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Cambrian palaeomagnetic data from Baltica: implications for true polar wander and Cambrian palaeogeography

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Abstract: A reliable Early Cambrian (*c.* 535 Ma) and a preliminary Late Cambrian (*c.* 500 Ma) palaeomagnetic pole from Baltica (Sweden) overlap within uncertainty, and they are also broadly compatible with Vendian (*c.* 583 Ma) palaeomagnetic data. Apparent polar wander for Baltica amounts to less than 25° between 583 and 500 Ma and, therefore, negates recent speculations that the Earth tipped 90° during the Early Cambrian (true polar wander).

Throughout Vendian and Cambrian times, Baltica lay at southerly latitudes (*c.* 30–60°S). Baltica was geographically inverted, and present-day northern Baltica faced the NW margin of Gondwana which covered the south pole. Laurentia-Eastern Baltica and Laurentia–West Gondwana were separated by the Iapetus Ocean, while the Ægir Sea separated Western Baltica from the Taimyr region of Siberia. During the Cambrian Baltica probably moved eastward along the Gondwana margin, and by *c.* 515–520 Ma subduction in the Ægir Sea was initiated. A major event is recognized in Late Cambrian or Early Ordovician times (*c.* 500–478 Ma) when Baltica must have undergone a 55° counter-clockwise rotation in *c.* 22 million years (3°/Ma). We relate this to the early Caledonian Finnmarkian Orogeny which involved arc–continent collision following subduction.

Keywords: Baltica, Cambrian, Finnmarkian orogeny, true polar wander, palaeogeography.

The Cambrian is one of the most important geological epochs in the evolution of planet Earth and, recently, inertial interchange true-polar-wander (IITPW) has been advocated to explain high plate-velocities and anomalous geochemical and biological trends (Kirschvink *et al.* 1997). This controversial hypothesis implies that the Earth's lithosphere and mantle rotated 90° with respect to the spin axis between 535 and 520 Ma. If correct, all continents should have experienced 90° of apparent polar wander (APW) during this time interval; a simple test for IITPW has been hampered by hiatuses in the palaeomagnetic record, uncertainty in rock and magnetization ages, magnetic polarity ambiguity, and, not least, the choice of reference palaeomagnetic data (Torsvik *et al.* 1998; Meert 1999).

Cambrian data from Baltica are pivotal in producing realistic palaeogeographic models and to test the IITPW hypothesis, largely because Baltica otherwise offers some of the best-constrained Late Precambrian and Palaeozoic palaeomagnetic datasets. However, use of Baltican data from the Cambrian has been hampered by unsuitable lithologies with unstable magnetizations and remagnetization problems. These problems are manifested by the large gap in the palaeomagnetic record for 583–480 Ma (Torsvik *et al.* 1996), hence excluding Baltica from any discussion of the IITPW theory for the Cambrian Period. In this account, we report new palaeomagnetic data from Early and Late Cambrian deposits in northern and southern Sweden (Fig. 1). These data do not support the theory of Cambrian IITPW. We instead utilize the new results to focus on the palaeogeographic implications within a plate-tectonic framework for the Early Palaeozoic.

Regional geology and sampling

In southern Sweden (Fig. 1a & b), the Early Cambrian consists mainly of shallow-marine arenaceous deposits, divided into four formations (Hardeberga, Norretorp, Rispebjerg and Gislöv; Fig. 2). The Gislöv and Hardeberga Fms were sampled at Gislövshammar (Bergström & Ahlberg 1981) and the Hardeberga Quarry (Ahlberg 1998) respectively, but none of these formations yielded coherent within-site palaeomagnetic data due to erratic demagnetization behaviour. The stratigraphic positions of these 'failed' studies are shown in Fig. 2.

The Middle–Upper Cambrian and Lower Ordovician (Tremadoc) units of Scandinavia have proved exceptionally difficult to analyse palaeomagnetically due to the dominance of dark grey or black, kerogen-rich, sulphide-bearing mudstones and shales with accessory lenses or beds of dark grey limestone. These are collectively referred to as the Alum Shale (Henningsmoen 1957; Gee 1972; Buchardt *et al.* 1997). Most of the Alum limestone lenses we have tested from several locations in Sweden yielded spurious data, but from Andrarum (Fig. 1b) we report on an Alum limestone that responded well to alternating field demagnetization. The studied limestone site contains *Olenus gibbosus* trilobites (Ahlberg 1998), which places it in the lowermost Upper Cambrian, i.e. *c.* 500 Ma (time-scale of Bowring & Erwin 1998).

In northern Sweden (Fig. 1), the Dividal Group comprises the Early Cambrian Torneträsk Fm and Middle Cambrian Alum shales (Kulling 1964; Thelander 1982). Our samples come from the lower part of the Torneträsk Fm, approximately 150 m below the Caledonian (Silurian) sole-thrust (Fig. 1c) and close to the inferred Caledonian Front. The Torneträsk Fm is almost flat-lying, metamorphism is low or absent with the overlying Alum Shale Fm having acted as the décollement horizon for the basal Caledonian thrust and thus absorbing most of the associated shear stress. The Lower Allochthon overlying the Alum shale consists of locally derived rocks, and metamorphism did not exceed chlorite grade (Kulling 1964).

The Torneträsk Fm is divided into five informal Members (Lower Sandstone, Lower Siltstone, Red and Green Siltstone,

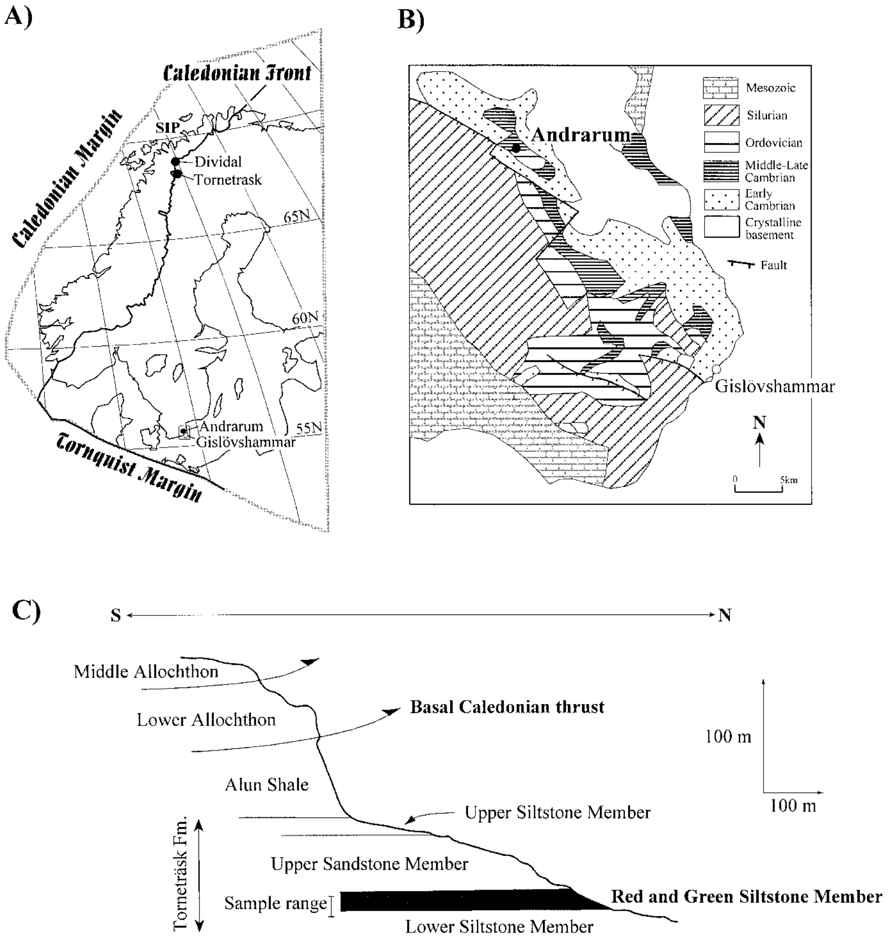

Fig. 1. (**a**) Western Baltica (Scandinavia) and location of sampling areas (Andrarum and Torneträsk) and other locations mentioned in the text. SIP, Seiland Igneous Province. (**b**) Simplified geological sketch map of SE Skåne (Andrarum), southern Sweden. (**c**) Vertical sampling profile of the Torneträsk Formation (Luovarri section), northern Sweden (Kulling 1964).

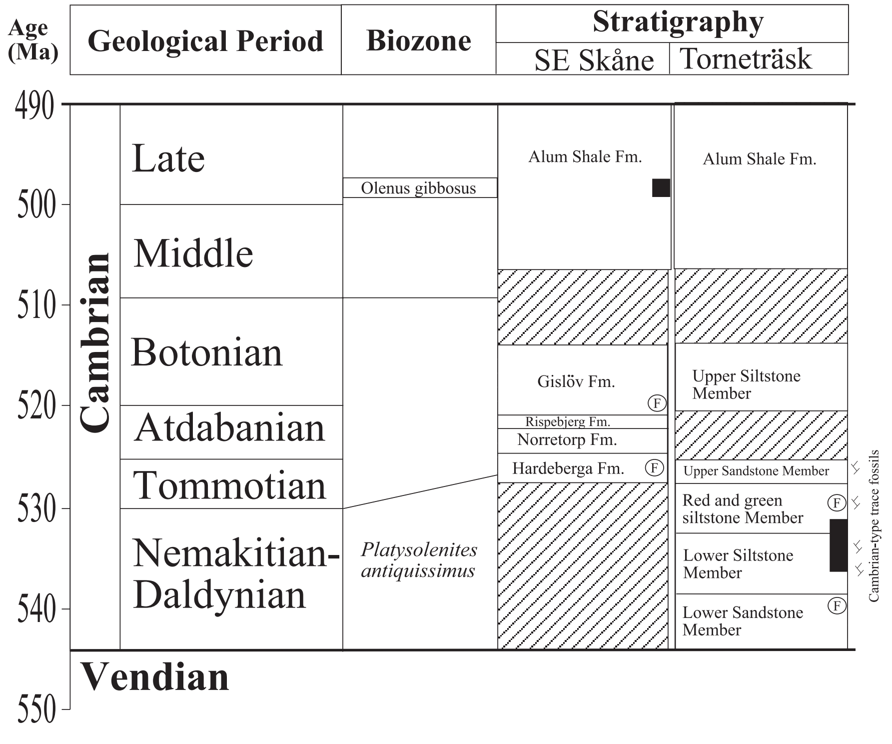

Fig. 2. SE Skåne (southern Sweden) and Torneträsk (northern Sweden) stratigraphy, Baltica biozones and correlation with the Siberian stages (based on Vidal *et al.* 1995; Ahlberg 1998; Jensen & Grant 1998 and Bowring & Erwin 1998).

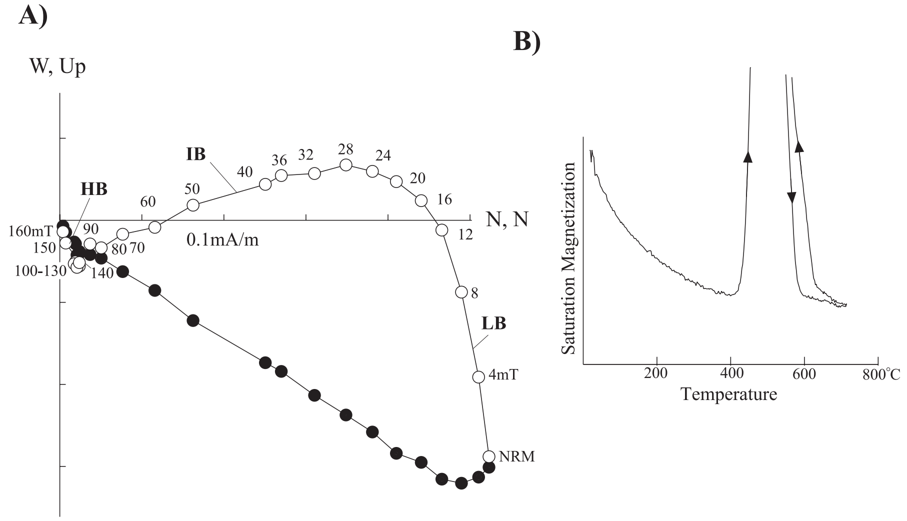

Fig. 3. (**a**) Typical example of AF demagnetization of a lower Late Cambrian limestone sample from Andrarum (southern Sweden). (**b**) Thermomagnetic analysis of an Andrarum sample. In vector plots, solid (open) symbols denote points in the horizontal (vertical) plane.

Upper Sandstone and Upper Siltstone). Only palaeomagnetic data from the upper part of the Lower Siltstone and red siltstone of the Red and Green Siltstone Member provided sensible palaeomagnetic data. The Red and Green Siltstone Member is widespread in Scandinavia, and a palaemagnetic study of the stratigraphic equivalent of this Member has been undertaken by Bylund (1993) in the nearby Dividal region of Norway (Fig. 1a).

The Torneträsk Fm is Early Cambrian in age (Jensen & Grant 1998), and following Vidal *et al.* (1995), the Baltican *Platysolenites antiquissimus* biozone correlates with the Nemakitian–Daldynian Siberian stage (Fig. 2); our sampling of the Torneträsk Fm is confined to this biozone and we assign a mean age of 535 Ma.

Laboratory experiments

The natural remanent magnetization (NRM) was measured with a 2 G DC Squid. Stability of NRM was tested by thermal and alternating field (AF) and remanence components were calculated with least square regression analysis (http://www.ngu.no/geophysics). Thermomagnetic analyses (TMA) were carried out on a horizontal translation balance.

Southern Sweden (Late Cambrian Alum Shale Fm)

NRM intensity is low (mean 0.3 mA m^{-1}), but three remanence components of excellent quality are readily identified from AF treatment (Fig. 3a & Table 1). A low-coercivity component (LB) with northerly declinations and steep positive inclinations is randomized below 8–10 mT, an intermediate (IB) component with NE declinations and shallow negative inclinations is observed between 30 and 100 mT, and finally a high coercivity component (HB) with easterly declinations and steep positive inclinations is detected above 140–150 mT (Fig. 3a); this is close to the maximum available AF field of 160 mT. Remanent intensity is *c.* 0.02–0.03 mA m^{-1} when the HB component is recognized as linearly decaying toward the centre of the orthogonal vector plots. Thermal demagnetization was less successful due to large magneto-mineralogical alterations (Fig. 3b). In some instances, HB directions are 'semi-stable' to approximately to 580°C, but viscous behaviour prevails. TMA indicates break-down of pyrrhotite and formation of magnetite, and saturation magnetization increases by an order of magnitude after heating and cooling. The LB component probably represents a present-day viscous magnetization, and is not discussed further.

Northern Sweden (Early Cambrian Torneträsk Fm)

Red siltstone samples from the Red and Green Siltstone Member (sites 4 & 5) have NRM intensities at around 5 mA m^{-1}, whereas the remaining samples have NRM intensities between 0.3 and 0.7 mA m^{-1}. LB components are present in most samples, but they are mostly scattered at site-level.

Samples from sites 1 and 2 yield HB components with easterly or NE declinations and steep positive inclinations (Fig. 4a). These are of reverse magnetic polarity. LB components are typically removed at 8–15 mT or at temperatures of 250–300°C. Site 3 samples show opposite magnetic polarity, i.e. HB directions with SW declinations and steep negative inclinations (Fig. 4b). The overlying Red and Green Siltstone Member (sites 4 and 5) yield reverse polarity directions (Fig. 4c & d) that are directionally concordant with those of sites 1 and 2 (Fig. 5). Red siltstone samples show directional stability up to 650°C which suggests hematite as a remanence carrier. Minor amounts of hematite are recognized from TMA, but magnetite (Curie-temperatures *c.* 580°C) predominates. Samples are thermochemically unstable and secondary magnetite is formed during heating and cooling (Fig. 4e). Substantial influence of magnetite is indicated from AF demagnetization which shows that the NRM intensity is reduced to *c.* 30% at AF fields of 100 mT. At higher AF fields, directional behaviour is often erratic, but AF demagnetized samples show a clear decay toward the centre of the orthogonal plots above 30–45 mT (Fig. 4d).

Interpretation of palaeomagnetic data

HB site-mean directions from Andrarum, Torneträsk and an Early Cambrian site-mean from Dividal (Fig. 1a) in northern Norway (Bylund 1993) are displayed in Fig. 5. Reverse polarity site-means cluster, and the normal polarity site 3 from Torneträsk is concordant with the reverse polarity data at the 95% confidence level. The Dividal site (Bylund 1993) corresponds stratigraphically to sites 4 and 5 from Torneträsk, and Torneträsk–Dividal data have therefore been combined to calculate an Early Cambrian *c.* 535 Ma pole for Baltica (Fig. 6, Table 1). The Alum shale at Andrarum is early Late Cambrian in age (*c.* 500 Ma; see Fig. 2), but the directional similarity from this locality with the Torneträsk Fm is noticeable (Fig. 5). These are, as yet, the only 'reliable' Cambrian palaeomagnetic data from Baltica, and at Torneträsk the stratigraphically linked reversal pattern (Site 3—normal polarity) is the best indication for a primary or early diagenetic magnetization. The Torneträsk section is situated 150 m below the basal

Table 1. *Site mean directions from the Andrarum Limestone (location: old Andrarum quarry 55.7°N and 14.0°E; bedding: 250°/7°S) and the Torneträsk Formation (Dividal Group), Northern Sweden (location: Luovarri 68.2°N and 19.5°N; bedding is flatlying)*

	Component IB			Component HB		
Site	Dec/Inc	*N*	α_{95}	Dec/Inc	*N*	α_{95}
Andrarum Limestone (Lower Lower Cambrian)						
SK6	29/−19	11	4.9	61/58	10	6.8
Pole	Lat.=20°S, Long.=343°E					
Bedding corrected	**31/−23**	**11**	**4.9**	**51/57**	**10**	**6.8**
Palaeomagnetic pole	Lat.=17°S, Long.=342°E, dp/dm=3/5			Lat.=52°N, Long.=111°E, dp/dm=7/10		
Torneträsk Fm (Lower Cambrian)						
B93 (Red and Green Siltstone)				56/68	11	10
T5 (Red and Green Siltstone)				50/58	9	7.0
T4 (Red and Green Siltstone)				47/60	7	8.3
T3* (Lower Siltstone)				238/−58	7	17.8
T2 (Lower Siltstone)				49/70	4	13.5
T1 (Lower Siltstone)				109/77	5	16.5
Mean sites				**57/66**	**6**	**8.9**
Palaeomagnetic pole				Lat.=56°N, Long.=116°E, dp/dm=12/15		

*Dec/Inc inverted for mean calculation; Dec/Inc=mean declination/inclination; *N*=samples; α_{95}=95% confidence circle; IB/HB, intermediate/high unblocking temperatures or coercivity. Lat./Long., latitude/longitude of palaeomagnetic pole; dp/dm, semi-axes of the cone of 95% confidence about the pole. Site B93 is site 10 of Bylund (1993) and is situated 70 km NNW of Torneträsk (location: Dividal 68.8°N and 19.8°N). B93 corresponds stratigraphically to our sites 4 and 5. Original Dec/Inc (57/68; tectonically corrected) recalculated to Torneträsk location.

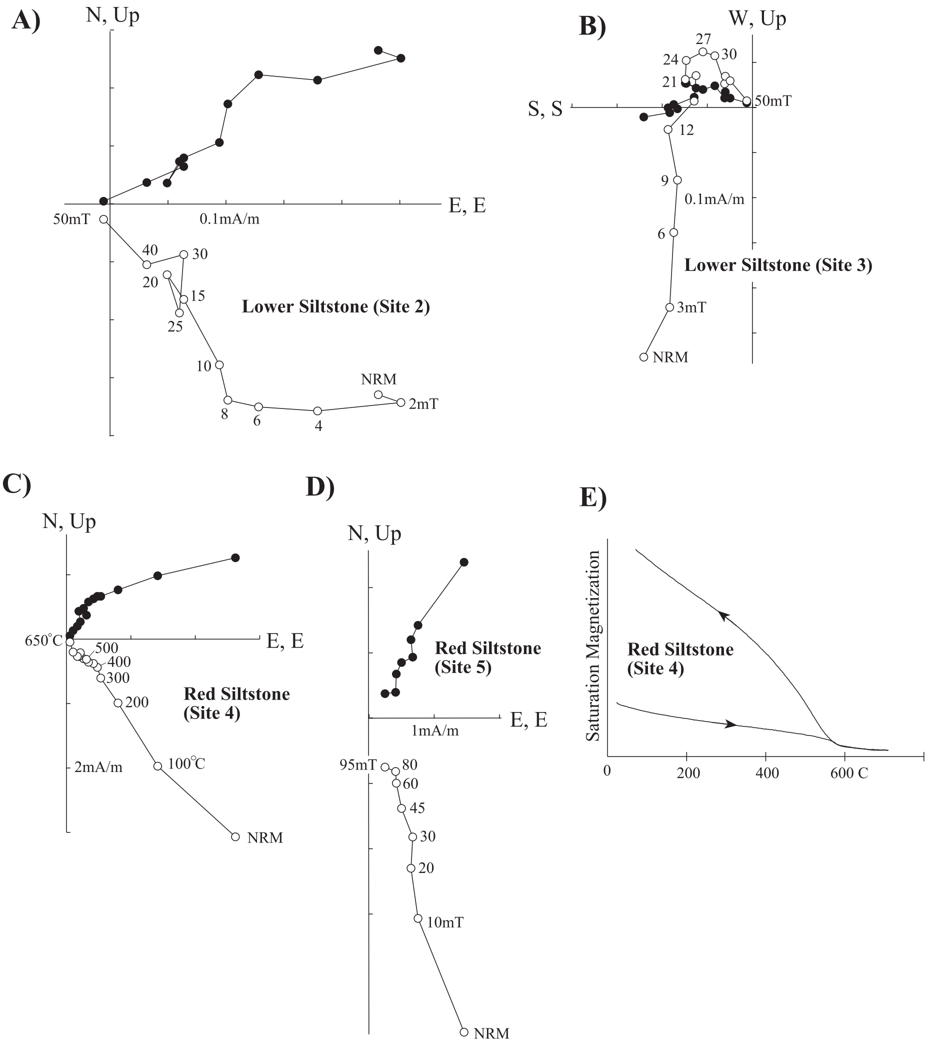

Fig. 4. Examples of AF (**a–b** & **d**) and thermal demagnetization (**c**) of samples from the Torneträsk Fm (Northern Sweden). (**e**) Thermomagnetic analysis of a red siltstone sample.

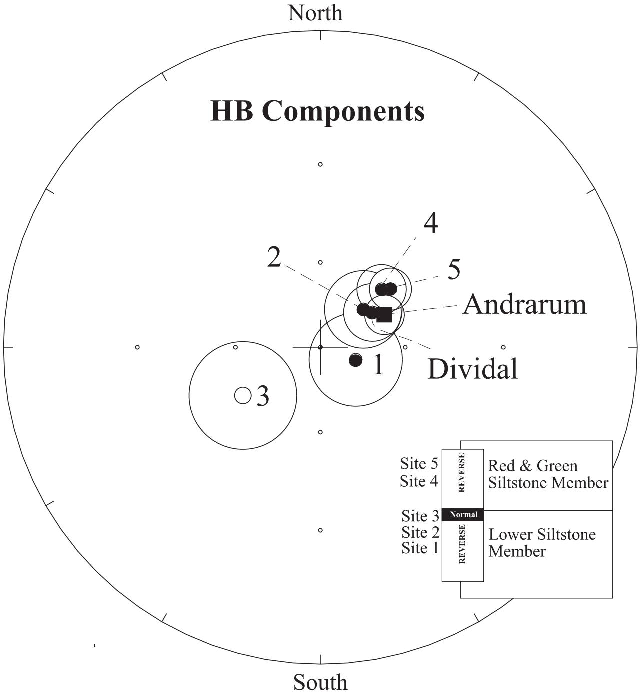

Fig. 5. Site-mean directions with α_{95} confidence circles from Torneträsk (sites 1–5), Andrarum and Dividal (Bylund 1993). Andrarum and Dividal data have been recalculated to the Torneträsk location for direct comparison. Inset diagram: magnetic polarity at Torneträsk location.

Caledonian (Silurian) thrust (Fig. 1c), but the Torneträsk pole plots in the vicinity of Vendian poles from Baltica, and far away from Silurian-aged poles (Fig. 6). While the Torneträsk Fm shows few signs of Caledonian overprinting, the Andrarum IB pole plots near Mid–Late Silurian (420–428 Ma) poles from Baltica (Fig. 6). This indicates Caledonian disturbance in Southern Sweden, which was probably related to the development of the German–Polish Caledonides along the Tornquist Margin (Fig. 1a). A thermal event is also recorded by increased values of vitrinite-like reflectance from the Andrarum locality (Buchardt *et al.* 1997). Local tilting (7°) could be post-Early Silurian in age (Lindström 1960), and the Andrarum IB component could be syn- or post-fold, Mid–Late Silurian in origin. However, given younger Late Palaeozoic and Mesozoic tectonism in southern Sweden, we cannot exclude the possibility that this folding/tilting may be considerably younger. In the latter case, a structurally corrected pole should be utilized (Fig. 6); regardless, the difference between the *in-situ* and structurally corrected pole-positions is only 3 degrees of arc.

Discussion and conclusions

Vendian–Early Palaeozoic APW path for Baltica: implications for IITPW

The Torneträsk and Andrarum poles allow us for the first time to construct a Late Precambrian to Early Palaeozoic APW path for Baltica. The Vendian segment is based on the Fen Complex pole of Meert *et al.* (1998), which supersedes two

Fig. 6. The most reliable Vendian to Silurian paleomagnetic poles from Baltica and a smoothed APW path (spherical spline). Poles are shown with 95% confidence cones (dp/dm) and numbers denote age in million years. A Finnmarkian pole (uplift-related) discussed in the text (stippled dm/dm confidences), was not used for APW construction.

older but broadly similar poles (see Torsvik *et al.* 1996). U–Pb, Rb–Sr and ^{40}Ar/^{39}Ar ages from Fen are concordant and have an average age of 583 Ma. Vendian poles have also been reported from mafic dykes in northern Norway and Russia (reviewed in Torsvik *et al.* 1995). These poles plot in the vicinity of the Fen Complex pole, but their ages are less well constrained and we use the well-dated Fen Complex as the key Vendian pole. The Torneträsk and Andrarum poles define the Cambrian part of the APW path: their stratigraphic ages are well known, but we acknowledge that the Andrarum pole is as yet based on only one site and should be regarded as preliminary. The Ordovician and Silurian segment is similar to that reported by Torsvik *et al.* (1996) and Torsvik (1998), but with stratigraphic ages adjusted to the time-scale of Tucker & McKerrow (1995). We also include a new Early Ordovician pole (Late Arenig *c.* 471 Ma pole in Fig. 6) from Gislövshammar (Fig. 1b), southern Sweden (Torsvik & Rehnström 2001).

The Early Cambrian Torneträsk and the early Late Cambrian Andrarum poles plot in the vicinity of, and partly overlap with, the Vendian Fen pole (Fig. 6); hence, a minimal APW is observed through both Vendian and Early–Mid-Cambrian times. This negligible APW makes IITPW untenable since all continents should show 90° of APW during the Early Cambrian. IITPW was partly intended to explain the bio-diversity revolution in the Early Cambrian (535–520 Ma), but a more recent analysis, coupled with a revised time-scale for the Cambrian suggests this bio-diversity revolution to have happened in the Mid-Cambrian (Bowring & Erwin 1998). The palaeomagnetic data selected to advance IITPW is contentious (Torsvik *et al.* 1998), and with regard to Baltica, Kirschvink *et al.* (1997) inverted the Fen Pole polarity because of the freedom afforded by lack of palaeomagnetic data for the 583–478 Ma time interval. This led to more than 90° of APW between Vendian and Early Ordovician times, but in the light of the Torneträsk and Andrarum poles our polarity interpretation (Fig. 6) is preferred, and minimizes Vendian–Cambrian APW. A 22 Ma gap still exists in the palaeomagnetic record from Late Cambrian to Early Ordovician (Tremadoc) times (considerably younger than the proposed IITPW interval), and implies an APW rate of *c.* 20 cm a^{-1}. Substantial counter-clockwise rotation of Baltica in latest Cambrian to earliest Ordovician time would explain this APW (see below).

Baltica drift story and geodynamics

The latitudinal drift history for Baltica (Fig. 7a) is exemplified with original palaeomagnetic poles, while the latitude drift of Oslo (60°N, 10°E), minimum plate velocity (only latitude movements) and angular rotation (Fig. 7b) are calculated from a spherical smoothed APW spline (Fig. 6). Maximum latitudinal velocity in the Cambrian amounts to 8 cm a^{-1} (Fig. 7b), but this, in part, corresponds to a large peak in counter-clockwise rotation (*c.* 3° Ma^{-1}).

In Vendian times, Baltica was 180° geographically inverted; southern Baltica, facing the equator, was located at 30°S and Baltica stretched to approximately 50°S (Fig. 7a). Northern Baltica was an active margin during Mid–Late Vendian times, and subduction-related arc/oceanic complexes with micro-continental blocks were probably accreted to this part of the Baltican margin during the Baikalian orogeny (*c.* 600–575 Ma; Olovyanishnikov *et al.* 1997; Roberts 2000). Early Cambrian to early Late Cambrian palaeolatitudes for Baltica are quite similar to those for Vendian times. A major event is recognized in Late Cambrian or Early Ordovician times (*c.* 500–478 Ma) when Baltica must have undergone a 55° counter-clockwise rotation in *c.* 22 million years (3° Ma^{-1}).

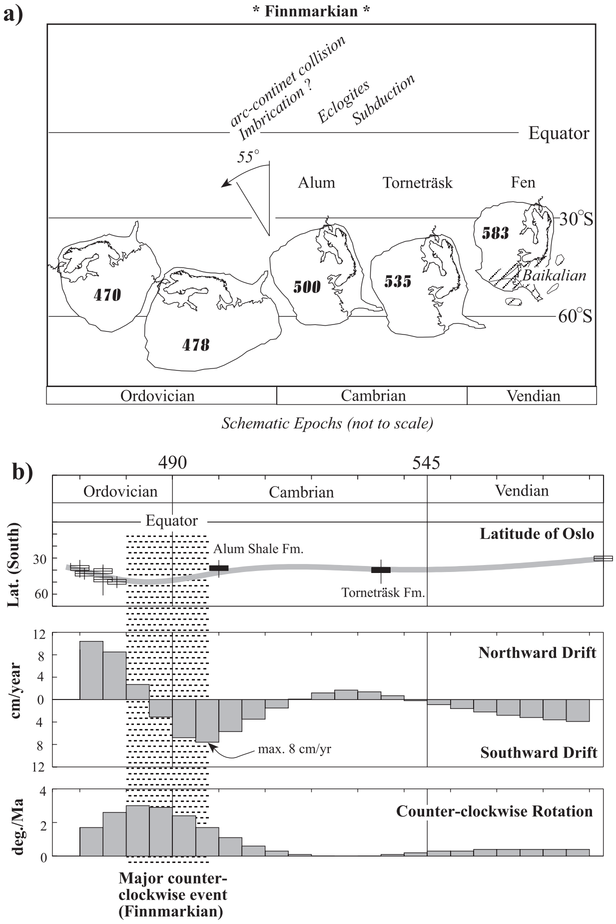

Fig. 7. (**a**) Reconstruction of Baltica from Vendian to Early Ordovician times using original palaeomagnetic poles (in million years) shown in Fig. 6. (**b**) Calculation of latitude change for Oslo location, latitudinal velocity, and counter-clockwise rotation for Oslo during Vendian to Ordovician times.

Two major orogenic events have been postulated for the development of the northern Scandinavian Caledonides: a Late Cambrian–Early Ordovician event (Finnmarkian) and a Silurian–Early Devonian (Scandian) event. The Scandian orogenic event resulted from the collision of Baltica with Laurentia and was marked by deep subduction of Baltican crust beneath Laurentia with concomitant eastward translation of nappes over the West Baltican margin. The nature of the Finnmarkian orogenic event, however, has been a subject of much debate, but there is agreement that it involved arc–continent collision following subduction (Stephens & Gee 1989; Sturt & Roberts 1991). In a palaeomagnetic study of the Seiland Igneous Province (SIP), northern Norway/Baltica margin (Fig. 1a), Torsvik *et al.* (1990) argued for Finnmarkian-linked uplift magnetizations (Early Ordovician *c.* 490 Ma). This study led to the postulation of a geographically inverted Baltica in southerly latitudes during Late Cambrian–Early Ordovician times (Torsvik & Trench 1991). With the later accumulation of reliable primary Early Ordovician poles from Sweden (Fig. 6), the SIP pole was not further used to construct

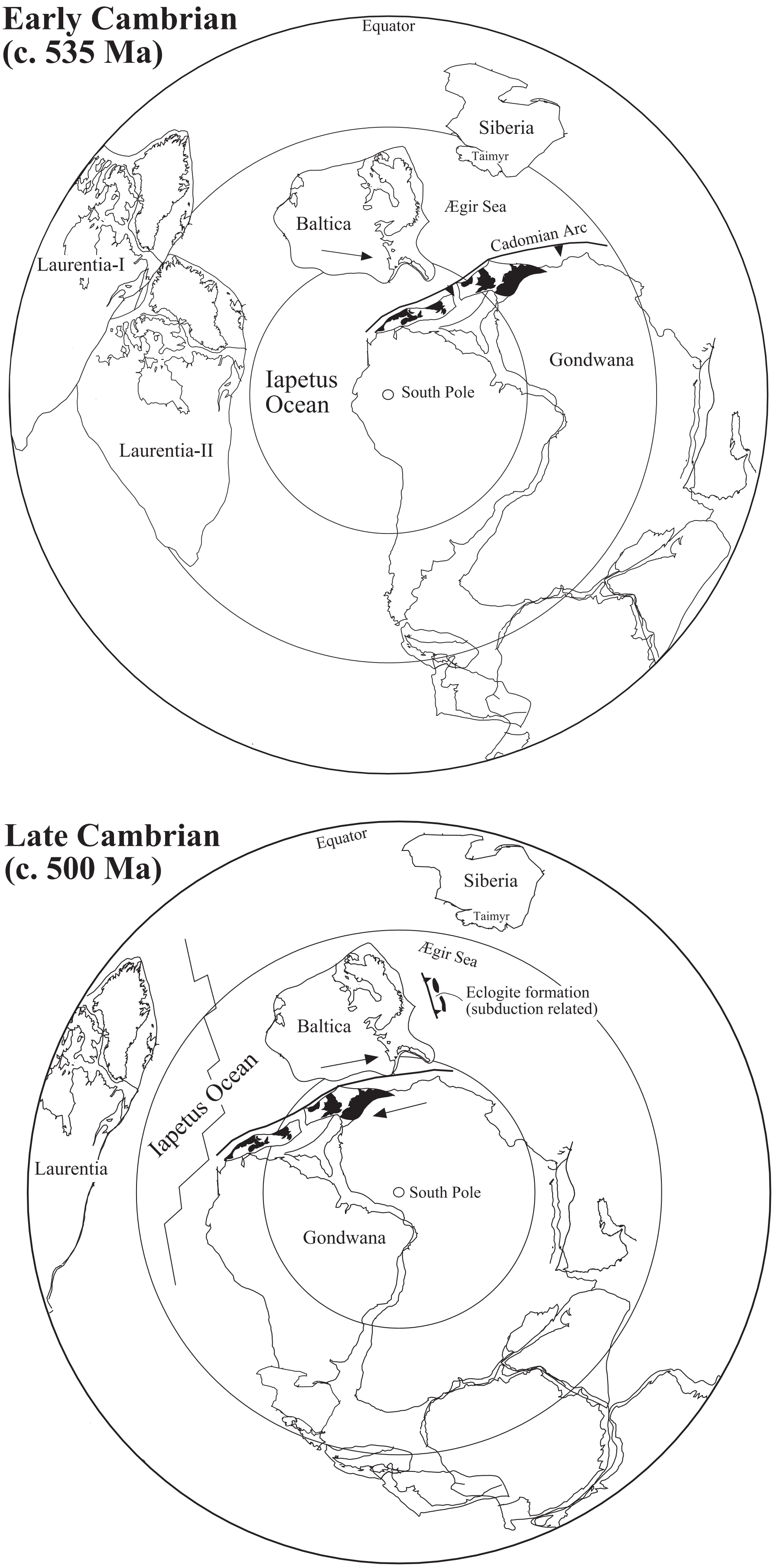

Fig. 8. (**a**) Early Cambrian reconstruction (*c.* 535 Ma). Reconstruction poles: *Laurentia-I*, 1.6°N/345.8°E (APW path, Torsvik *et al.* 1996); *Laurentia-II*, 20°N/320°E (alternative pole based on interpolation of the most reliable Vendian and Late Cambrian poles for Laurentia). The alternative pole implicate a much narrower Iapetus Ocean (see text). *Siberia*, 45.6°N/322.4°E (Kessyusa Fm, Pisarevsky *et al.* 1998); *Gondwana*, −15.1/334.9 (Todd River dolomite, Australia: Kirschvink 1978); *Baltica*, Torneträsk pole (Table 1).

(**b**) Late Cambrian reconstruction. Reconstruction poles: *Laurentia*, 5.7°S/345.2°E (APW path, Torsvik *et al.* 1996); *Siberia*, 38.8°N/299.9°E (mean of Lena and Myero River sediments: Smethurst *et al.* 1998; Gallet & Pavlov 1996); *Gondwana*, 9.6°N/1.5°E (mean of Lake Frome Group combined and Giles Creek dolomite: Klootwijk 1980); *Baltica*, Andrarum pole (Table 1).

Gondwana (Australia) poles listed in African coordinates (Australia to South Africa Euler pole: Lat.=−29.16°, Long.=−57.19° & Rotation angle=54.02°: Lottes & Rowley 1990). Siberia poles listed in south-Siberia co-ordinates (north Siberia block corrected for an Euler pole of Lat.=60°, Long.=100° & Rotation angle=−20°: Smethurst *et al.* 1998). Gondwana reconstruction fits after Lottes & Rowley (1990) except Florida (Lawver & Scotese 1987). Avalonia fitted in a possible tight fit with NW Gondwana.

APW paths for Baltica. We notice that the SIP pole plots in the Late Cambrian–Tremadoc 'gap' (Fig. 6), and thus probably records Early Ordovician post-metamorphic Finnmarkian uplift along the northwest margin of Baltica as originally advocated by Torsvik *et al.* (1990).

Cambrian palaeogeography

Cambrian reconstructions (Fig. 8) highlight the positions of Laurentia, Baltica, Siberia and Gondwana. Specific uncertainty surrounds the Early Cambrian position of Laurentia (Fig. 8a). Vendian (577–564 Ma) poles demonstrate that Laurentia was in high southerly latitudes and probably in the vicinity of South America (Amazon craton) and Baltica (Meert & Van der Voo 1994; Torsvik *et al.* 1996; Meert *et al.* 1998; McCausland & Hodych 1998; Meert 1999). Mid–Late Cambrian poles show that Laurentia had drifted into low latitudes (Fig. 8b), but the timing of this high-to-low latitudinal drift has been the subject of debate. Poles of proposed Early Cambrian magnetization ages suggest that it took place rapidly in latest Vendian times (Torsvik *et al.* 1996), but some of these poles are of questionable reliability. A palaeomagnetic result from the 550 Ma Skinner Cove volcanics (allochthonous) in Newfoundland (McCausland & Hodych 1998) may support a low latitude position of Laurentia during the Early Cambrian (Laurentia-I in Fig. 8a), but it is as yet uncertain if the Skinner Cove palaeolatitude estimate is representative for Laurentia. The most reliable palaeomagnetic poles for Laurentia implicate that the opening of the southern Iapetus Ocean is pre-564 and post-508 Ma. If we interpolate between the most reliable Vendian and Mid to Late Cambrian poles, Laurentia would plot in higher southerly latitudes (Laurentia-II in Fig. 8a), thereby reducing the width of the Iapetus Ocean and drift rates for Laurentia.

Both Baltica and Siberia were geographically inverted and separated by the Ægir Sea in the Early Cambrian. Siberia was located in low latitudes, and the present Taimyr region was located at *c.* 30°S. Gondwana stretched from the south-pole (Amazonia) to equatorial latitudes, and Avalonia and the European Massifs (not shown in diagrams) fringed the high-latitude South American and African part of Gondwana. In Vendian and Early Cambrian times, Avalonia and the European Massifs were situated along the active Cadomian margin of Gondwana. The Cadomian orogen records the vestiges of volcanic arc systems formed by subduction beneath the northern margin of Gondwana in late Precambrian and Early Cambrian times (Nance & Thompson 1996).

Northern Baltica (Fig. 7a) was also an active convergent margin during parts of the Vendian, and this Baikalian event is broadly contemporaneous with the Cadomian (Roberts 2000). In the Early Ordovician it is customary to place Baltica east of Avalonia and the European Massifs (e.g. Torsvik & Trench 1991), but this is not permissible in the Early Cambrian given the location of Gondwana. We therefore place Baltica NW of Avalonia and propose that the former Cadomian subduction zone along NW Gondwana developed into a major dextral strike-slip fault during the Cambrian. This position of Baltica in the Early Cambrian has the added attraction of placing the Baikalian margin of Baltica as a conjugate or alternatively, as an extension, to the Gondwana-convergent Cadomian margin in Vendian times (Roberts 2000).

In the Late Cambrian, Laurentia and Siberia occupied southerly latitudes of 30° or less (Fig. 8b). Gondwana still extended from the south pole to the equator, but the south pole had shifted to NW Africa, and Gondwana covered almost the entire polar region above 60°S. This configuration results in a tight fit with Baltica which occupied high southerly latitudes throughout the Cambrian. Western Baltica (Scandinavian Caledonide margin) was a passive margin during Vendian and Early–Mid-Cambrian times, and the orogenic history of the Scandinavian Caledonides began with Finnmarkian Late Cambrian/Early Ordovician subduction, eclogite formation and possible imbrication and obduction of ophiolites across the former passive continental margin (Sturt & Roberts 1991; Andréasson 1994; Andreasson & Albrecht 1995; Sturt & Ramsay 1999). Evidence of subduction is seen in eclogites that formed at *c.* 19 kbar and 700°C (Santallier 1988) by high-pressure (HP) metamorphism of dolerites and pillow lavas (Kullerud *et al.* 1990; Andréasson *et al.* 1985; Essex *et al.* 1997). Sm–Nd isochron (503 ± 14 & 505 ± 18 Ma; Mørk *et al.* 1988) and U–Pb titanite ages (500–475 Ma; Essex *et al.* 1997; Gromet *et al.* 1996) have been interpreted as the age of eclogite-facies metamorphism. Deep subduction (>50 km) at 500–505 Ma indicates that subduction began at *c.* 515–520 Ma. Subduction-related eclogites are now preserved in the Seve Nappe Complex (North Scandinavian Caledonides), but the geographical location and nature of this Late Cambrian–Early Ordovician subduction zone and imbrication story is uncertain. Baltica was probably a 'conjugate' margin to northern Siberia (Taimyr Peninsula) in Cambrian (Fig. 8) and Ordovician times (Torsvik *et al.* 1996). Taimyr was a passive margin carbonate platform in Vendian time and throughout most of the Palaeozoic (Inger *et al.* 1999). Subduction must therefore have taken place beneath a microcontinent or an island-arc (Fig. 8b) that later collided with Baltica to produce the early Caledonian Finnmarkian orogeny. Baltica underwent 55° counter-clockwise rotation between *c.* 500 and 480 Ma, which we link with the Finnmarkian orogeny. Due to the geographically overturned position of Baltica throughout Vendian to Mid-Ordovician times, Western Baltica faced Siberia rather than Laurentia. We suggest that the ocean between Baltica, Siberia and NW Gondwana (Fig. 8) is named the Ægir Sea (Ægir was the God of Oceans in Nordic mythology) and that the Iapetus Ocean during the Vendian and Cambrian marks the ocean between Laurentia–Eastern Baltica and Laurentia–West Gondwana (South America).

This paper is dedicated to the memory and appreciation of our close friend Brian A. Sturt. Brian devoted his life to many of the issues discussed in this paper and he made outstanding contributions to our understanding of the Scandinavian Caledonides. We thank Brian along with David Roberts, Elizabeth A. Eide, Ian Dalziel and Conall Mac Niocaill for valuable comments. VISTA, NFR and NGU are acknowledged for financial support.

References

Ahlberg, P. 1998. *Guide to excursions in Scania and Västergötland, Southern Sweden*. Lund Publications in geology, **141**.

Andréasson, P.G. 1994. The Baltoscandian margin in Neoproterozoic-early Palaeozoic times; some constraints on terrane derivation and accretion in the Arctic Scandinavian Caledonides. *Tectonophysics*, **231**, 1–32.

Andréasson, P.G. & Albrecht, L. 1995. Derivation of 500-Ma eclogites from the passive margin of Baltica and a note on the tectonometamorphic heterogeneity of eclogite-bearing crust. *Geological Magazine*, **132**, 729–738.

Andréasson, P.G., Gee, D.G. & Sukotji, S. 1985. Seve eclogites in the Norrbotten Caledonides. *In:* Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen—Scandinavia and Related Areas*. John Wiley & Sons, Chichester, 887–901.

Bergström, J. & Ahlberg, P. 1981. Uppermost Lower Cambrian biostratigraphy in Scania, Sweden. *Geologiska Föreningen Förhandlingar*, **103**, 193–214.

Bowring, S.A. & Erwin, D.H. 1998. A new look at evolutionary rates in deep time: Uniting paleontology and high-precision geochronology. *Geological Society America Today*, **8**(9), 1–8.

Buchardt, B., Nielsen, A.T. & Schovsbo, N.H. 1997. Alun skiferen i Skandinavia. *Geologisk Tidsskrift*, **3**, 1–30.

Bylund, G. 1993. Palaeomagnetism of Vendian-Early Cambrian sedimentary rocks from E Finnmark, Norway. *Tectonophysics*, **231**, 45–57.

Essex, R.M., Gromet, L.P., Andreasson, P.G. & Albrecht, L. 1997. Early Ordovician U-Pb metamorphic ages of the eclogite-bearing Seve Nappes, northern Scandinavian Caledonides. *Journal of Metamorphic Geology*, **15**, 665–676.

Gee, D.G. 1972. *The regional geological context of the Tsjö uranium project, Caledonian Front, Central Sweden*. Sveriges Geologiska Undersökring, Serie C, **671**.

Gallet, Y. & Pavlov, V.E. 1996. Magnetostratigraphy of the Moyero river section (north-western Siberia): constraints on geomagnetic reversal frequency during the Early Palaeozoic. *Geophysical Journal International*, **125**, 95–105.

Gromet, L.P., Sjöström, H., Bergman, S., Claesson, S., Essex, R.M., Andreasson, P.G. & Albrecht, L. 1996. Constratsin ages of metamorphism in the Seve nappes: U-Pb results from the central and northern Swedish Caledonides. *Geologiska Föreningen Förhandlingar*, **118**, 36–38.

Henningsmoen, G. 1957. *The trilobite family Olenidae, with description of Norwegian material and remarks on the Olenid and Tremadocian Series*. Norsk Vidensskaps Akademi Skrifter, Matematisk-Naturvidenskaplige Klasse, **1**.

Inger, S., Scott, R.A. & Golionko, B.G. 1999. Special paper: Tectonic evolution of the Taimyr Peninsula, northern Russia: implications for Arctic continental assembly. *Journal Geological Society, London*, **156**, 1069–1072.

Jensen, S. & Grant, W.F. 1998. Trace fossils from the Dividal Group, northern Sweden: implications for Early Cambrian biostratigraphy of Baltica. *Norsk Geologisk Tidsskrift*, **78**, 305–317.

Kirschvink, J.L. 1978. The Precambrian Cambrian boundary problem: palaeomagnetic directions from the Amadeus Basin, central Australia. *Earth and Planetary Science Letters*, **40**, 91–100.

Kirschvink, J.L., Ripperdan, R.L. & Evans, D.A. 1997. Evidence for a large-scale reorganization of Early Cambrian continental landmasses by inertial interchange true polar wander. *Science*, **277**, 541–545.

Klootwijk, C.T. 1980. Early Palaeozoic palaeomagnetism in Australia. *Tectonophysics*, **64**, 249–332.

Kullerud, K., Zachrisson, E. & Stephens, M.B. 1990. Pillow lavas as protoliths for eclogites: evidence from a late Precambrian-Cambrian continental margin, Seve Nappes, Scandinavian Caledonides. *Contributions to Mineralogy and Petrology*, **105**, 1–10.

Kulling, O. 1964. *Översikt över Norra Norrbottensfjällens Kaledonberggrund*. Sveriges Geologiska Undersökring, Serie Ba, **19**.

Lawver, L. & Scotese, C.R. 1987. A revised reconstruction of Gondwanaland. *In:* McKenzie, G.D. (ed.) *Gondwana Six:Structure, Tectonics, and Geophysics*. American Geophysical Union. Geophysical Monograph, **40**, 17–23.

Lindström, M. 1960. On some sedimentary and tectonic structures in the Ludlovian Colonus Shale of Scania. *Geologiske Föreningen Förhandlinger*, **82**, 319–341.

Lottes, A.L. & Rowley, D.B. 1989. Reconstruction of the Laurasian and Gondwana segments of Permian Pangaea. *In:* McKerrow, W.S. & Scotese, C.R. (eds) *Palaeozoic Palaeogeography and Biogeography*. Geological Society, London. Memoirs, **12**, 383–395.

McCausland, P.J.A. & Hodych, J.P. 1998. Palaeomagnetism of the 550 Ma Skinner Cove volcanics of western Newfoundland and the opening of the Iapetus Ocean. *Earth and Planetary Science Letters*, **163**, 15–19.

Meert, J.G. 1999. A palaeomagnetic analysis of Cambrian true polar wander. *Earth and Planetary Science Letters*, **168**, 131–144.

Meert, J.G. & Van der Voo, R. 1994. Palaeomagnetism of the Catoctin volcanic province: a new Vendian-Cambrian apparent polar wander path for North America. *Journal Geophysical Research*, **88**, 4625–4641.

Meert, J.G., Torsvik, T.H., Eide, E.A. & Dahlgren, S. 1998. Tectonic significance of the Fen Province, S. Norway: Constraints from Geochronology and Palaeomagnetism. *Journal of Geology*, **106**, 553–564.

Mørk, M.B.E., Kullerud, K. & Stabel, A. 1988. Sm-Nd dating of Seve eclogites, Norrbotten, Sweden—evidence for early Caledonian (505 Ma) subduction. *Contributions to Minearology and Petrology*, **99**, 344–351.

Nance, R.D. & Thompson, M.D. 1996. Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic: An introduction. *In:* Nance, R.D. & Thompson, M.D. (eds) *Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic*. Geological Society of America Special Papers, **304**, 333–335.

Olovyanishnikov, V.G., Siedlecka, A. & Roberts, D. 1997. Aspects of the geology of the Timans, Russia, and linkages with Varanger Peninsula, NE Norway. *Norges Geologiske Undersøkelse Bulletin*, **433**, 28–29.

Pisarevsky, S.A., Gurevich, E.L. & Khramov, A.N. 1998. Palaeomagnetism of Lower Cambrian sediments from the Olenek River section (northern Siberia): palaeopoles and the problem of magnetic polarity in the Early Cambrian. *Geophysical Journal International*, **125**, 95–105.

Roberts, D. 2000. The Baikalian Timanides of NW Russia/NE Norway and linkages with the peri-Gondwanan Cadomian-Avalonian orogenic belt (abstract). *Geonytt*, **1**, 145–146.

Santallier, D. 1988. Mineralogy and crystallization of the Seve eclogites in the Vuoggatjålme area, Swedish Caledonides of Norrbotten. *Geologiska Föreningen Förhandlingar*, **110**, 89–98.

Smethurst, M.A., Khramov, A. & Torsvik, T.H. 1998. The Neoproterozoic and Palaeozoic palaeomagnetic data for the Siberian Platform: From Rodinia to Pangea. *Earth Science Reviews*, **43**, 1–24.

Stephens, M.B. & Gee, D.G. 1989. Terranes and polyphase accretionary history in the Scandinavian Caledonides. *In:* Dallmeyer, R.D. (ed.) *Terranes in the Circum-Atlantic Palaeotoic orogens*. Geological Society of America Special Papers, **230**, 17–30.

Sturt, B.A. & Roberts, D. 1991. Tectonostratigraphic relationships and obduction histories of Scandinavian ophiolitic terranes. *In:* Peters, T. *et al.* (ed.) *Ophiolite genesis and evolution of the Oceanic lithossphere*. Ministry of Petroleum and Minerals, Sultanate of Oman, 745–769.

Sturt, B.A. & Ramsay, D.M. 1999. Early Ordovician terrane-linkages between oceanic and continental terranes in the central Caledonides. *Terra Nova*, **11**, 79–85.

Thelander, T. 1982. *The Torneträsk Formation of the Dividal Group Northern Swedish Caledonides*. Sveriges Geologiska Undersökring, Serie C, **789**.

Torsvik, T.H. 1998. Palaeozoic palaeogeography: A North Atlantic viewpoint. *Geologiske Foreningen Förhandlinger*, **120**, 109–118.

Torsvik, T.H. & Rehnström, E.F. 2001. The Tornquist Sea and Baltica–Avalonia docking. *Tectonophysics*, in press.

Torsvik, T.H. & Trench, A. 1991. Short Paper: The Ordovician history of the Iapetus Ocean in Britain: New palaeomagnetic constraints. *Journal Geological Society London*, **148**, 423–425.

Torsvik, T.H., Olesen, O., Ryan, P.D. & Trench, A. 1990. On the palaeogeography of Baltica during the Palaeozoic: New palaeomagnetic data from the Scandinavian Caledonides. *Geophysical Journal International*, **103**, 261–279.

Torsvik, T.H., Roberts, D. & Siedlecka, A. 1995. Riphean and Vendian palaeomagnetic data from Northwest Russia and Northern Norway—A Review. *Norges Geologiske Undersøkelse Special Publications*, **7**, 315–326.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A. & Walderhaug, H.J. 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic: A tale of Baltica and Laurentia. *Earth Science Reviews*, **40**, 229–258.

Torsvik, T.H., Meert, J.G. & Smerthurst, M.A. 1998. Technical comment: Polar Wander and the Cambrian. *Science*, **279**, 9a.

Tucker, R.D. & McKerrow, W.S. 1995. Early Palaeozoic chronology: a review in light of new U-Pb zircon ages from Newfoundland and Britain. *Canadian Journal of Earth Sciences*, **32**, 368–379.

Vidal, G., Moczydlowska, M. & Rudavskaya, V.R. 1995. Constraints on the early Cambrian radiation and correlation of the Tommotian and Nemakit-Daldynian regional stages of eastern Siberia. *Journal Geological Society London*, **152**, 499–510.

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