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Continental break-up and collision in the Neoproterozoic and Palaeozoic — A tale of Baltica and Laurentia

T.H. Torsvik [a], M.A. Smethurst [a], J.G. Meert [b], R. Van der Voo [c], W.S. McKerrow [d], M.D. Brasier [d], B.A. Sturt [e], H.J. Walderhaug [f]

[a] Geological Survey of Norway, P.B. 3006 Lade, N-7002 Trondheim, Norway
[b] Department of Geography and Geology, Indiana State University, Terre Haute, IN 47809, USA
[c] Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-106, USA
[d] Department of Earth Sciences, University of Oxford, Parks Road, OX 3PR, UK
[e] Geological Survey of Norway, P.B. 3006 Lade, N-7002 Trondheim, Norway
[f] University of Bergen, Institute of Solid Earth Physics, Allegt. 41, N-5007 Bergen, Norway

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Abstract

During the Neoproterozoic and Palaeozoic the two continents of Baltica and Laurentia witnessed the break-up of one supercontinent, Rodinia, and the formation of another, but less long-lived, Pangea. Baltica and Laurentia played central roles in a tectonic *menage a trois* that included major orogenic events, a redistribution of palaeogeography and a brief involvement of both with Gondwana. Many of these plate re-organisations took place over a short time interval and invite a re-evaluation of earlier geodynamic models which limited the speeds at which large continental plates could move to an arbitrarily low value.

Baltica and Laurentia probably shared a common drift history for the time interval 750–600 Ma as they rotated clockwise and drifted southward from an equatorial position during the opening of the Proto-Pacific between Laurentia and East Gondwana (initial break-up of Rodinia). On their combined approach toward the south pole, Baltica and Laurentia were glaciated during the Varanger glaciations. Although the two continents drifted toward the south pole during the Late Proterozoic, they began to separate at around 600 Ma (rift to drift) to form the Iapetus Ocean through asymmetric rifting and relative rotations of up to 180°. Initiation of rifting on the Baltic margin is marked by the 650 Ma Egersund tholeiitic dykes (SW Norway) which contain abundant lower crustal zenoliths, and the tholeiitic magma was probably derived from a mantle plume.

In latest Precambrian time, the final redistribution of Rodinia is characterised by high plate velocities. In particular, Laurentia began a rapid, up to 20 cm/yr, ascent to equatorial latitudes and essentially stayed in low latitudes throughout most of the Palaeozoic. The high velocities suggest either that Laurentia was pushed off a lower mantle heat anomaly originating from supercontinental mantle insulation or that Laurentia was pulled toward a subduction-generated cold spot in the proto-Pacific. Baltica, except for a short and rapid excursion to lower latitudes in the Late Vendian, remained mostly in intermediate to high southerly latitudes and closer to the Gondwana margin until Early Ordovician times.

In Early Ordovician times, Arenig–Llanvirn platform trilobites show a broad distinction between the continents of Laurentia/Siberia/North China Block (Bathyurid), Baltica (Ptychopygine/ Megalaspid) and the areas of NW Gondwana/Avalonia/Armorica (Calymenacean–Dalmanitacean). During the Ordovician, Baltica rotated and moved northward, approaching close enough to Laurentia by the late Caradoc for trilobite and brachiopod spat to cross the intervening

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Iapetus Ocean. Docking appears to have been irregular both in time and manner: the collision between Scotland/Greenland and western Norway resulted in the early Scandian Orogeny in the Silurian (c. 425 Ma), but further south, there is evidence of late Silurian impingement with subduction of Avalonian continental crust (in England and Ireland) below the eastern edge of Laurentia until the Emsian. In the northern Appalachians the main time of collision appears to have been during the Emsian/Eifellian Acadian Orogeny.

Recent analyses invalidates the traditional concept of a sustained orthogonal relationship between Baltica and Laurentia across a single Iapetus Ocean throughout the Caledonide evolution. The active margin of Baltica (Scandinavian Caledonides) faced Siberia during the Late Cambrian and Early Ordovician with oceanic separation between these landmasses in the order of 1200–1500 km. This may explain the local occurrences of Siberia–Laurentian type Bathyarid trilobite faunas in Central Norwegian Caledonian nappes, earlier interpreted as Laurentia–Baltica trilobite mixing. Subsequent counterclockwise rotation of Baltica transferred the Caledonian margin in the direction of Laurentia by Silurian times, when the two continents once again started to collide to form Euramerica. This rotation, along with the strongly asymmetric opening of the Iapetus at around 600 Ma, demonstrates a complexity in Precambrian–Palaeozoic plate tectonics, i.e. a collage of metastable plate boundaries which have perhaps too often been simplified to an orthogonal Wilson cycle tectonic scenario.

1. Introduction

Late Precambrian continental reconstruction's have recently received much attention following the postulate of a Neoproterozoic Supercontinent (Fig. 1), Rodinia (McMenamin and Schulte McMenamin, 1990), which was formed at around 1100 Ma (Moores, 1991; Dalziel, 1991, 1992; Hoffman, 1991).

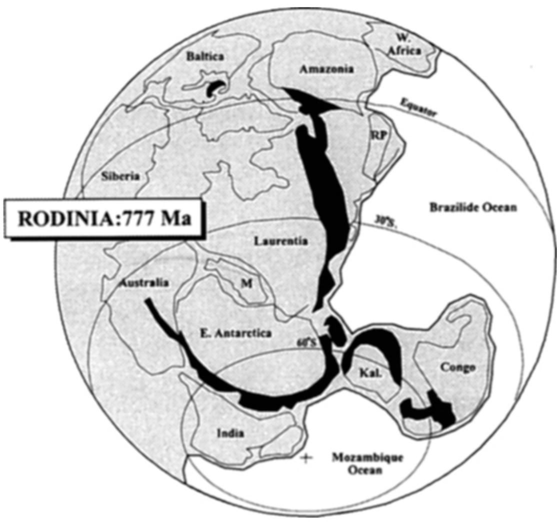

Fig. 1. The Rodinia supercontinental distribution at c. 777 Ma (simplified from Dalziel, 1991, 1992). *M* = Marie Byrd Land, *Kal.* = Kalahari craton, *RP* = Rio Plata craton (South America). Rotation of Laurentia relative to the globe is lat. = 4.5°N, long. = 41.4°W, angle = 92.4° (entry 62 in Table 2). Finite rotation poles for continental fits are listed in Dalziel (1992); see also Fig. 6. Grenvillian–Sveconorwegian–Kibaran crustal provinces are shown as black ornaments.

Attention has also focused upon the many postulates of Late Precambrian glaciations at low and even equatorial palaeo-latitudes (cf. Chumakov and Elston, 1989; Schmidt et al., 1991; Meert and Van der Voo, 1994; Schmidt and Williams, 1995; Torsvik et al., 1995a and references therein; Williams et al., 1995). Details in the Rodinia supercontinent fit and temporal aspects of its break-up are subjects of debate, but there is general agreement on the timing of initial break-up at 725–750 Ma, followed by final redistribution in Late Precambrian–Early Cambrian times (Powell et al., 1993; Storey, 1993; Dalziel et al., 1994; Soper, 1994a, b). Significant increases in the latitudinal velocities of Gondwana, Baltica and Laurentia during Vendian times are broadly coeval with the final redistribution of Rodinia (Meert et al., 1993; Gurnis and Torsvik, 1994).

An increasing number of reliable palaeomagnetic data has become available during the past few years. In this account we have compiled the most reliable palaeomagnetic data-sets from Laurentia (North America, Greenland and Scotland) and Baltica (Scandinavia, Spitsbergen, Russia and Ukraine). New apparent polar wander (APW) paths for these two palaeocontinents are constructed using spherical spline methods (Jupp and Kent, 1987). Secondly, we introduce a range of reconstruction's for various times in which we attempt to integrate palaeomagnetic, biological, lithological and structural data in order to test and possibly refine postulated Neoproterozoic and Palaeozoic tectonic scenarios. The resulting palaeogeographic snapshots indicate the palaeo-positions of Baltica and Laurentia from 750

Ma, shortly before the postulated break-up of Rodinia, to approximately 425 Ma when the two continents once again collided to form Euramerica. Finally, we calculate apparent crustal velocities and angular rotations for Baltica and Laurentia and examine how these relate to the evolving palaeogeography.

2. Palaeomagnetic data

All palaeomagnetic data were graded according to Rob Van der Voo's classification system (Van der Voo, 1988) which formed the basis of our selection of palaeomagnetic data for Baltica and Laurentia (Tables 1 and 2). Our tables of data follow and extend the earlier evaluations offered by Torsvik et al. (1992a), Van der Voo (1993), Meert et al. (1994) and Mac Niocaill and Smethurst (1994). Only poles with $Q \geq 3$ (Van der Voo, 1988) are included in our analysis and all paleopoles (Tables 1 and 2) are quoted as south-poles.

Our analysis of stratigraphic ages (Tables 1 and 2) for the Palaeozoic accords with the time-scale of Harland et al. (1990), but we have adjusted their Vendian–Cambrian boundary from 570 Ma to 545 Ma (Tucker and McKerrow, 1995). The revised time-scale of Tucker and McKerrow (1995) for Cambrian to Devonian times differs significantly (4–15 Ma) from that of Harland et al. (1990), but in this account we use the latter time-scale, except the Vendian–Cambrian boundary estimate, since it covers the entire Palaeozoic time-period that we attempt to analyse and the fact that most palaeomagnetic ages based on stratigraphic ages are derived from the time-scale of Harland et al. (1990). Following

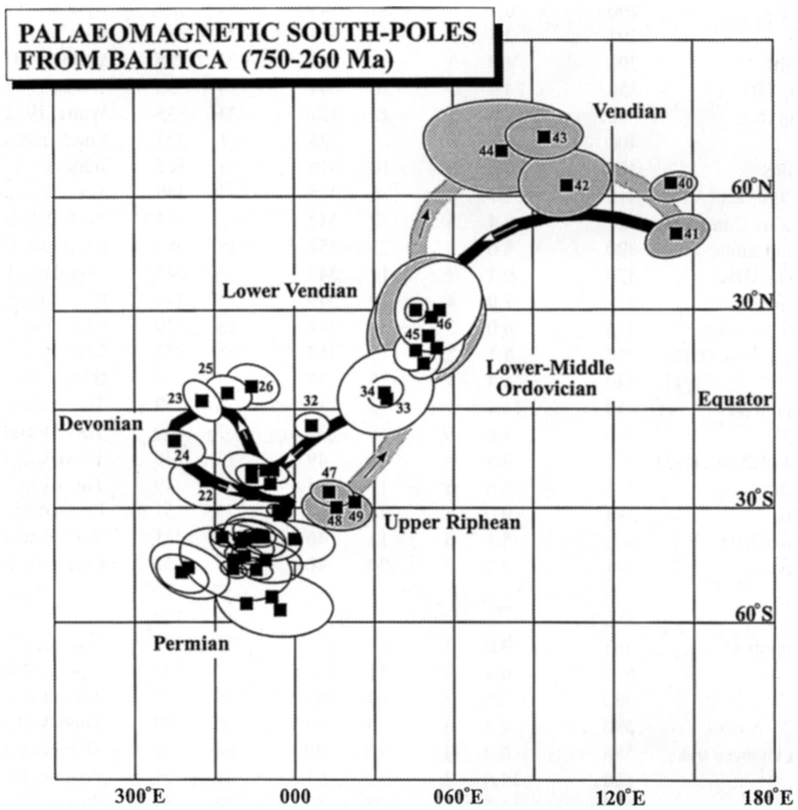

Fig. 2. Upper Riphean to Permian palaeomagnetic southpoles from Baltica (c. 750–260 Ma — Table 1) shown with ovals of 95% confidence (cf. Table 1 for pole codes). A smooth APW path has been fitted to the data (cf. text and Figs. 4A and 5). Upper Riphean and Vendian poles are shown with grey-shaded 95% confidence ovals whereas the Palaeozoic segment of the smoothed APW path is drawn as a solid black line (Galls projection)

Table 1
Selected Permian to Upper Riphean Palaeomagnetic data (south-poles) from Baltica (Scandinavia, Spitsbergen, Ukraine and Russia)

No.	Rock unit	Age (Ma)	α_{95}	Q	Original S-pole		APW path		Reference
					Lat.	Long.	Lat.	Long.	
1	Arendal Diabase A	260	5.2	4	−43	341	−48	337	Halvorsen, 1972
2	Arendal Diabase B	260	8.9	5	−47	320	−48	337	Halvorsen, 1972
3	Arendal Diabase C	260	3.7	5	−39	333	−48	337	Halvorsen, 1972
4	Arendal Diabase (D1 + D2)	260	5.7	5	−48	318	−48	337	Halvorsen, 1972
5	Bohuslen Dolerite (D)	260	29.1	5	−56	342	−48	337	Thorning and Abrahamsen, 1980
6	Bohuslen Dykes (RPM)	260	8.8	4	−45	349	−48	337	Thorning and Abrahamsen, 1980
7	Bohuslen Dykes (RPC)	260	3.6	5	−47	346	−48	337	Thorning and Abrahamsen, 1980
8	Bohuslen Porphyry Dykes (PD)	260	20.8	5	−57	355	−48	337	Thorning and Abrahamsen, 1980
9	Ny–Hellesund Dykes	265	2.9	5	−39	341	−46	339	Halvorsen, 1970
10	Oslo Graben Lavas (HB)	270	13.4	5	−45	337	−44	341	Douglass, 1988
11	Oslo Igneous Rocks (B)	270	8.8	5	−40	340	−44	341	Storetvedt et al., 1978
12	Oslo Igneous Rocks (I)	270	3.0	5	−47	337	−44	341	Van Everdingen, 1960
13	Scania Melaphyres	270	11.0	4	−54	352	−44	341	Bylund, 1974
14	Sarna Body	281	11.0	4	−38	348	−40	347	Bylund and Patchett, 1977
15	Sarna Body (2)	281	8.8	4	−39	345	−40	347	Smith and Piper, 1979
16	W-Vastergotland sill	284	6.3	5	−38	346	−38	349	Mulder, 1970
17	Scania Dolerites (A)	290	11.0	5	−39	360	−36	353	Mulder, 1970
18	Scania Dolerites (B)	290	6.5	5	−39	349	−36	353	Bylund, 1974
19	Stabben Sill (HB)	291	2.4	5	−32	354	−35	354	Sturt and Torsvik, 1987
20	E-Vastergotland Sill	293	4.0	5	−31	354	−34	355	Mulder, 1970
21	Billefjorden Group (R)	350	24.9	5	−26	344	−24	335	Watts, 1985
22	Billefjorden Group (N)	350	12.6	5	−22	327	−24	335	Watts, 1985
23	ORS W. Ukraine	400	7.1	6	3	325	−1	323	Smethurst and Khramov, 1992
24	Dicksonfjorden ORS	400	10.0	5	−10	315	−1	323	Jelenska and Lewandowski, 1986
25	Seiland Igneous Complex (A)	410	7.7	4	5	335	−1	336	Torsvik et al., 1990b
26	Honningsvåg Igneous Complex	411	8.4	5	7	344	−2	337	Torsvik et al., 1992b
27	Gotland Medby Limestone	420	8.0	3	−23	351	−15	345	Claesson, 1979
28	Ringerike Sandstone (HB)	420	9.1	7	−19	344	−15	345	Douglass, 1988
29	Gotland Dacker Limestone	425	2.0	4	−19	349	−18*	349*	Claesson, 1979
30	Gotland Follingbo Limestone	425	6.0	3	−21	344	−18	349	Claesson, 1979
31	Gotland Visby Limestone (HB)	428	5.1	5	−19	352	−18	352	Trench and Torsvik, 1991
32	Oslo Limestone	440	5.4	5	−5	7	−9*	7*	Bøhm, 1989
33	Swedish Limestone I(N)	459	13.4	5	3	35	3	32	Torsvik and Trench, 1991a
34	Vestergotland (N3)	465	4.8	6	5	34	7	39	Torsvik and Trench, 1991b
35	Vestergotland (N1–N2 and R13)	471	4.4	6	14	49	13	46	Torsvik and Trench, 1991b
36	Gullhøgen (R1 + R2)	476	6.8	6	19	54	19	49	Torsvik et al., 1995c
37	Swedish Limestones	481	9.0	5	30	55	25	51	Perroud et al., 1992
38	Swedish Limestones I(R)	481	5.1	6	18	46	25	51	Torsvik and Trench, 1991a
39	Swedish Limestones	481	2.2	5	30	46	25	51	Claesson, 1978
	Interpolated	490					32*	53*	
	Interpolated	550					49*	147*	
40	Fen Carbonate complex	565	3.0	3	63	142	57	141	Poorter, 1972
41	Fen Tinguates	565	6.4	4	51	144	57	141	Piper, 1988
42	Komagnes Dyke	580	4.5	3	63	103	68*	98*	Torsvik et al., 1995b
43	Sredny Dyke	580	2.3	3	73	95	68	98	Torsvik et al., 1995b
44	Sredny Peninsula Diabase dyke	580	5.0	3	70	79	68	98	Shipunov, 1988
45	Egersund Dykes	650	14.0	4	22	51	24	51	Poorter, 1972
46	Egersund Dykes	650	11.5	3	28	52	24	51	Storetvedt, 1966
47	Kildinskaya Formation	750	7.2	3	−26	13	−28	17	Torsvik et al., 1995b
48	Sredny–Kildin Red Beds	750	11.0	4	−30	16	−28	17	Shipunov and Chumakov, 1991
49	Vadsø Group (2–4 and 8)	750	31.4	3	−28	23	−28	17	Bylund, 1994

α_{95} = 95% confidence circle; Age = rock age; Lat./long. = pole latitude/longitude; * poles used for reconstructions.

Sokolov and Fedonkin (1984) we prefer to place the Vendian–Upper Riphean boundary at c. 650 Ma which witnesses the start of the Varanger epoch (see later).

Vendian to Permian palaeomagnetic data from Baltica were most recently summarised by Torsvik et al. (1992a). In the present analysis, however, we include palaeomagnetic data back to 750 Ma (Fig. 2, Table 1); these include Late Riphean (c. 750 Ma) palaeomagnetic results (Shipunov and Chumakov, 1991; Bylund, 1994; Torsvik et al., 1995b), all derived from formations south of the Trollfjord–Komagelva–Fault Zone (i.e. the assumed NW boundary of Baltica in Precambrian times). Vendian poles are represented by the Egersund dykes (SE Norway), now dated to c. 650 Ma (Rb/Sr and Sm/Nd; mean of four ages; Sundvoll, 1987; Sundvoll, in prep.) and ≈ 580 Ma dolerite dykes from northern Norway and northern Russia (Shipunov, 1988; Torsvik et al., 1995b).

The Palaeozoic section of the Baltic APW path is in essence that of Torsvik et al. (1992a) except inclusion of a new Early Ordovician (Late Arenig) pole from southern Sweden and a minor revision of the Swedish Ordovician pole ages (Torsvik et al., 1995c).

For Laurentia we have upgraded the Meert et al. (1994) data selection for Precambrian through Early Ordovician time (c. 500 Ma), exclusively from North America, and the selction of Mac Niocaill and Smethurst (1994) for the rest of the Palaeozoic, drawn from both North American and British (north of the Iapetus suture) sites (Fig. 3a and b). Dealing with palaeomagnetic data from both sides of the North Atlantic ocean, we chose to combine the two data sets by rotating the North American data into the European reference frame using the fit of Bullard et al. (1965) comprising a rotation pole at 87°N, 27°E and rotation angle of 38°. Poles with pre-580 Ma ages were rotated separately for a specific com-

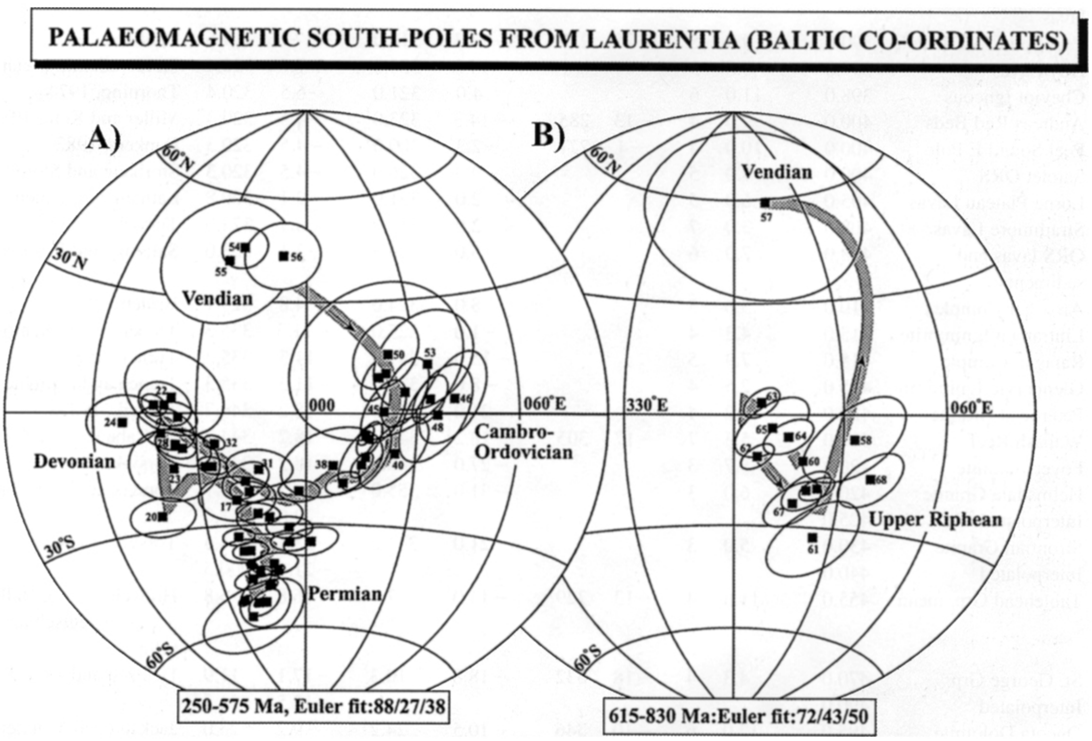

Fig. 3. Upper Riphean to Permian palaeomagnetic southpoles from Laurentia shown with ovals of 95% confidence (cf. Table 2 for pole codes). Equal area projections. (A) 250–575 Ma poles and a smooth APW path in Baltic co-ordinates (Bullard et al., 1965 fit; lat. = 88°N, long. = 27°E, angle = 38°). (B) 615–830 Ma poles, a smooth APW path, also in Baltic co-ordinates but with a different fit (lat. = 72°N, long. = 43°E, angle = 50°). Cf. text for details.

Table 2
Selected Permian to Upper Riphean Palaeomagnetic data (south-poles) from Laurentia (North America, Greenland and Scotland)

No.	Rock unit	Age (Ma)	α_{95}	Q	Laurentia ref.		Baltica ref.		APW path		Reference
					Lat.	Long.	Lat.	Long.	Lat	long	
1	Dewey Lake Fm.	250.0	5.9	6	−51	306	−52.2[1]	344.8[1]	−53.1	343.0	Molina-Garza et al., 1989
2	Ochoan Redbeds	250.0	15.0	4	−55	299	−56.2[1]	337.7[1]	−53.1	343.0	Peterson and Nairn, 1971
3	Guadalahara Redbeds	255.0	5.0	5	−50	311	−51.1[1]	349.9[1]	−50.4	342.4	Peterson and Nairn, 1971
4	Peterhead Dyke	260.0	1.3	4			−41.0	342.0	−48.4	341.7	Torsvik, 1985a
5	Casper Fm. I	275.0	1.5	5	−51	303	−52.2[1]	341.7[1]	−47.7	342.3	Diehl and Shive, 1981
6	Abo Fm. (unrotated)	275.0	2.1	5	−50	298	−51.2[1]	336.5[1]	−47.7	342.3	Steiner, 1988
7	Laborcita Fm.	280.0	2.0	5	−42	312	−43.1[1]	350.6[1]	−45.9	344.4	Steiner, 1988
8	Pictou Red Beds	280.0	3.0	7	−42	306	−43.2[1]	344.5[1]	−45.9	344.4	Symons, 1990
9	Dunkard Fm.	288.0	5.0	5	−44	303	−45.2[1]	341.5[1]	−44.2	345.9	Helsley, 1965
10	Casper Fm. II	290.0	1.8	4	−46	309	−47.1[1]	347.7[1]	−43.9	346.3	Diehl and Shive, 1981
11	Morien Group	297.0	6.0	6	−40	311	−41.1[1]	349.6[1]	−41.8	347.3	Scotese et al., 1984
12	Riversdale Grp.	310.0	6.0	5	−36	302	−37.2[1]	340.4[1]	−38.5	347.2	Roy, 1977
13	Barachois Group	320.0	7.0	6	−34	323	−34.9[1]	1.6[1]	−36.2	349.1	Murthy, 1985
14	Argyllshire Dykes	320.0	4.9	5			−35.0	355.0	−36.2	349.1	Esang and Piper, 1984
15	Shepody Fm.	320.0	4.6	7	−36	304	−37.2[1]	342.4[1]	−36.2	349.1	DiVenere and Updyke, 1990
16	Maringouin Fm.	329.0	4.0	7	−32	301	−33.2[1]	339.3[1]	−31.5	343.8	DiVenere and Updyke, 1990
17	Deer Lake Fm.	335.0	9.0	7	−22	302	−23.2[1]	340.2[1]	−26.9	342.4	Irving and Strong, 1984
18	Jeffreys Village Member	340.0	8.0	6	−27	311	−28.1[1]	349.4[1]	−23.6	341.8	Murthy, 1985
19	Burntisland–Kinghorn lavas	350.0	7.0	6			−14.0	332.0	−17.0	334.3	Torsvik et al., 1989
20	Peel Sound MDL Pole	390.0	9.0	5	−25	279	−26.3[1]	317.0[1]	−17.6	319.6	Dankers, 1982
21	Hoy Lavas	397.0	3.8	3			−14.0	334.0	−7.7	320.4	Storetvedt and Meland, 1985
22	Cheviot Igneous	398.0	11.0	6			4.0	321.0	−6.5	320.4	Thorning, 1974
23	Andreas Red Beds	400.0	9.0	4	−13	285	−14.3[1]	323.0[1]	−4.5	320.3	Miller and Kent, 1988
24	Peel Sound E Pole	400.0	10.0	4	−1	271	−2.3[1]	309.0[1]	−4.5	320.3	Dankers, 1982
25	Sarclet ORS	400.0	7.0	5			−9.0	326.0	−4.5	320.3	Storhaug and Storetvedt, 1985
26	Lorne Plateau Lavas	405.0	6.0	5			2.0	321.0	−2.1	320.8	Latham and Briden, 1975
27	Strathmore Lavas	408.0	3.0	7			2.0	318.0	−3.1	323.0	Torsvik, 1985b
28	ORS lavas and sediments	408.0	7.0	6			−5.0	320.0	−3.1	323.0	Sallomy and Piper, 1975
29	Arrochar Complex	410.0	5.0	5			−8.0	324.0	−4.8	325.7	Briden, 1970
30	Lintrathen Ignimbrite	415.0	4.3	4			−1.0	325.0	−11.3	335.3	Trench and Haughton, 1990
31	Ratagan Complex	415.0	7.9	5			−15.0	347.0	−11.3	335.3	Turnell, 1985
32	Glenbervie Ignimbrite	415.0	2.5	4			−8.0	335.0	−11.3	335.3	Trench and Haughton, 1990
33	Peterhead Granite	420.0	5.2	4			−21.0	358.0	−18.2	344.7	Torsvik, 1985a
34	Wabash Reef	420.0	5.3	7	−17	305	−18.2[1]	343.2[1]	−18.2	344.7	McCabe et al., 1985
35	Foyers Granite	420.0	5.7	3			−27.0	346.0	−18.2	344.7	Torsvik, 1984
36	Helmsdale Granite	420.0	6.0	3			−31.0	355.0	−18.2	344.7	Torsvik et al., 1993a
	Interpolated	425.0							−22.0*	351.0*	
37	Strontian Granite	430.0	5.0	3			−21.0	344.0	−23.4	354.5	Torsvik, 1984
	Interpolated	440.0							−21.6*	000.5*	
38	Tablehead Grp. mean	455.0	11.6	4	−13	329	−14.0[1]	7.4[1]	−16.8	6.8	Hodych (1989), Hall and Evans (1988), Deutsch and Prasad (1987)
39	St. George Grp.	470.0	4.3	4	−18	332	−18.8[1]	10.3[1]	−17.1	11.9	Deutsch and Prasad, 1987
	Interpolated	490.0							−12.5*	21.3*	
40	Oneota Dolomite	495.0	12.0	6	−10	346	−10.5[1]	24.2[1]	−9.2	23.0	Jackson and Van der Voo, 1985
41	Morgan Creek	505.0	10.0	5	−11	338	−11.6[1]	16.2[1]	−4.2	23.3	Loucks and Elmore, 1986
42	Florida Mountains	505.0	10.0	6	6	349	5.6[1]	26.9[1]	−4.2	23.3	Geissman et al., 1991
43	Royer Dolomite	510.0	4.0	6	−13	337	−13.7[1]	15.2[1]	−3.6	23.5	Nick and Elmore, 1990
44	Taum Sauk Limestone	510.0	7.0	5	4	356	3.7[1]	33.9[1]	−3.6	23.5	Dunn and Elmore, 1985

Table 2 (continued)

No.	Rock unit	Age (Ma)	α_{95}	Q	Laurentia ref.		Baltica ref.		APW path		Reference
					Lat.	Long.	Lat.	Long.	Lat	long	
45	Moores Hollow	515.0	9.0	5	1	343	0.4[1]	21.0[1]	−3.0	23.7	Farr and Gose, 1991
46	Catoctin B (recalculated)	515.0	13.0	4	4	3	3.9[1]	40.9[1]	−3.0	23.7	Meert et al., 1994
47	Point Peak, Wilberns	515.0	5.0	5	−6	339	−6.6[1]	17.1[1]	−3.0	23.7	Van der Voo et al., 1976
48	Unicoi Basalts	520.0	14.0	3	0	358	−0.2[1]	36.0[1]	−3.1	23.2	Brown and Van der Voo, 1982
49	Tapeats Sandstone	525.0	3.0	5	−5	338	−5.7[1]	16.1[1]	−3.3	22.1	Elston and Bressler, 1977
50	Buckingham Flows mean (tilt corr.)	550.0	8.0	5	16	345	15.5[1]	22.6[1]	12.7*	22.0*	Dankers and LaPointe, 1981
51	Long Range Dykes A	550.0	18.0	4	11	344	10.5[1]	21.8[1]	12.7	22.0	Murthy et al., 1992
52	Johnnie Rainstorm Fm. (unrotated)	550.0	7.0	4	10	342	9.4[1]	19.8[1]	12.7	22.0	Van Alstine and Gillett, 1979
53	Double Mer Fm.	550.0	12.0	3	13	356	12.7[1]	33.7[1]	12.7	22.0	Murthy et al., 1992
54	Callander Complex	575.0	3.0	6	46	301	44.8[1]	338.5[1]	43.2	342.4	Symons and Chiasson, 1991
55	Catoctin A (recalculated)	575.0	9.0	6	43	298	41.9[1]	345.4[1]	43.2	342.4	Meert et al., 1994
56	Sept Iles Intrusion B	575.0	5.0	6	44	315	43.0[1]	352.2[1]	43.2	342.4	Tanczyk et al., 1987
	Interpolated	580.0							48.3*	335.4*	
57	Long Range Dyke VGP	615.0	15.0	5	69	350	59.4[2]	15.2[2]	58.9	12.9	Murthy et al., 1992
58	Brock Inlier Sills	723.0	16.0	4	2	345	−6.1[2]	33.3[2]	−15.6	26.9	Park, 1981a
59	Franklin Dykes	723.0	5.0	6	−9	333	−19.2[2]	23.4[2]	−15.6	26.9	Christie and Fahrig, 1983
60	Thundercloud Fm.	755.0	22.0	4	−1	330	−11.9[2]	18.9[2]	−24.4	21.4	Park and Jefferson, 1991
61	Redstone River	755.0	11.0	5	−22	331	−32.4[2]	24.0[2]	−24.4	21.4	Park and Jefferson, 1991
62	Tsezotene Sills mean	777.0	5.0	5	2	318.0	−10.6[2]	6.4[2]	−11.2	7.0	Park et al., 1989
63	Little Dal Grp.	815.0	5.0	4	16	321	3.6[2]	7.6[2]	1.1	8.0	Park, 1981b
64	Reynolds Point Fm.	830.0	7.0	3	6	327	−5.4[2]	14.8[2]	−13.6	18.4	Palmer et al., 1983
65	Mudcracked Fm.	830.0	11.0	4	9	323	−3.0[2]	10.5[2]	−13.6	18.4	Park, 1984
66	Katherine Grp.	830.0	7.0	3	−9	330	−19.8[2]	20.3[2]	−13.6	18.4	Park and Aitken, 1986a
67	Tsezotene Fm.	830.0	8.0	4	−12	326	−23.4[2]	16.7[2]	−13.6	18.4	Park and Aitken, 1986b
68	Shaler Grp. P1 – P3	830.0	9.0	3	−9	348	−16.2[2]	38.7[2]	−13.6	18.4	Park, 1992

Legend as Table 1. Fits = [1] Bullard et al. (1965) (lat. = 88°N, long. = 27°E, angle = 38°), [2] This paper (lat. = 72°N, long. = 43°E, angle = 50°).

parison to be discussed below about a rotation pole at 72°N, 43°E through an angle of 50°. Table 2, therefore, consists of a list of data in their original reference frame and the same data rotated according to the aforementioned rotation poles.

3. APW paths

The spherical spline method of modelling apparent polar wander paths (Jupp and Kent, 1987) was first used by Torsvik et al. (1990a, 1992a) and has since been employed in a large number of published palaeomagnetic investigations. The computer implementation of the method by Torsvik and Smethurst called GMAP was used in most of them, including the present account. In summary, what is referred to as a ''spherical spline'' by Jupp and Kent (1987) — a spline constrained to lie on the surface of a sphere — is fitted to the palaeomagnetic poles, weighted according to the precision's of the input palaeopoles. The ages of poles are also taken into account, but uncertainties in ages are not.

The real uncertainty surrounding individual palaeopole positions is a combination of reported angular error, uncertainty in age, uncertainty surrounding the averaging of secular variation and so on. We therefore choose to weight data according to their performance in the Van der Voo (1988) reliability classification scheme so that the path is firmly anchored to the most reliable data and only loosely guided by the rest (Torsvik et al., 1992a). It follows that parts of the resulting spline/APW path will be better constrained by data than others and therefore more reliable than other segments. Although there is a method for estimating the precision of the path when angular errors are used for weighting (Silverman and Waters, 1984), our experience has shown us that the human eye often proves to be a satisfactory tool in the evaluation of the fit, especially when uncertainties are difficult to parameterise. For those who use GMAP and wish to reproduce our path, we used a smoothing parameter of 200 and weighted the data according to Van der Voo's *Q*-factor.

The fitted paths for Baltica and Laurentia (Figs. 2 and 3) are included in Tables 1 and 2, alongside the data from which they are derived. Each original data item has listed next to it the position in the fitted path corresponding to it in time.

The Late Riphean south APW path for Baltica (c. 750 Ma) starts in South Africa, it moves northeastward toward northeast Baltica (Urals) during Vendian times followed by a large self-closing clockwise loop through Asia during Cambrian times (Fig. 2). The APW path then tracks southwest during most of Ordovician and Silurian times followed by the characteristic Siluro-Devonian cusp (cf. discussion in Torsvik et al., 1992a) near Brazil. The Permian section of the APW path ends in the South Atlantic.

Our pre-580 Ma Laurentia–Baltica fit maintains a close link between Laurentia and Baltica (see below) during Upper Riphean and lower Vendian times (Fig. 4). The APW path for Laurentia (in European/Baltic co-rordinates) therefore also starts in South Africa but shows a large anticlockwise loop during Vendian times in marked contrast to the Baltic APW path (Figs. 3 and 5. The post-580 Ma section of the Laurentian APW path (Fig. 5) is shown in a Bullard et al. (1965) fit and there is a clear convergence between the two paths by Mid-Silurian (c. 425 Ma) times.

4. Palaeogeography

4.1. Rodinia

The Rodinia supercontinent postulate is to a large extent based on an attempt to link the Grenvillian–

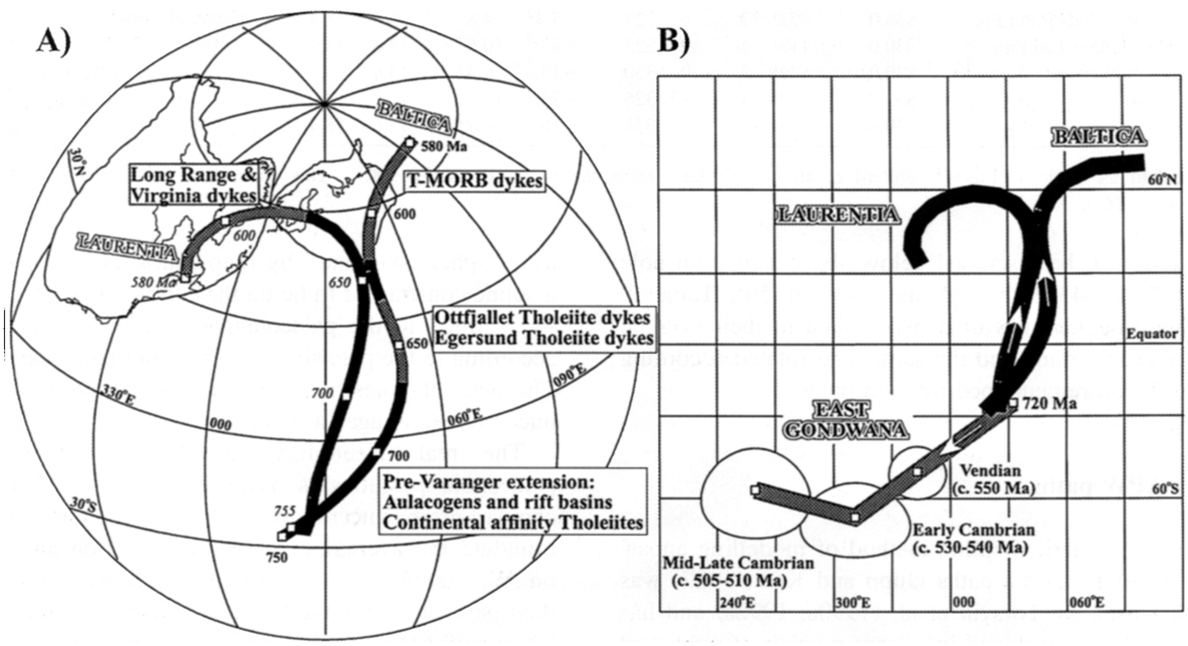

Fig. 4. (A) Comparison of the Baltic and Laurentian APW paths from 750–580 Ma. Laurentian APW path (Table 2) in Baltic coordinates using an euler-pole of lat. = 72°N, long. = 43°E, angle = 50°. The continental outlines of Laurentia and Baltica in this fit is also indicated in the diagram (Baltica fixed). Alongside the paths we have also indicated major periods of extension and dyke activity (cf. text). (B) Baltica and Laurentia APW paths as (A) but compared with palaeomagnetic mean poles from East Gondwana (data from Powell et al., 1993, originally reported in Indian co-ordinates, but now rotated into a Baltic framework; cf. text).

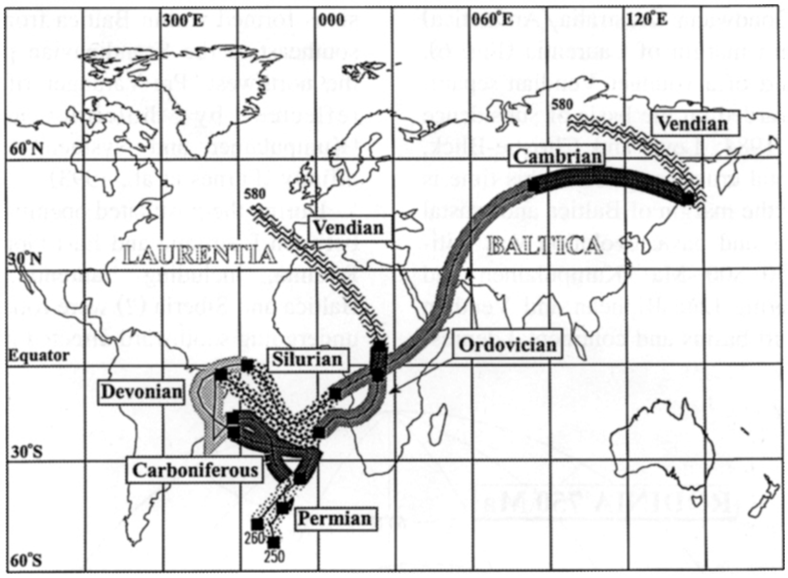

Fig. 5. Comparison of the Baltic and Laurentian APW path (Tables 1 and 2) from Latest Vendian (580 Ma) to Permian (250–260 Ma) times. Paths are show in Baltic co-ordinates using a Bullard et al., 1965 fit (lat. = 88°N, long. = 27°E, angle = 38°). In this fit we notice a clear convergence of the APW paths during the Silurian (Galls projection).

Sveconorwegian orogenic belts around the world (c. 1100–1300 Ma). Laurentia forms the core of this supercontinent (Fig. 1), the Scandinavian Caledonide margin of Baltica is constrained to face northeast Laurentia (Greenland) whilst the Tornquist margin is turned towards Amazonia (South America) of West Gondwana (Dalziel, 1992). East Gondwana (E. Antarctica and Australia) is facing the West Laurentia margin.

Palaeolongitudes cannot be calculated from palaeomagnetic data, hence cannot be used as direct evidence for the Rodinia postulate, but such data can disprove the postulate if there is a clear misfit in palaeolatitudes. A strongly rotated position of Baltica relative Laurentia in the Lower Palaeozoic shed doubts on conventional Baltica–Laurentia Wilson (1966) type rifting and convergence models during Late Precambrian and Palaeozoic times (Torsvik et al., 1991). Palaeolatitudinal estimates for Baltica and Laurentia in Late Riphean times can, however, be taken as *supporting* evidence for a link between the two continents. A close Grenvillian–Sveconorwegian fit and the APW paths for Laurentia and Baltica can be reconciled at 750 Ma with an approximate Euler pole of latitude = 72°N, longitude = 43°E and a rotation angle of 50° (assuming that our VGP polarity choices are valid). In this fit, Baltica is approximately 45° rotated with respect to the present-day orientation of Laurentia in such a way that southwest Norway (intersection of the Caledonian and Tornquist margins) is located next to Central Greenland. In accordance with Dalziel's (1992) fit, Siberia, which is geographically inverted, faces northern Baltica. The paleoposition of Siberia, however, is contentious. Our Rodinia configuration (Fig. 6) follows that of Dalziel (1992), except a different Baltica–Laurentia fit. Our overall palaeogeographic location of Rodinia at c. 750 Ma (Fig. 6), however, differs substancially from the c. 777 Ma Rodinia position of Dalziel (Fig. 1). The latter Rodinia configuration is based on paleomagnetic pole from Laurentia (Park et al., 1989; entry 62 in Table 2) whereas our 750 Ma configuration is based on an average of Laurentian and Baltic palaeomagnetic data.

4.2. *Initial break-up of Rodinia and Vendian glaciations*

The initial break-up of Rodinia is estimated to 750–725 Ma (Powell et al., 1993; Dalziel et al.,

1994) when East Gondwana (Australia/Antarctica) rifted off the western margin of Laurentia (Fig. 6). Arguments in support of a younger Vendian separation have been forwarded on the basis of subsidence data (Bond et al., 1984; Levy and Christie-Blick, 1991). Intercontinental crustal rupture at this time is also indicated along the margin of Baltica and crustal extensional tectonics and basin evolution was initiated at around 750–800 Ma (Kumpulainen and Nystuen, 1985). During Late Riphean and Vendian times, aulacogens, rift basins and continental depressions formed within Baltica from the Ukraine in the southeast to the Scandinavian part of the craton in the northwest. Pre-Varanger rifting (> 650 Ma) is reflected by tholeiitic magmatic activity (Kumpulainen and Nystuen, 1985) of continental affinity (Furnes et al., 1993).

During the postulated opening of the Proto-Pacific between Laurentia and East Gondwana, remnants of Rodinia, including Laurentia, West Gondwana, Baltica and Siberia (?) were rotating clockwise while undergoing southward directed movements. By Early

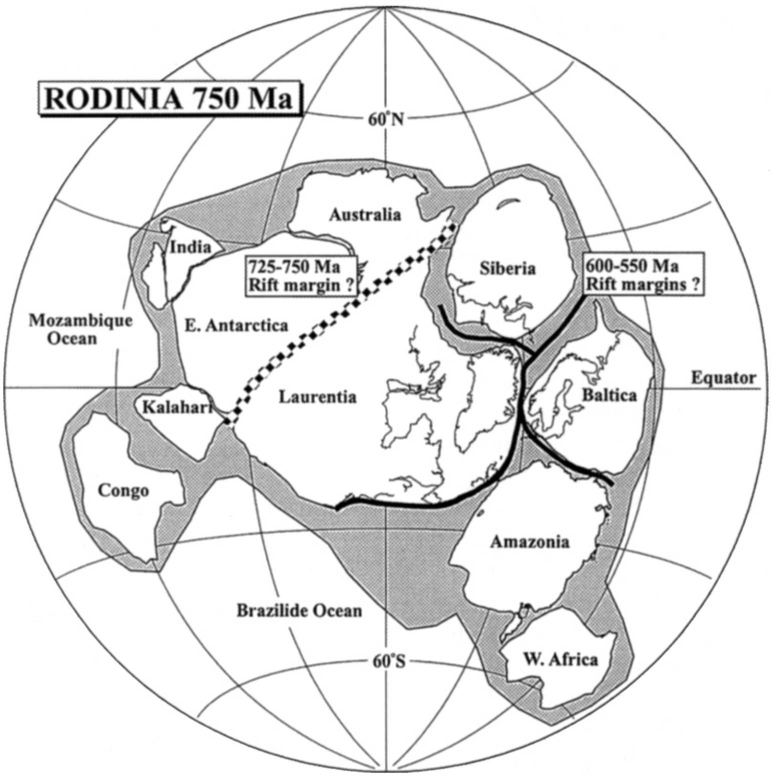

Fig. 6. The Rodinia supercontinent at 750 Ma based on the present analysis. Rodinia fit after Dalziel (1992) except the Baltica–Laurentia fit. Common reconstruction pole is 14.4°S, 327.6°E, $A95 = 8.3°$ {Laurentia co-ordinates: mean of entries 47–49 (Table 1) and 60–61 (Table 2)}. Finite rotation poles relative Laurentia are:

Baltica	72.0°N	043.0°E	−50.0°
Kalahari/Congo	2.8°N	318.7°E	−167.6°
Siberia	29.3°N	341.2°E,	19.6°
India	53.1°N	145.1°E	167.9°
West Africa	18.3°N	351.0°E	−138.6°
Amazonia	2.3°N	336.4°E	−99.3°
Madagaskar	28.6°E	123.8°E	170.2°
East Antarctica	12.8°N	119.9°E	134.8°
Australia	28.9°N	126.1°E	132.1°

Vendian times and during the Varangerian ice age (c. 650 Ma), Baltica and the northeastern margin of Laurentia (East Greenland and western Scotland) had drifted to southerly latitudes in excess of 30° whilst central parts of Laurentia were still within temperate latitudes (Fig. 7A). Continuing southward-directed movement eventually brought all of Laurentia into palaeolatitudes in excess of 30°S during the Ice Brook glaciations (c. 610–590 Ma). The temporal distribution of Vendian tillites appears to correlate with progressive polar directed movements of Baltica and Laurentia (see also Meert and Van der Voo, 1994 and Torsvik et al., 1995a) and they are typically located at palaeolatitudes in excess of 30 degrees. Parts of Baltica, including sites in Scandinavia, the Russian platform and the Urals (Fig. 8), were glaciated during Vendian times and the southpole with respect to Baltica was tracking through the eastern parts of Baltica (Urals) during Vendian times (Fig. 8). In Laurentia, Varanger aged glaciogenic deposits are found in northeastern Greenland, northern Scotland/Ireland and northwestern Laurentia (Ice Brook). In Siberia there is no known Late Precambrian glaciogenic deposits.

Young (1995) has advocated that the Vendian glaciogenic successions reflect the tectonic setting associated with the fragmentation of the Rodinia supercontinent and that glaciations were initiated by drawdown of CO_2 due to weathering of a tropical supercontinent or were confined to the uplifted flanks of rift basins. If rift-related, crustal extension and magmatism, however, should in general increase at-

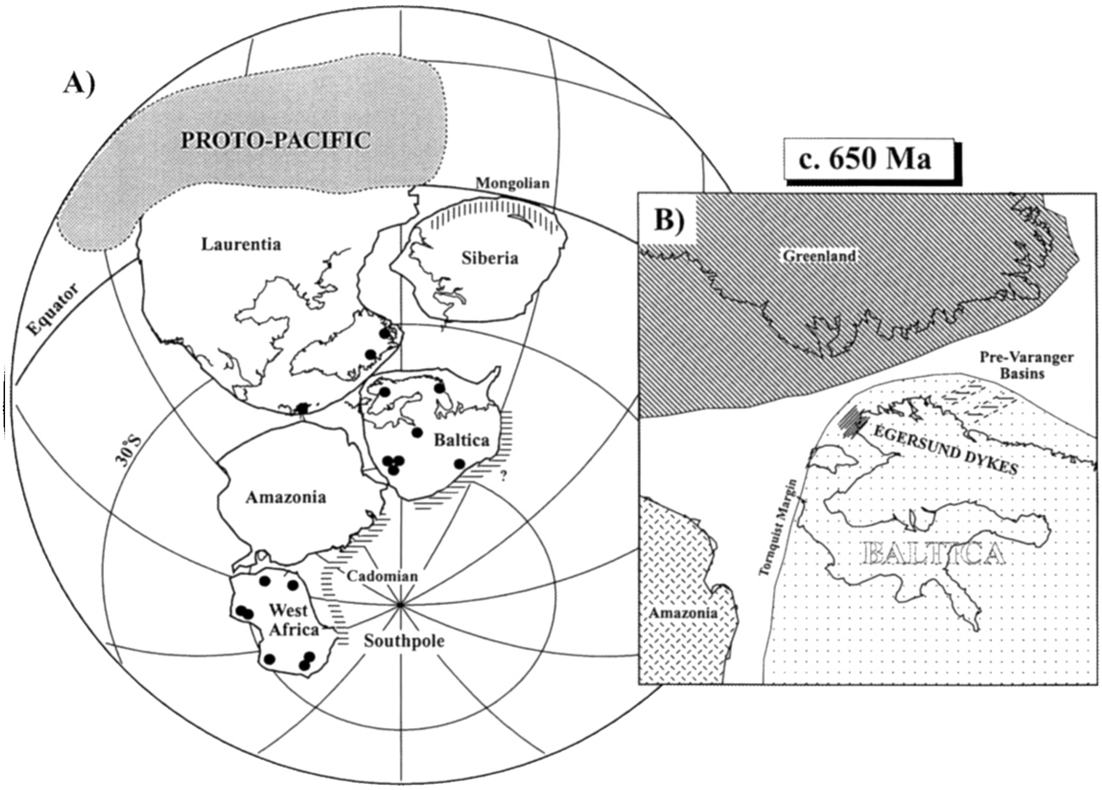

Fig. 7. (A) Palaeogeographic reconstruction at c. 650 Ma. Varangerian glaciogenic deposits are indicated as dots. Laurentia–Amazonia–West Africa–Baltica fit as 750 Ma (see Fig. 6); joint reconstruction pole is 24°N and 051°E (Baltic co-ordinates; Table 1). Siberia positioned using a pole of, 19.5°N and 357.5°E (Torsvik and Khramov, in progress). Approximate position of Cadomian, Mongolian (note that Siberia is geographically inverted) and possible Uralian arcs are indicated. (B) Details in the 650 Ma reconstruction showing the position and trend of the 650 Ma Egersund dykes and a likely palaeogeographic position of pre-Varanger Basins (cf. text). These basins were also intruded by Late Precambrian dykes and they are now preserved in Caledonian Nappes on the Baltic Shield (cf. text).

mospheric CO_2 levels rather than initiate drawdown of CO_2. Our analysis suggests that the Baltica and Laurentia glaciations are to a first approximation latitudinally, and hence climatically controlled.

Admittedly, some Vendian-aged glaciogenic deposits (e.g. the South Australian tillites; see Schmidt et al., 1991; Schmidt and Williams, 1995; Williams et al., 1995) are found at lower palaeolatitudes than their Phanerozoic counterparts (usually at $> 45°$) and are, to a large extent, preserved along former Rodinia rift-margins perhaps in the uplifted regions. There is also a debate concerning the exact age of the Varangerian tillites in Norway and on a global scale a clear distinction between Varangerian (c. 650–600 Ma), Late Sinian (c. 580–540 Ma) and even the older Sturtian (c. 700–800 Ma) glaciations is not straightforward due to the lack of reliable radiometric evidence. In northern Norway, stratigraphic correlation and isotopic age data from interglacial (653 ± 7 Ma) and postglacial (612 ± 18 Ma) units suggest an early Vendian age of approximately 650 Ma (Pringle, 1973; Føyn, 1985; Kumpulainen and Nystuen, 1985; Torsvik et al., 1995a) but others quote an age at around 580–600 Ma (Harland et al., 1990; Young, 1995). Recent palaeomagnetic data from the interglacial (653 ± 7 Ma) Nyborg Formation, northern Norway, are broadly similar to palaeomagnetic data from the c. 650 Ma Egersund dykes (see below) which supports an early Vendian age for the glacial deposits in Norway (Torsvik et al., 1995a). Irrespective of age assignment, however, the palaeomagnetically derived latitude from the interglacial unit in northern Norway show palaeolatitudes in excess of 30°S.

4.3. Late break-up of Rodinia and the opening of the Iapetus Ocean

The voluminous Egersund dyke swarm in southwestern Norway (Fig. 7B) is dated to 650 Ma (mean of 4 Sm–Nd and Rb–Sr ages, Sundvoll, 1987, and in prep.). Individual dykes, 3–30 m in width, can be traced for up to 60 km and are broadly coeval with the Varangerian tillites in northern Norway. These NW–SE trending dykes probably reflect initiation of rifting prior to the opening of the Iapetus Ocean (Sundvoll, 1987; Miller and Barton, 1992; Torsvik et al., 1995a). Chemically, these dykes, which contain abundant lower-crust xenoliths are Ol-tholeiites, tholeiites and trachybasalts and major and trace element abundance's and ratios for primitive Ol-tholeiites (OIM and E-MORB) suggest derivation from a plume (Miller and Barton, 1992).

The c. 100 km-long Ottfjället diabase dyke swarm of the Caledonian Särv Nappe of southcentral Sweden, has widely been regarded as indicating the initiation of rifting (Kumpulainen and Nystuen, 1985) and the age of these tholeiitic dykes is generally placed at 665 ± 10 Ma ($^{40}Ar-^{39}Ar$, Claesson and Roddick, 1983). The geochronology, however, is poorly constrained, the dykes cut Varangerian tillites and they probably date from Early Vendian times (650–640 Ma). We suggest that they may represent in-thrust age equivalents of the Egersund dykes and that they intruded Neoproterozoic and early Vendian Basins once fringing the western Baltic margin (Fig. 7B). In Troms, northern Norway, dolerite dykes in the Corrovarre Nappe have been Sm/Nd-dated to 582 ± 30 Ma (Zwaan and van Roermund, 1990). These particular dykes are of T-MORB character and are considered to have been intruded immediately prior to the inception of Iapetus sea-floor spreading (Roberts, 1990) in this part of the Iapetus system. Dyke swarms of comparable geochemistry (T-MORB and N-MORB) and age (c. 600 Ma, Stølen, 1994a, b) are found in other nappe units in broadly the same region. Vendian dykes, but commonly with ambiguous geochronology, are also widespread in the northernmost parts of Norway, northeast Russia and southeastern Norway (Dahlgren, 1994; Andersen and Sundvoll, 1995; Roberts and Onstott, 1995; Torsvik et al., 1995b).

Initiation of Iapetus opening (the rift–drift transition) may therefore have occurred at around 600–580 Ma. A Vendian rift event ($>$ 580–600 Ma) is coeval with Vendian syn-rift sequences found in Greenland (Soper, 1994a). These particular sequences are succeeded by Early Palaeozoic carbonate-dominated shelf sedimentation, interpreted as a thermally controlled passive margin sequence following the opening of Iapetus (Bond et al., 1984; Soper, 1994a).

Rift-related mafic dykes are also present on Laurentia although they generally have a slightly younger age. The Long Range dykes of southeastern Labrador are precisely dated to 615 ± 2 Ma (Kamo et al., 1989). The Catoctin basalt's (Virginia) and related mafic dykes are dated to 600–580 Ma (Badger and Sinha, 1988; Aleinikoff et al., 1995), suggesting that rifting along the eastern margin of Laurentia proceeded from present north to south. Earlier evidence for rifting along the eastern margin of Laurentia is documented at around 700–750 Ma although it appears that this rifting never proceeded to the oceanic stage (Kamo et al., 1989; Su et al., 1994).

Vendian rifting accords with palaeomagnetic data from Baltica and Laurentia which indicate that these two palaeocontinents were in contact until at least 620–630 Ma. In our Laurentia–Baltica fit, the shapes of the two APW paths show gross similarities during Late Riphean and Vendian times although the time-calibration differs (Fig. 4A) and makes it difficult to conclude when they finally diverge. The time-calibration is especially poor for Baltica since actual data exist only for c. 750 (mean age), 650 and 580 Ma. Likewise, the Laurentian data have a large time-gap between 723 and 615 Ma. The two paths, however, clearly separate before 580 Ma (Fig. 4A); hence, the rift-to-drift transition probably occurred during Vendian times.

We have also included palaeomagnetic mean-poles for East Gondwana. Originally listed by Powell et al. (1993) in Indian co-ordinates, we have rotated them into the Baltic reference (Fig. 4B). The collective data demonstrate, if the continental fits are applica-

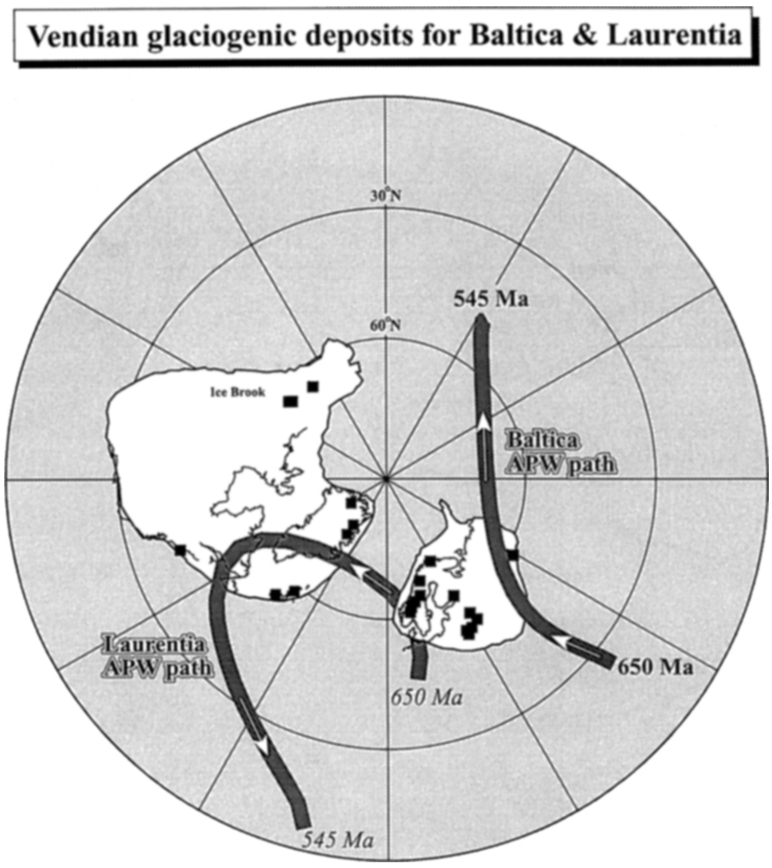

Fig. 8. Distribution of Varanger glaciogenic deposits (solid squares) for Baltica and Laurentia along with the Vendian segment of the APW paths for Baltica and Laurentia, the latter now in North-American coordinates. The continental outlines and glaciogenic deposits from Greenland and North Scotland/Ireland are shown in a pre-drift North Atlantic configuration (North America fixed). We notice that the southpole (APW path) with respect to both Baltica and Laurentia tracks across both palaeocontinents during Vendian times and hence indicate intemediate to high polar latitudes for the glaciogenic deposits. Glaciogenic sites compiled from Hambrey and Harland (1981, 1985) and Aitken (1991).

ble, that East Gondwana, Laurentia and Baltica formed a coherent unit (Rodinia) to at least 725 Ma. Whilst the APW trend for Baltica and Laurentia are broadly similar during Upper Riphean and most of the Vendian, the East Gondwana paths tracks in the opposite direction (Fig. 4B) which suggests that East Gondwana rifted off Rodinia (after 725 Ma) prior to rifting between Baltica and Laurentia. However, it should be borne in mind that the APW paths for Laurentia and East Gondwana are interpolated between 720 and 600 Ma, and therefore our interpretation remains uncertain.

The opening of the Iapetus Ocean involved large relative rotations (asymmetric rifting) between Laurentia (anticlockwise) and Baltica (clockwise) though both continents remained in high southerly latitudes (Fig. 9A). However, this interpretation, as pointed out by Torsvik et al. (1995a), may cause a continental space problem if the proposed Laurentia–Amazonia fit at 750 Ma is valid until latest Vendian–Early Cambrian time (Dalziel et al., 1994; Fig. 9B); we notice that there is no room to place Baltica near the south pole at 580 Ma. This, however, could relate to inaccuracy in the existing palaeomagnetic data, an incorrect fit between Laurentia–Amazonia or, that Amazonia (West Gondwana) had rifted off East Laurentia prior to 580 Ma. Rift-related magmatism along the Appalachian margin of Laurentia is estimated to 550–615 Ma (see review in Soper, 1994a), thermal subsidence curves may indicate con-

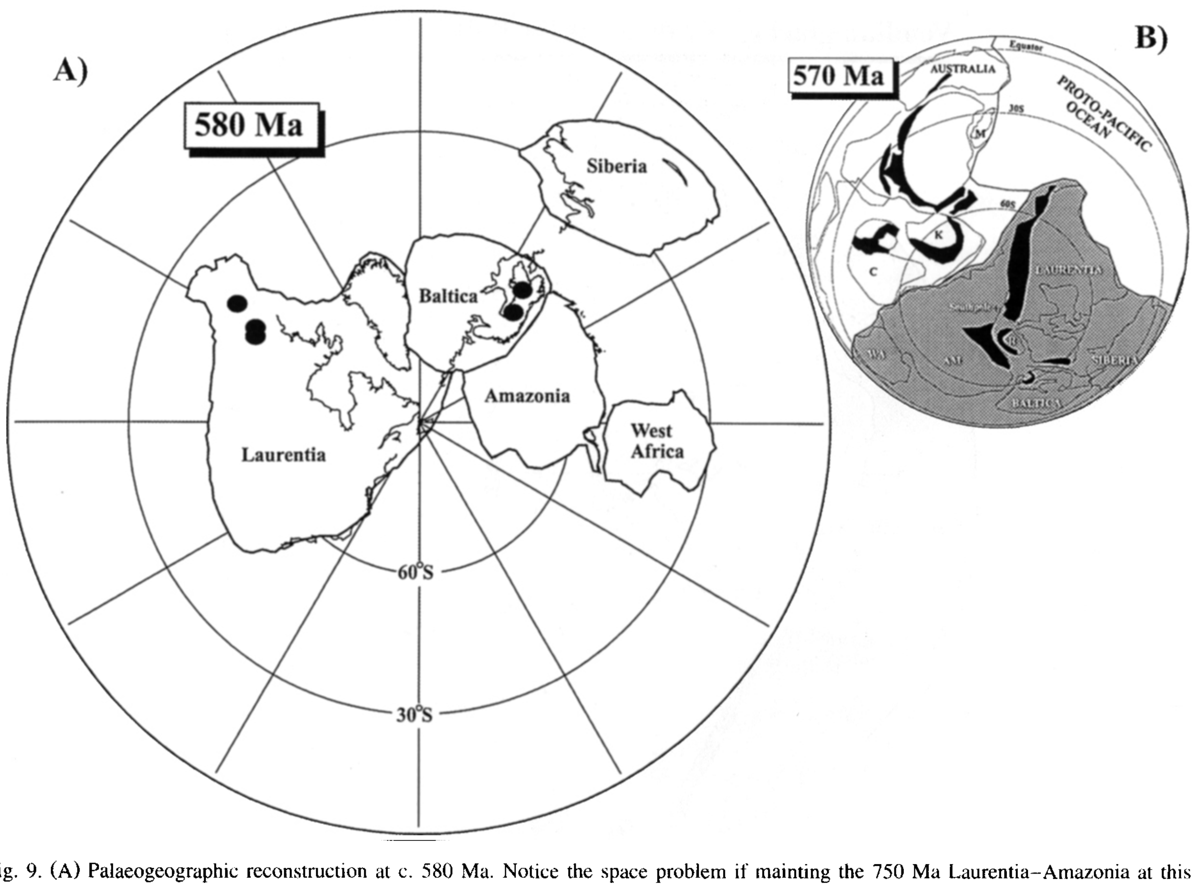

Fig. 9. (A) Palaeogeographic reconstruction at c. 580 Ma. Notice the space problem if mainting the 750 Ma Laurentia–Amazonia at this time. c. 580–610 Ma glaciogenic deposits located to Laurentia (Ice Brook) and Baltica are indicated as dots. Laurentia–Amazonia–West Africa fit as 750 and 650 Ma. Reconstruction pole is 48.3°N and 335.4°E (Table 2; Baltic co-ordinates). Baltica positioned with 68°N and 098°E (Table 1). Siberia shown according to a pole of 32.9°N and 353.3°E (Torsvik and Khramov, in progess). (B) 570 Ma reconstruction after Dalziel et al. (1994). In this reconstruction, the 750 Ma fit in figure 1 is maintained for Laurentia–Amazonia (AM)–West Africa (WA)–Baltica–Siberia throughout Vendian times (shaded area). M = Marie Byrd Land, K = Kalahari craton, C = Congo craton. Grenvillian–Sveconorwegian–Kibaran crustal provinces are shown as black ornaments.

tinental break-up at 600 ± 25 Ma (Bond et al., 1984), whilst MORB-type volcanite in northeastern Laurentia (Scotland) are dated to 595 ± 5 Ma (Halliday et al., 1989). The collective data may therefore indicate broadly coeval rift to drift development between Laurentia, Amazonia, Baltica and probably Siberia during Vendian times, hence eliminating the space problem (Fig. 9). In this tectonic scenario, Scotland and southeast Norway would have formed a triple-junction during the opening of Iapetus (Laurentia–Baltica–Amazonia) and the Palaeo-Tornquist Sea (Baltica–Amazonia). Admittedly, though, the space problem (Fig. 9A) might be accounted for within the uncertainties in both the paleomagnetic and isotopic age data.

Although there is ample evidence for Vendian rifting along the margins of Laurentia and Baltica there are clearly problems in identifying conjugate margins. There are, for example, few compelling similarities in the Neoproterozoic geology of the Baltoscandian and the East Greenland marginal basins (Soper, 1994a); nor are there too many similarities in magmatic products. Kumpulainen and Nystuen (1985), in an attempt to resolve lithological differences, suggest that the Baltoscandian and East Greenland Basins were located on either side of an intervening, sediment-starved, deep-water seaway within a broad segment of a strongly stretched continental crust, or alternatively that the basins formed elongate and parallel intra-cratonic structural depressions separated by a continental ridge. Soper (1994a) sees the Tornquist margin as a conjugate margin to

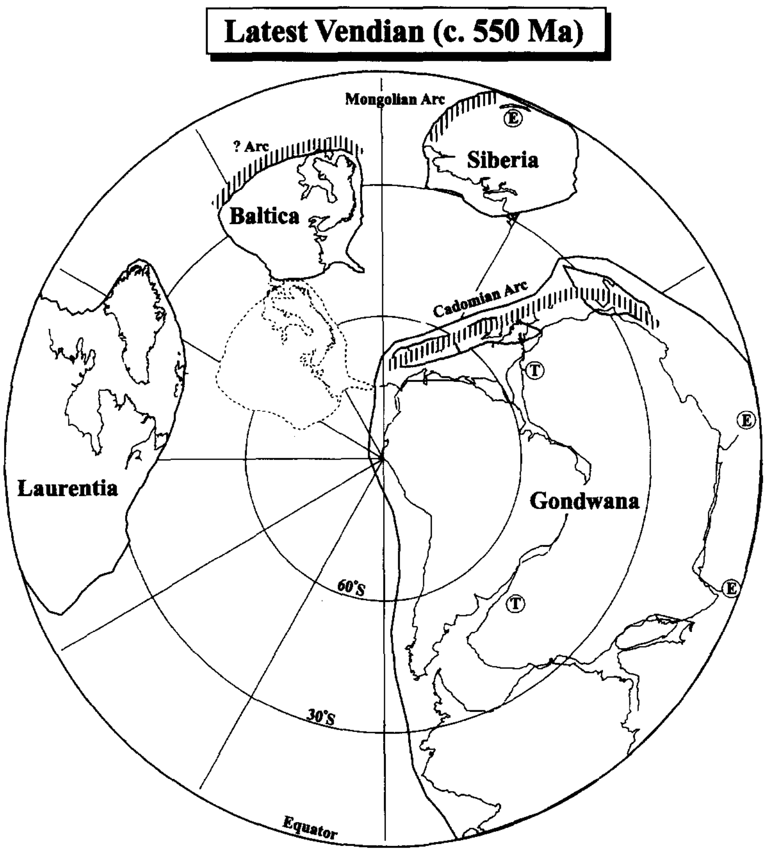

Fig. 10. Latest Vendian (c. 550 Ma) palaeogeographic reconstruction. Reconstruction poles; Laurentia: 12.7°N and 022.0°E (Baltic coordinates; Table 2), Baltica: 49°N and 147°E (Table 1). Siberia: 36°N and 317°E (Torsvik and Khramov, in progress). Gondwana: 22°S and 332°E (Meert et al., 1995). Avalonia and Armorica shown in a likely position. Occurences of Late Sinian tilloids (Algeria and Namibia, *T*) and evaporites, *E*, are indicated. Evaporite data from McKerrow et al. (1992); these authors favour a more southerly position of Baltica (stippled in diagram) and minor adjustments of Siberia and Gondwana in order to bring the occurences of evaporites into the tropical belt.

Baltica (negative evidence) prior to rifting whilst our Iapetus pre-rift fit locates the intersection of the Baltoscandian–Tornquist margin next to Greenland.

4.4. Gondwana and the dawn of the Phanerozoic

The assembly of Gondwana is intimately linked with the break-up of Rodinia and is conventionally perceived as a large-scale collision between East (India, Antarctica and Australia) and West (Africa and South America) Gondwana along the Mozambique orogenic belt. More recent Proterozoic plate models, however, treat West Gondwana as a series of distinct cratonic blocks assembled during a sequence of orogenic events spanning 200 Ma (680–480 Ma). East Gondwana is traditionally treated as a coherent unit from at least 1300 Ma until its break-up in the Mesozoic. This however, has recently been questioned by Meert and Van der Voo (1994) and Wilson et al. (1995) who propose that East Gondwana was assembled through polyphase accretion of cratonic blocks between 770 and 550 Ma.

By the end of the Precambrian (c. 550 Ma), some 50 Ma after the opening of the Iapetus, Laurentia had drifted rapidly into lower latitudes (Fig. 10) where it essentially stayed during Cambrian and Ordovician

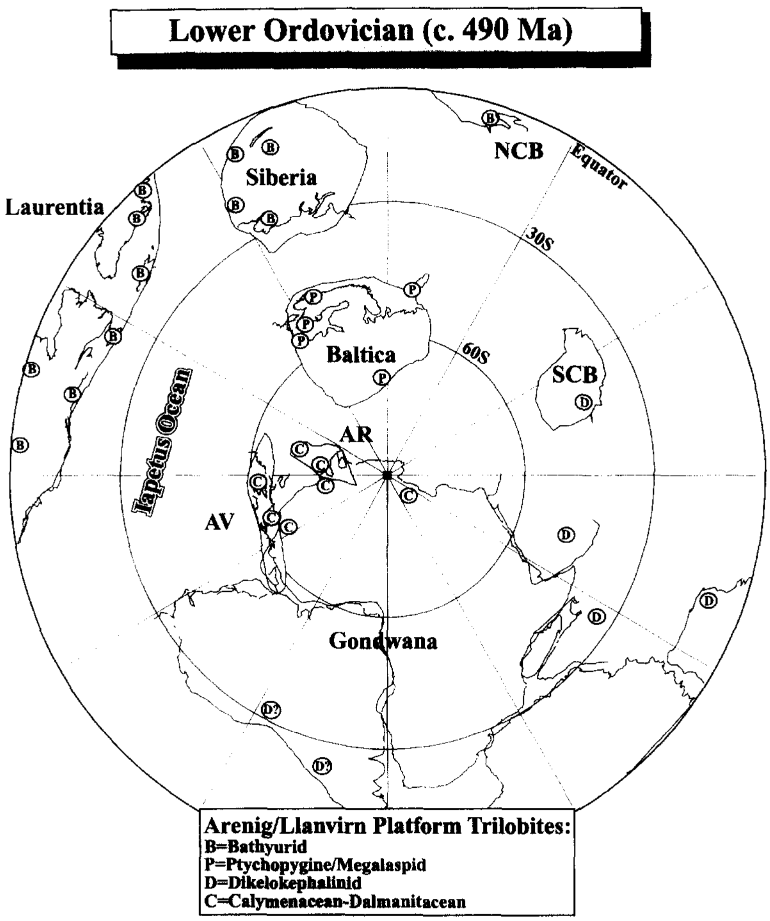

Fig. 11. Lower Ordovician reconstruction and the distribution of Arenig–Llanvirn platform trilobites. Reconstruction poles; Laurentia: 12.6°S and 021.3°E (Baltic coordinates; Table 2), Baltica: 32°N and 053°E (Table 1). Siberia: 42°N and 310°E (Torsvik et al., 1995d). Avalonia: 56°N and 306°E (Torsvik and Trench, 1991c; notice that Avalonia is positioned correctly in latitude but has been given a preferred orientation to maintain the facing of the apparent Iapetus margin in Southern Britain), Armorica: 39°N and 344°E (Torsvik et al., 1990a), Gondwana: 34°N and 007°E (Van der Voo, 1988), North China Block: 43°S and 153°E (Van der Voo, 1993), South China Block: 39°N and 056°E (Van der Voo, 1993).

times. West Gondwana (Amazonia) had rifted from Laurentia and Gondwana assembly was nearly complete. Gondwana stretched from high southerly polar latitudes (West Gondwana) to intermediate northerly latitudes (East Gondwana). Palaeomagnetically derived latitudes for Baltica are uncertain for the latest Precambrian (few data) and Cambrian (no data), but a strongly rotated (inverted) Baltica at intermediate southerly latitudes is indicated at around 550 Ma. Our palaeomagnetically controlled reconstruction at 550 Ma is broadly similar to that of McKerrow et al. (1992) for the 550–530 Ma interval, when fossil remains first became abundant, except for a generally more northerly position of Baltica and a slightly more southerly position of Gondwana at 550 Ma. This places occurrences of Late Precambrian evaporates in East Gondwana within the tropical rain belt (< 10°) rather than in the temperate belt (10–35°) according to McKerrow et al. (1992). The location of Early Cambrian tillites (520–560 Ma, Bertrand-Sarfati et al., 1995) in North Africa (Algeria) would be placed in excess of 50°S in our reconstruction (Fig. 10).

Recent postulates (Dalziel et al., 1994) maintain the Amazonia–Laurentia connection until 550 Ma. Our reconstruction at 550 Ma shows that, despite uncertainties in paleo-longitude, a 550 Ma connection between Laurentia and Amazonia is not tenable (if Gondwana was fully formed) since there is clear latitudinal separation of the Andean margin of South America and the eastern margin of Laurentia.

Avalonia and much of southern Europe formed widely separated parts of Gondwana before the Ordovician (Fig. 10). At around 600 Ma both regions were on active Cadomian margins of Gondwana, but the sedimentary environments were different. The clearest distinction between the Cambrian (c. 530–520 Ma) of Avalonia and contemporaneous beds in European Gondwana is the presence of warm water carbonates with archaeocyathans in Morocco, Spain, Sardinia, southern France, Normandy and Germany: such facies are absent in Avalonia, Mauritania, Senegal, Florida and Venezuela (McKerrow et al., 1992). Cambrian (palaeomagnetic) latitude estimates for western Avalonia vary between 40 and 50°S (Liss et al., 1993).

Palaeogeographic reconstruction's for the early Ordovician are well constrained due to the abundance of reliable palaeomagnetic data and fossil remains (Fig. 11). Laurentia was still positioned in equatorial latitudes at the beginning of the Ordovician whereas Baltica was located to intermediate to high southerly latitudes. The active Caledonian margin of Baltica was facing northern Siberia whilst a passive or transform Tornquist margin faced Avalonia/Armorica/northwestern Gondwana at high southerly latitudes. Early Ordovician (Arenig–Llanvirn) platform trilobites (Fig. 11) show a general distinction between the low-latitude continents of Laurentia, Siberia and the North China Block [Bathyurid]; the mid-latitude Baltica [Ptychopygine/ Megalaspid] and the high-latitude areas of NW Gondwana/Avalonia/Armorica [Calymenacean–Dalmanitacean] (Cocks and Fortey, 1990). It should be emphasized, however, that the platform fauna difference indicates continental seperation beyond spat travel distance (> 1000 km) rather than temperature (/latitude).

In our early Ordovician palaeomagnetically controlled reconstruction (palaeolongitude unknown), the width of the Iapetus Ocean varies between c. 5000 km (Laurentia–Avalonia) and c. 3000 km (Laurentia–Baltica). Reservations regarding a wide Iapetus Ocean due to some mixing of Baltic and Laurentian trilobite fauna (cf. discussion in Sturt and Roberts, 1991) is eliminated in our 490 Ma reconstruction since we place Baltica as a conjugate margin to Siberia which has a virtually identical trilobite fauna to that of Laurentia. Oceanic separation between Baltica and Siberia was probably at around 1200–1500 km.

4.5. Closure of the Tornquist Sea

Early–Mid Ordovician break-up of Gondwana included the rifting of Avalonia away from its northwest margin (Llanvirn), by which time the Iapetus Ocean across the British Isles was reduced from 5000 (Late Tremadoc–Early Arenig) to 3000 km (Torsvik and Trench, 1991c). Coeval closure of the Tornquist Sea between Baltica and Avalonia, occurred, as indicated by the convergence in their palaeomagnetically derived latitudes, evidence for subduction of oceanic crust beneath eastern Avalonia (Noble et al., 1993), and by the onset of faunal mixing between Avalonia and Baltica. Faunal bonds between Avalonia and Gondwana declined (McKerrow et al., 1991), and certainly by the Middle Ordovician the faunas of Avalonia were looking more like those of Baltica than Gondwana (Cocks and Fortey, 1982, 1990), and less like those of Bohemia, Armorica and Morocco (Havli'c'ek, 1989). By the end of the Ordovician or the earliest Silurian (Fig. 12) the Tornquist Sea between Avalonia and Baltica had closed sufficiently to form Balonia (Torsvik et al., 1993b); benthic ostracods, which have no pelagic spat, crossed the Tornquist suture in the Early Silurian (Berdan, 1990).

From Mid–Late Ordovician times, Caradoc, palaeolatitudes for Avalonia and Baltica are broadly similar (Torsvik et al., 1993b; Fig. 12). The convergence history and cessation of tectonic activity is not readily determined from palaeomagnetic data since the Tornquist Sea closure probably involved a principal component of palaeo-East–West closure. The timing may be equated with the early Ashgill Shelvian Orogeny in Britain (Toghill, 1992). The closure of the Tornquist Sea did not involve a full-scale crustal continent–continent collision, but was probably dominated by dextral amalgamation of the two continents (Torsvik and Trench, 1991c).

By the Late Ordovician, Baltica and eastern Avalonia (Balonia) had moved to low latitudes, so that, unlike parts of Gondwana (Fig. 12), there is no evidence for glacial environments in the Late Ordovician of Avalonia and Baltica. The lower latitudes for Baltica and Avalonia are also marked by

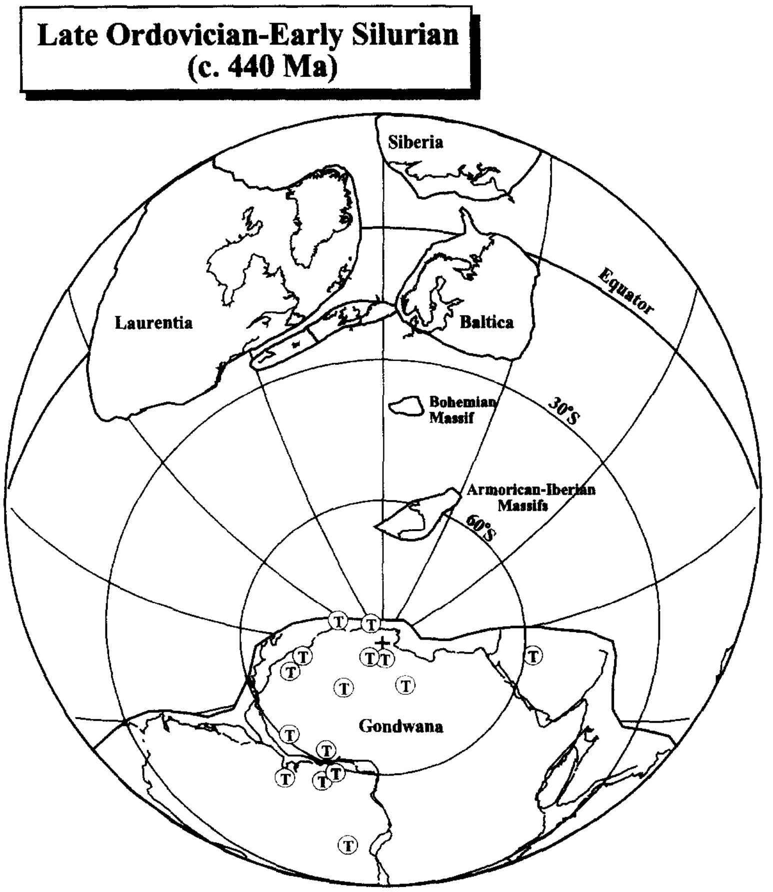

Fig. 12. Late Ordovician–Early Silurian reconstruction. Known localities of Late Ordovician glaciogenic deposits are indicated (*T*, after Scotese and Barrett, 1990. Reconstruction poles: Laurentia: 21.6°S and 000.5°E (Baltic co-ordinates, Table 2), Baltica: 9°S and 007°E (Table 1), Avalonia: 18°S and 359°E (Torsvik et al., 1993b), Siberia: 000° and 290°E (Torsvik et al., 1995d), Gondwana: 34°N and 007°E (Van der Voo, 1988), Bohemia: 79.5°N and 181.2°E (Tait et al., 1995), Armorica (Armorican–Iberian Massif): 20°N and 346°E (Torsvik et al., 1990a).

the first appearance of warm-water carbonates (Bahamian type reefs) in Late Ordovician and Mid-Silurian times, respectively.

The length of the Tornquist margin is currently marked by the complex amalgamation of eastern Avalonia and several other terranes or massifs which now constitute Variscan Europe. During the Early Palaeozoic they were all fringing the northern areas of Gondwana (Figs. 10 and 11). Avalonia separated first from Gondwana, and were eventually welded along the Baltic and Laurentia margins (New England and Newfoundland), effectively destroying the

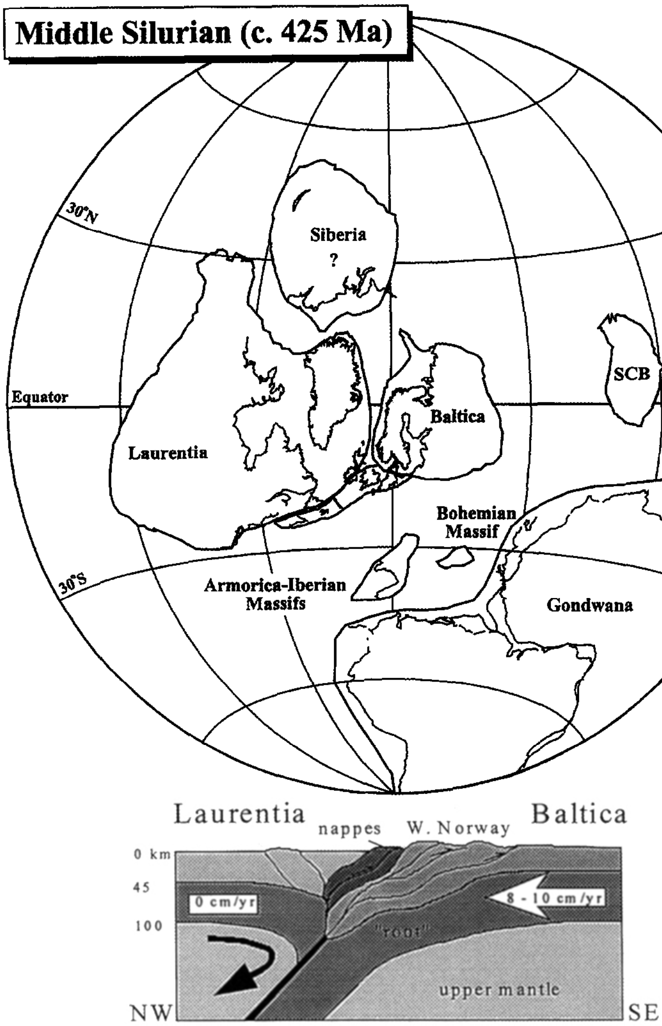

Fig. 13. Mid-Silurian reconstruction. Position for Baltica and Laurentia is well-constrained — Also palaeolatitudes for Avalonia is known but Silurian rocks in South England have suffered post-Silurian (Acadian and Hercynian) rotations, hence palaeo-orientation is not known in detail (cf. Torsvik et al., 1993b). Reconstruction poles: Laurentia: 22°S and 351°E (Baltic co-ordinates; Table 2), Baltica: 18°S and 349°E (Table 1); South China Block: 5°S and 015°E (Van der Voo, 1993), Gondwana: 43°S and 009°E (Hargraves et al., 1987 — Gondwana is tentatively positioned 10° further to the south in our diagram since new isotopic age data from the Air pole suggest that the age should be adjusted to 408 Ma; cf. Van der Voo, 1994), Bohemia: 68°N and 154°E [average of an Upper Ordovician (Tait et al., 1995) and an Upper Silurian (Tait et al., 1994b) pole from Bohemia]. No reliable data for Armorica but a likely position north of Gondwana is indicated. No Mid-Silurian data exist for Siberia and again we have indicated a likely palaeoposition (cf. Torsvik et al., 1995d). Bottom diagram is a 2D-cartoon that exemplifies the mid-Silurian collision between Laurentia and Baltica attendant on extreme crustal thickening and later extensional collapse during early Devonian times (cf. text). Approximate latitudinal velocities for Laurentia and Baltica are derived from Figs. 14 and 15.

Tornquist Sea and eventually also the Iapetus Ocean. A three plate collision model, established from faunal (Cocks and Fortey, 1982) and palaeomagnetic data (Torsvik et al., 1992a), is supported by deep seismic reflectivity patterns (Meissner et al., 1994; Rabbel et al., 1995). The fate of the European massifs is as yet not well established though palaeomagnetic data clearly indicate that Armorica/Bohemia was at high latitudes together with Gondwana and Avalonia during the early Ordovician (Perroud et al., 1984; Torsvik et al., 1993a; Tait et al., 1994a). Armorica was probably peripheral to Gondwana throughout the Ordovician, whereas new palaeomagnetic data from Bohemia (Tait et al., 1995) indicate that Bohemia rifted off Gondwana during Mid-Ordovician times; this suggest that Armorica, Bohemia and Avalonia had disparate drift-histories. By the Caradoc, Bohemia had reached latitudes at around 40°S, and approximately 20°S and adjacent to the Baltic Tornquist margin by Upper Silurian times (Tait et al., 1994b, 1995). Suturing was associated with large anticlockwise rotations prior to the final consolidation of Hercynian Europe in Permo-Carboniferous times. The European massifs are rooted in the lower crust, probably due to rapid post-collisional orogenic collapse and delamination (Meissner and Sadowiak, 1992) which probably allowed subsequent "thin-skinned" rotations. The European massifs were essentially jam-packed between the convergence of Laurentia–Baltica–Avalonia with Africa, and which finally formed Variscan Europe (see Matte, 1991).

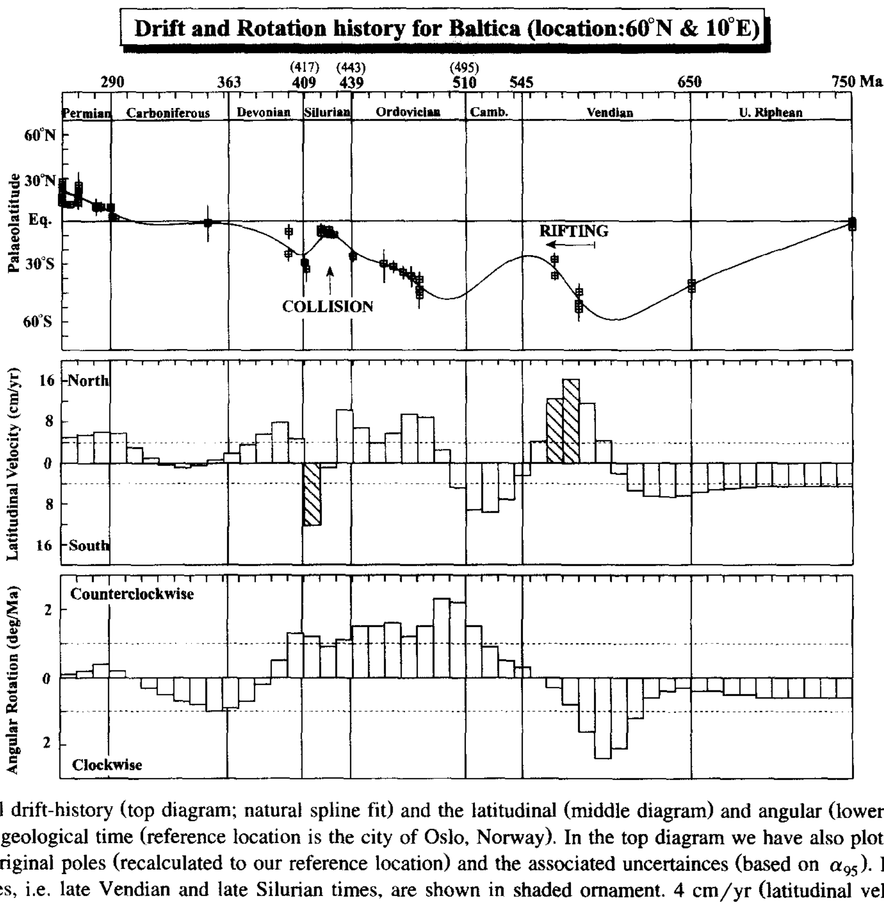

Fig. 14. Latitudinal drift-history (top diagram; natural spline fit) and the latitudinal (middle diagram) and angular (lower diagram) velocity of Baltica through geological time (reference location is the city of Oslo, Norway). In the top diagram we have also plotted palaeolatitudes derived from the original poles (recalculated to our reference location) and the associated uncertainces (based on α_{95}). Important peaks in latitudinal velocities, i.e. late Vendian and late Silurian times, are shown in shaded ornament. 4 cm/yr (latitudinal velocity) and 1°/Ma (angular rotation) levels are indicated as dotted lines. Palaeozoic time-scale after Harland et al. (1990) except the Vendian–Cambrian boundary (Tucker and McKerrow, 1995). Numbers in brackets (Ordovician–Devonian) refer to the time-scale of Tucker and McKerrow (1995) which differs 4–15 Ma from that of Harland et al. (1990).

4.6. Closure of the Iapetus Ocean and changing plate boundaries

The Early Ordovician rotated palaeoposition of Baltica (Fig. 11) invalidates traditionally accepted concepts of orthogonal relationships of Baltica and Laurentia across a single Iapetus Ocean throughout the period of Caledonide evolution (Torsvik et al., 1994, 1995d). The present Atlantic margin of Baltica (Fig. 11) was probably facing Siberia, and early Caledonian eclogite facies metamorphism, in the Tremadoc, is correlated with palaeo-northward subduction of Baltic continental crust in an ocean–ocean/arc zone (< 1500 km) between Baltica and Siberia. This subduction event, with inferred arc development locally, was closely followed by uplift and retrograde metamorphism of the eclogites and obduction of Early Ordovician (pre-Arenig) ophiolites (Sturt and Roberts, 1991; Sturt et al., 1995) across the margin of Baltica.

From Mid-Ordovician to early Silurian times, Baltica rotated counterclockwise which probably gave rise to a deep-seated, strike-slip regime in the narrowing oceanic tract between Baltica and Siberia, and between the obliquely converging plates of a rotating Baltica and a southward-drifting Laurentia (Torsvik et al., 1995d). At c. 425 Ma Balonia collided, probably obliquely, with Laurentia causing the early stages of the Scandian Orogeny (western Norway) and closing the intervening part of the Iapetus Ocean (Fig. 13). During the collisonal event, Laurentia was stationary at the equator whereas Baltica had a northward directed latitudinal velocity component in the order of 8–10 cm/yr (Figs. 14 and 15). The collision which caused palaeo-westward subduction of Baltic crust resulted in extreme crustal thickening in the Caledonian Belt exemplified by the preserved high-pressure terranes in western Norway and East Greenland (Andersen et al., 1991; Dewey et al., 1993). Sinistral transpressive deformation prevailed (Hutton, 1987) and Scandian thrust-related orogenisis continued on into Devonian times in northern areas of Norway. The Scandian event was followed by extensional collapse, at least in the southwestern parts of Norway, but from central Scotland to New York there were the compressional events of the Emsian/Eifellian Acadian Orogeny (McKerrow, 1988).

5. Dynamics

APW paths can be used to calculate palaeo-latitudinal drift-rates (minimum drift-rates) and rates of rotation for a given geographic location (Torsvik et al., 1992a). It should be pointed out that APW segments with large time-gaps (no data) inevitably result in low peak drift-rates due to "constant speed" interpolation. Also, rates of rotation depend in part on the position of the continent on the globe and are "unreliable" at high palaeo-latitudes (> 70°; e.g. Laurentia during the Late Precambrian).

The latitudinal drift and rotational history for Baltica (Location Oslo at 60°N, 10°E) is demonstrated in Fig. 14. In Late Riphean times (c. 750 Ma) Baltica was confined to equatorial latitudes but during Vendian times Baltica drifted southward and reached peak southerly latitudes at around 600 Ma when it separated from Laurentia and probably also Amazonia and Siberia (opening of Iapetus). The Iapetus rift-to-drift transition is associated with one of the highest recorded latitudinal drift rates (up to 16 cm/yr) for the Neoproterozoic–Palaeozoic (Fig. 14) as well as younger times (Gurnis and Torsvik, 1994).

No palaeomagnetic data exists for Cambrian times, hence drift-rates are entirely interpolated. From Early Ordovician times Baltica moved northward from c. 60°S and reached equatorial latitudes in Mid-Silurian times, i.e. during the collision with Laurentia (formation of Euramerica), followed by a period of rapid southward directed movement. Subsequent northward movement during Devonian and Carboniferous times places Baltica at low northerly latitudes by the Permian (c. 250 Ma).

With the exception of Vendian times, the latitudinal drift-rates for Baltica are below 10 cm/yr and there is an overall decrease from Vendian to Permian times. These estimates represent minimum values. Large rotations are observed in Vendian (clockwise) and Ordovician (anticlockwise) times and we notice a general decrease towards Permian times. A first-order correlation of latitudinal drift-rates and angular rotation suggest plate-movements controlled by low-latitude Euler poles close to the continent (Torsvik, 1995) give rise to the high rotation rate.

The Laurentian drift curve also indicates low latitudes during Late Riphean times followed by southward and peak southerly latitudes at around 600

Ma (Fig. 15), a pattern which is broadly similar to the Baltica drift-curve. During the latest Vendian Laurentia rifted off Baltica, Siberia (?) and West Gondwana (Fig. 16), and then drifted rapidly (up to 20 cm/yr) towards the equator and stayed essentially in low latitudes during Cambrian and Ordovician times. After the Mid-Silurian collision with Baltica at around 425 Ma, the drift-curves for the two continents are essentially similar and the post-Mid-Silurian APW paths for Baltica and Laurentia (Fig. 5) can be satisfactorily matched in a Bullard et al. (1965) fit. There are minor differences but we relate this to inaccuracies in the data-sets. Laurentia's drift-rates are also generally below 10 cm/yr though two distinct velocity bursts (c. 20 cm/yr) are indicated during Late Vendian and Silurian times, associated, respectively with divergence and convergence with Baltica.

The high crustal velocities for Laurentia and Baltica during Late Vendian and Mid–Late Silurian times exceed accepted speed-limits for large continental plates (Forsyth and Uyeda, 1975). At present, it is thought that plates are essentially driven by subducting slabs and lithospheric cooling, but Gurnis and Torsvik (1994) argue that deep roots can enhance the velocity of continental plates if the driving force is located in the lower mantle. In appealing to a deep driving force they suggested that Laurentia and Baltica were pushed off a lower mantle source arising from continental (Rodinia) insulation of the mantle or that continents were pulled toward a cold-spot generated by prolonged subduction; perhaps located within the Proto-Pacific which had opened between Laurentia and East Gondwana (Fig. 16). In the latter model there should be a pronounced sea-level rise when Laurentia settled above the cold-spot; indeed this is the case for Early Cambrian Laurentia, although sea-level rise took place almost everywhere in the Cambrian. During the final redistribution of Rodinia the arguments presented above are applicable, but the Mid–Late Silurian velocity peak for Laurentia and Baltica (Figs. 14 and 15) is more problematic, and may reflect a component of *true* polar wander (Van der Voo, 1994) or post-orogenic

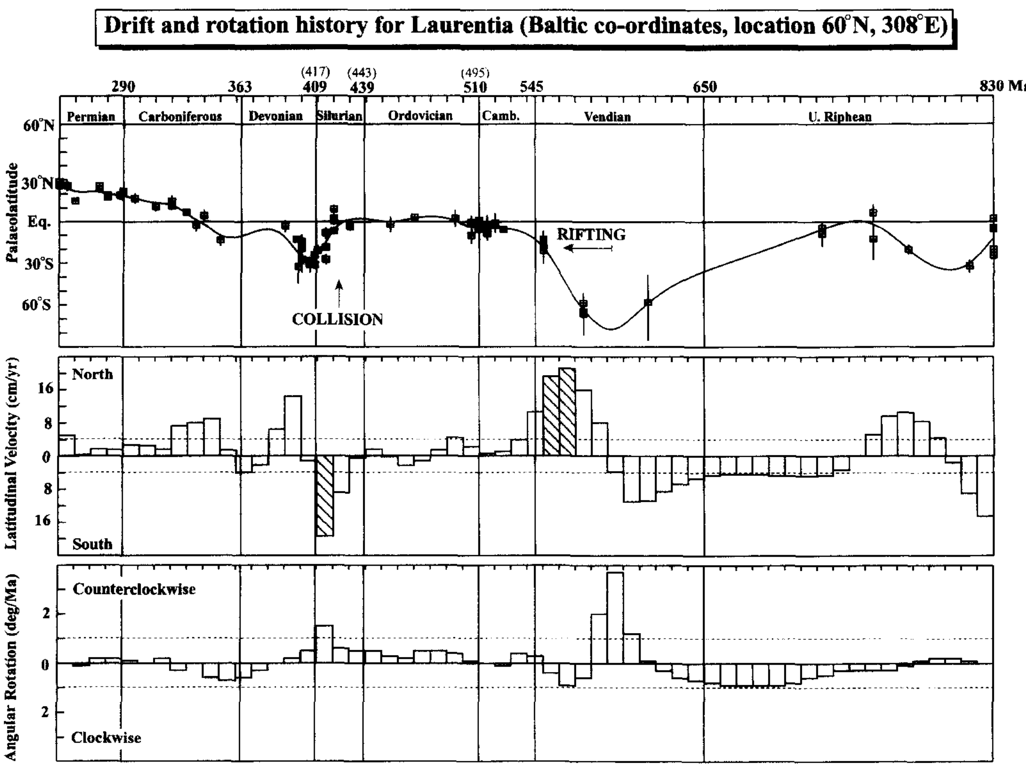

Fig. 15. Latitudinal drift-history, latitudinal drift-rates and angular rotations for Laurentia. Cf. Fig. 14 for caption details.

collapse and delamination processes. The velocity peak took place shortly after continental collision (Fig. 13 – formation of Euramerica) subsequent to prolonged subduction and destruction of the Iapetus Ocean. Euramerica, perhaps initially formed above a low geoid (mantle flushing) at the equator, may have facilitated *true* polar wander.

6. Conclusions

The Neoproterozoic and the dawn of the Phanerozoic is a remarkable period in geological history for many reasons. Several lines of evidence indicate the formation of a *long-lived* supercontinent, Rodinia, at around 1100 Ma (Dalziel, 1992) which, in part, may have lasted some 500 Ma. Plate motions, mantle convection and palaeogeography are strongly linked (Anderson, 1982, 1994; Gurnis, 1988) and supercontinents insulate the mantle. The redistribution of Rodinia was marked by high crustal velocities driving continents in the direction of cold, downwelling mantle regions, accompanied by sea-level rise and the subsequent biotic explosion that heralded the start of the Phanerozoic.

The Rodinia postulate is to some extent based on palaeomagnetic data, providing palaeolatitude and palaeo-orientation control, but the primary geometry and continental fits for many landmasses are very much governed by an attempt to match the 1100–1300 Ma Grenvillian–Sveconorwegian–Kibaran crustal provinces. This alone, however, does not provide a unique solution since crustal provinces can either be interpreted as having formed continuous belts or as conjugate margins. Correlation of tectonic events spanning 200 Ma also should be treated with caution as this may lead to the integration of distinct events into a single tectonic pulse. Such arguments could be the equivalent of linking the Hercynian and Caledonian orogenies into a single event. *The question should be posed as to how Baltica could have rifted off Laurentia by the end of the Precambrian, then drift and rotate independently of Laurentia for nearly 200 Ma and subsequently converge at almost the same place where they originally diverged.* Our tale is not that of Wilson (1966) Cycle tectonics, except for the observation that oceans do open and eventually close again, but rather a more catastrophic system characterised by metastable plate boundaries producing unpredictable geometry's.

With these cautious notes in mind and acknowledging that a tight Neoproterozoic Baltica–Laurentia (Grenvillian–Sveconorwegian) fit is a rather dogmatic approach and also that our starting point, the novel Rodinia postulate (Dalziel, 1991), is likely to be modified and refined, we feel it is possible to draw the following inferences:

- Baltica and Laurentia share a common drift history for the time interval 750–600 Ma while they maintained a tight Grenvillian–Sveconorwegian fit (Euler pole at lat. = 72°N, long. = 43°E and a rotation angle of 50°) and assuming that our polarity interpretations are correct.

- During the initial break-up of Rodinia (c. 725–750 Ma), Laurentia–Baltica drifted southwards from an equatorial position, and their combined approach

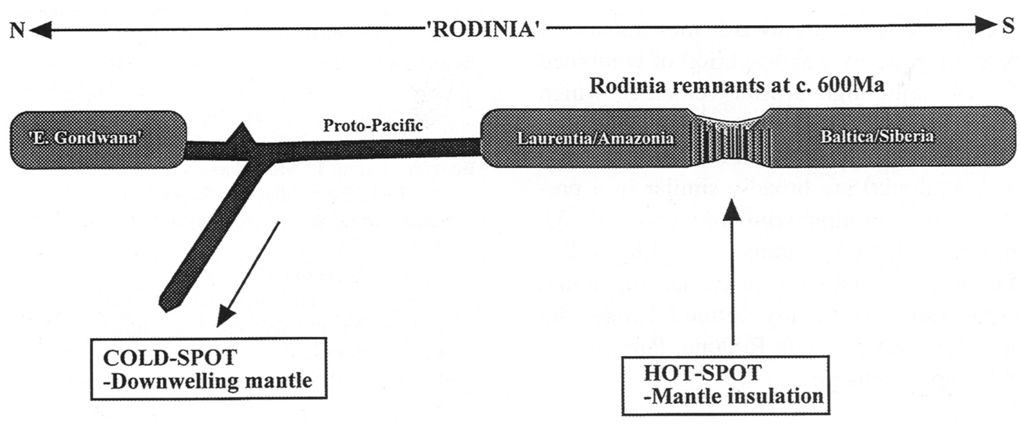

Fig. 16. Schematic model for the final breakup of Rodinia (cf. text).

toward the south pole helps to explain the latitudinal distribution of Vendian glaciogenic sequences which we argue were mostly located at latitudes in excess of 30°S.

- Initiation of rifting, prior to Iapetus opening, on the Baltic margin is marked by intrusion of the 650 Ma Egersund dykes in southwest Norway which were probably plume-related, though on the Laurentian margin by the somewhat later (615 Ma) Long Range dikes (Labrador), the Catoctin volcanic province (Virginia) and associated dykes at 580–600 Ma. Laurentia and Baltica clearly had separated by 600–580 Ma, and the opening of the Iapetus Ocean involved asymmetric rifting and large relative rotations. The timing of separation of Amazonia and Laurentia is a problem and is likely to have heralded Catoctin volcanism (580 Ma).

- The final Vendian redistribution of Rodinia involved Laurentia, Baltica, Siberia and West Gondwana and was characterised by exceptionally high plate velocities, up to 20 cm/yr. This situation possibly relates to supercontinental insulation of the mantle and/or continents being pulled toward cold-spots generated by prolonged subduction.

- The Late Cambrian–Early Ordovician active margin of Baltica (Scandinavian Caledonides) formed a plate boundary with Siberia. The effect of the subsequent counterclockwise rotation of Baltica was to transfer this Baltic margin in the direction of Laurentia by Late Ordovician–Early Silurian times, and at the same time the Tornquist Sea, separating Baltica and Avalonia, closed.

- Laurentia and Baltica initially collided at c. 425 Ma (Scandian orogeny). Southward directed movement of Laurentia and northward movements of Baltica were followed by a short period of combined southward drift with high crustal velocities which could be attributed to *true* polar wander.

- Post-Mid-Silurian APW paths for Laurentia and Baltica (and Avalonia) are broadly similar in a pre-drift Atlantic configuration (Bullard et al., 1965). Their joint amalgamation (Euramerica) with the European Massifs and Gondwana during Devonian and Carboniferous times eventually formed Pangea by Permian times. Compared with Rodinia, Pangea was a short-lived supercontinent.

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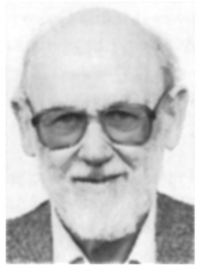
Trond H. Torsvik, born October 12, 1957. M.Sc. and Ph.D. degrees in 1982 and 1985 from the University of Bergen (Norway). Research Fellow University of Bergen (1982–1986) and Oxford University (1987 and 1989–1990). Senior Geophysicist, Geological Survey of Norway (1988 and 1991–1993) and visiting scientist at University of Michigan (1993–1994). Strategic Research Coordinator, Geological Survey of Norway, 1995 to present, and Professor of Geophysics, University of Bergen.

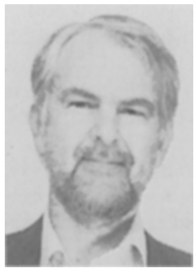
Mark. A. Smethurst, born February 24, 1961. Ph.D. degree in 1987 from the University of Leeds (UK). Post-Doctoral Research Fellow in Geophysics, University of Oxford (1987–1990). Senior Geophysicist, Geological Survey of Norway (1990–1995). Visiting Research Scientist, Lamont-Doherty Earth Observatory of Columbia University (1995–1996).

Joseph G. Meert, born December 7, 1957. M.Sc., 1988 from the University of Florida; Ph.D., 1993 from the University of Michigan. Research Fellow, 1993–1994 University of Michigan. Assistant Professor of Geophysics at Indiana State University, Department of Geography and Geology, 1994–present.

Rob Van der Voo, born August 4, 1940. B.Sc., M.Sc. and Ph.D. degrees in, 1961, 1965 and 1969 all from the University of Utrecht, the Netherlands. Professor of Geological Sciences at the University of Michigan, Ann Arbor, USA



W. Stuart McKerrow, born June 28, 1922. D.S.C., 1943, while in Royal Navy. B.Sc. (Glasgow), 1947; D.Phil. (Oxon), 1953; D.Sc. (Oxon), 1977. Demonstrater and Lecturer Oxford University, 1947–1989; Fellow, Wolfson College, Oxford, 1965–1989; Emeritus Fellow, 1989 to present. Research Fellow, California Institute of Technology, 1964–1965. Visiting Professor: University of Chicago, 1973, 1977, 1981; University of Alberta, 1984; University of Auckland, New Zealand, 1988; Williams College, Mass., 1991. Lyell Medal, Geological Society of London, 1981; Clough Medal, Edinburgh, 1988; Foumarier Medal, Belgium, 1995. President, Palaeontological Association, 1970–1972. Vice-Precident, Geological Society of London, 1987–1989.



Martin D. Brasier, born April 12, 1947. B.Sc. (London), 1969; Ph.D. London (1973). Palaeontology Department British Geological Survey (1972–1973). Lecturer, Reading University (1973–1974). Lecturer, Hull University (1974–1986). Reader in Palaeobiology, Hull University (1986–1988). Lecturer, Oxford University and Tutorial Fellow St. Edmund Hall (1988–date). Leader of IGCP Project 303 on Precambrian–Cambrian Event Stratigraphy (1990–1994). Chairman of International Subcommision on Cambrian Stratigraphy (1992–1996).

Brian A. Sturt, Research Director of the Geological Survey of Norway and formerly Professor of Geology at the University of Bergen.

Harald J. Walderhaug, born September 12, 1962. M.Sc. and Ph.D. degrees in 1987 and 1992 from the University of Bergen, Norway. Senior lecturer at the Institute of Solid Earth Physics, University of Bergen, 1992 to present.