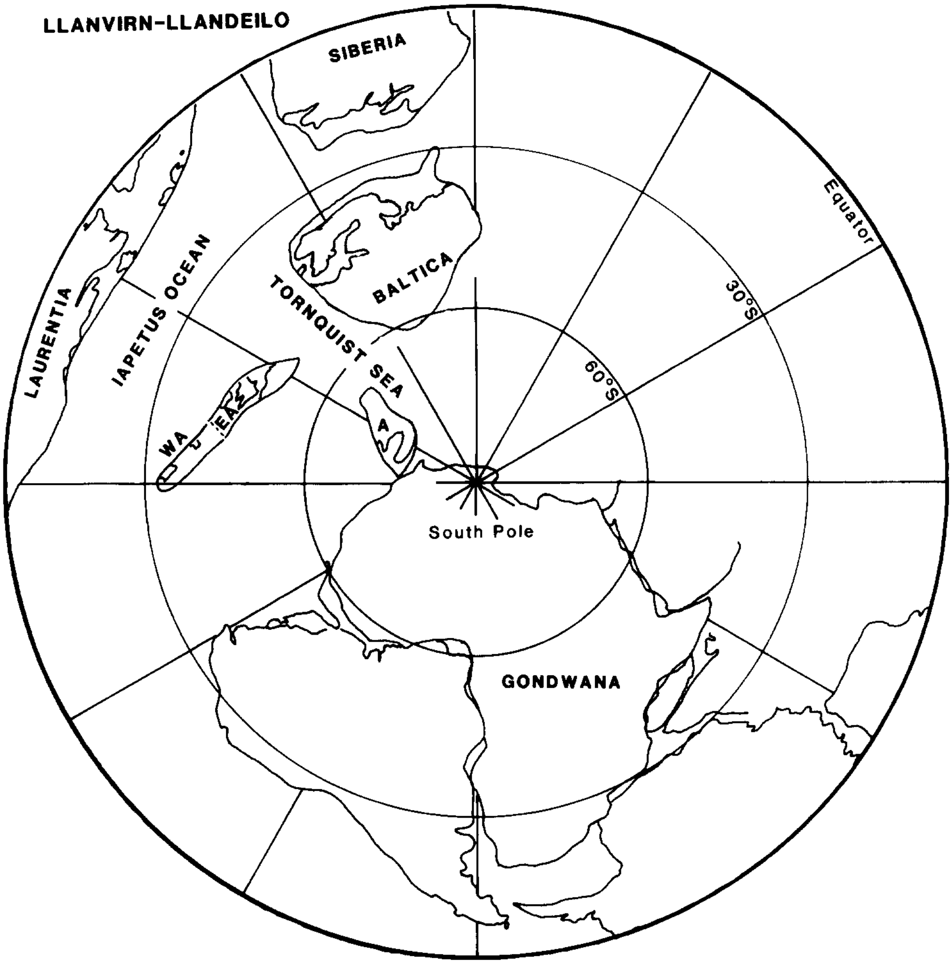

Fig 9 Mid-Ordovician, Llanvirn (ca. 470 Ma), reconstruction. Baltica drawn according to a palaeomagnetic pole at 18.5°N, 48.8°E (471 Ma pole in Table 2). Laurentia, Siberia, Eastern and Western Avalonia (EA and WA), Armorica (A) after Torsvik and Trench (1991c). With regard to Laurentia, North America and Scotland are portrayed in a Bullard et al. (1965) fit. The width of the Iapetus Ocean is reduced to ca. 3300 kilometres at this time. The width of the Tornquist Sea is unknown (palaeo east-west orientation) and is here left open to take account of faunal and sedimentary differences between Baltica and the northern margin of Gondwana.

strongly temperature ("latitudinal") controlled.

Eastern Avalonia probably rifted away from Gondwana in Arenig times (Torsvik and Trench, 1991c). The Tornquist Sea, between Avalonia and Baltica, probably started to close while Iapetus diminished by some 2000 km from late Tremadoc/early Arenig to Llanvirn–Llandeilo times (compare Figs. 8 and 9). During Llandeilo–Caradoc times the faunas of southern Britain show increasing similarity with those of Baltica, whilst faunal links with Gondwana declined (Whittington and Hughes, 1972; Vannier et al., 1989; Romano, 1990; Trench et al., 1992). By Ashgill time platform faunas from southern Britain and Baltica formed a single coherent province (Cocks and Fortey, 1982). Late-Ordovician palaeomagnetic palaeolatitudinal estimates for southern Britain and Baltica are similar and can be taken as evidence for a closed or narrow Tornquist Sea by that time (Fig. 10). Mid-Silurian palaeomagnetic data, however, are difficult to interpret in terms of a simple tectonic scenario. The Silurian segment of the APW path for southern Britain is exclusively based on the contentious mid-Silurian Somerset–Glouchester Lavas result of Piper (1975). That result suggests that southern Britain lay to the south of its present position relative to Baltica (Fig. 11a). We however, prefer to place southern Britain and Baltica in their present relative position in mid-Silurian times (Fig. 11a stippled) based on geological evidence. A single Baltic/British province of benthic ostracods, which were probably unable to cross even a narrow ocean, dictates the close proximity of Eastern Avalonia to Baltica during the Llandovery (McKerrow et al., 1992).

Iapetus margin

Laurentia was dominated by warm-water carbonate facies (Webby, 1984), including reefs and stromatolites, during most of the Ordovician and was positioned in equatorial latitudes (Figs. 8–10).

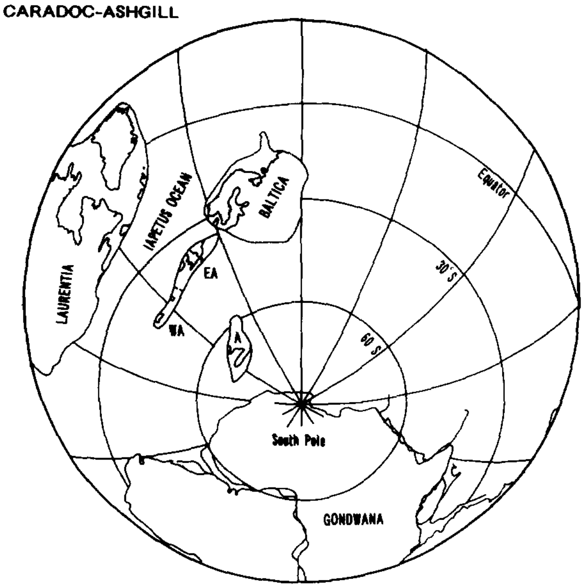

Fig. 10. Late Ordovician, Caradoc (ca 450 Ma), reconstruction showing the position of Laurentia according to Torsvik et al 1990a and b; Baltica according to Table 2; Eastern Avalonia according to Trench and Torsvik, 1991b. Gondwana is positioned as in Figs. 8 and 9 Both palaeomagnetic and palaeontological evidence indicates a narrow or closed Tornquist Sea at this time, whereas, on palaeomagnetic grounds the Iapetus Ocean has a width in the order of 1000–1500 kilometres.

Ordovician poles from Siberia are well grouped (Khramov et al., 1981; Torsvik et al., 1990a). The reliability of the Siberian palaeomagnetic data is supported by a reversal stratigraphy which is consistent with data from Baltica (Trench et al., 1991). Ordovician data indicate that Siberia occupied equatorial latitudes with the Mongolian margin of Siberia facing northward (Torsvik and Trench, 1991c). Post-Ordovician poles from Siberia are less consistent and Siberia is therefore not depicted in our post-middle-Ordovician reconstructions.

A component of southerly directed movement and anticlockwise rotation is recognized for Laurentia from Upper Ordovician to Early Devonian times (Figs. 8–11). Conversely, a pronounced northward drift of Baltica occurred in mid-Ordovician to mid-Silurian times (Fig. 7), a conclusion which is supported by the appearance of warm-water carbonates by Ashgillian times (Webby, 1984). By mid-Silurian times (ca. 425 Ma), Laurentia and Baltica collided (Fig. 11a), probably obliquely, giving rise to the Scandian Orogeny and extreme crustal thickening in western Norway prior to extensional collapse during the Early Devonian (Andersen and Jamtveit, 1990). After the main collision Laurentia and Baltica drifted southward (compare Figs. 11a and b). Baltica may also have undergone a minor counterclockwise rotation relative to Laurentia in order to provide an explanation for the somewhat younger deformation events in northern Norway (c. 410 Ma), in that northern Norway may have collided with Laurentia later than southern Norway.

By Early-Devonian times, Euramerica (Fig. 11b), consisting of Laurentia, Baltica and Avalonia were assembled. This involved the final closure of the Iapetus Ocean and the Tornquist Sea.

CONCLUDING REMARKS

Based on a reliability grading of the existing palaeomagnetic data we have constructed a new APW path for Baltica which is marked by two prominent loops for Vendian/Cam-

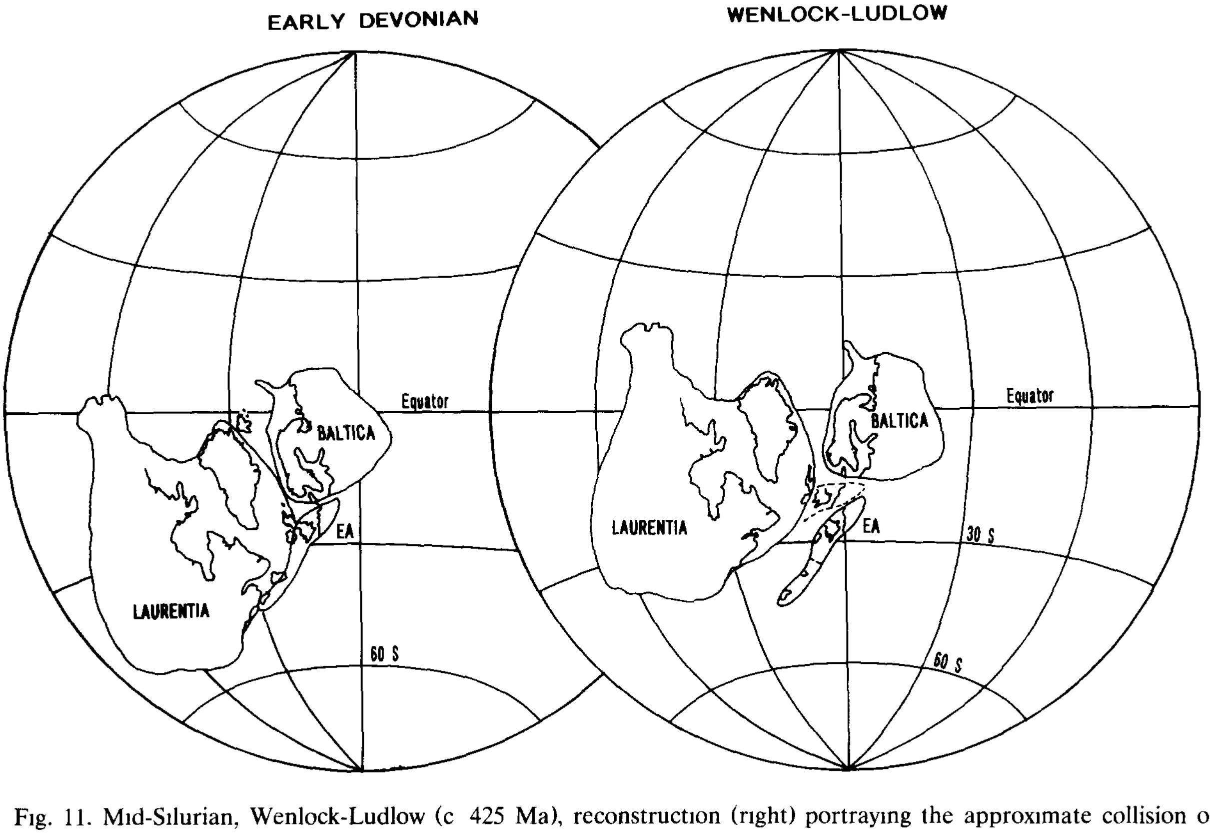

Fig. 11. Mid-Silurian, Wenlock-Ludlow (c 425 Ma), reconstruction (right) portraying the approximate collision of Baltica and Laurentia. The palaeolatitude gap between Baltica/Laurentia and Eastern Avalonia may suggest an open Tornquist Sea and an open Iapteus Ocean across the British sector at this time. The Mid-Silurian position of Eastern Avalonia, however (pole· 3.5S and 323E, Trench and Torsvik 1991b), should be treated cautiously and alternatively we have also indicated Eastern Avalonia attached to Baltica (stippled) Laurentia and Baltica positioned using mean poles of 15S and 335E (mean Laurentian pole outlined in Torsvik et al, 1990a and b) and 18.5S and 349E (Table 2). Gondwana not included due to uncertainty in the Siluro-Devonian palaeomagnetic data-sets. Early Devonian (c. 409 Ma) reconstruction (left). All continents positioned with a common pole of 4S and 324E (mean of APW paths outlined in Torsvik et al., 1990a,b, Trench and Torsvik, 1990b and Table 2) in a Bullard et al (1965) fit.

brian and Silurian/mid-Carboniferous times. These loops probably reflect major changes in plate-reconfiguration. The older one might be related to the rifting of Baltica from an as yet unknown continent and the younger one to Silurian convergence and the accretion of the Atlantic bordering continents to form Euramerica by Early-Devonian times.

Our new APW path, when compared with those from neighbouring continents and geological evidence, permits us to draw the following conclusions:

(1) Baltica was an individual continent in early-Palaeozoic times, positioned in high southerly latitudes in an "inverted" orientation. The Tornquist Zone is interpreted as a passive or dextral transform margin at that time.

(2) Baltica drifted northward through most of the Palaeozoic. A short period of southerly movement in Siluro-Devonian time resulted from collision with the larger Laurentian continent.

(3) High latitudinal velocities for Baltica, up to 9 cm/yr, are noted in Late-Precambrian/early-Palaeozoic times. A significant decrease in the latitudinal velocity of Baltica throughout Palaeozoic time may reflect the progressive accretion of continents to form, first, Euramerica by Devonian times and Pangea by Permian times.

(4) Marked counterclockwise rotation of Baltica throughout the Palaeozoic is recognized with angular velocities up to 1.6°/Ma from Late Cambrian to Early Ordovician and Late-Ordovician to mid-Silurian times.

(5) The microcontinents that ultimately collided with Baltica along the Tornquist Zone, including the European massifs and Eastern Avalonia were peripheral to Gondwana in high southerly latitudes during the Early Ordovician. Eastern Avalonia, rifted off Gondwana in the Early Ordovician and probably collided with Baltica during Late Ordovician times. The suturing of peri-Gondwanan micro-continents may have induced dextral shear along the Tornquist Zone.

(6) Laurentia was situated in equatorial and southerly latitudes during most of the lower Palaeozoic. Laurentia collided with Baltica in mid-Silurian times, involving an early collisional episode between southwest Norway and Greenland–Scotland leading to the early Scandian Orogeny (425 Ma). Since Baltica was geographically inverted in early Palaeozoic times, the margin of Baltica which rifted off Laurentia (??) in Late-Precambrian times was not the same margin which was to later collide with Laurentia to form the present day Iapetus suture. This is an important observation which should be taken into account in future plate tectonic investigations.

(7) Euramerica was assembled by Early-Devonian times and drifted northwards in the latter half of the Palaeozoic. By Permian time Baltica occupied northerly latitudes between 15 and 40 degrees.

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