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Was Baltica right-way-up or upside-down in the Neoproterozoic?

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Abstract: Baltica is a progeny of Rodinia, born from the breakup of the supercontinent in the Neoproterozoic. Within Rodinia, Baltica is generally placed adjacent to NE Laurentia but in a variety of configurations, which vary by up to 3000 km along the strike of the Laurentian margin and include both right-way-up and upside-down orientations (current coordinates). Geological and palaeomagnetic data show that the only viable reconstruction juxtaposes the western Scandinavian margin of Baltica, in its right-way-up orientation, against the Rockall–Scotland–SE Greenland segment of Laurentia.

The supercontinent Rodinia was assembled along a series of end-Mesoproterozoic orogenic belts and broke apart about Neoproterozoic rift zones (e.g. Hoffman 1991; Dalziel 1997). Laurentia is the keystone at the centre of the supercontinent but the position of the various blocks that formed its encircling conjugate margins is uncertain (e.g. Hoffman 1991; Dalziel 1997; Wingate *et al*. 2002; Pisarevsky *et al*. 2003). Establishing the position of any of these enclosing blocks is crucial in constraining Rodinian palaeogeography, as changes in the history of one segment of the margin must be accommodated by rearrangements and refinement in the positions of the other blocks. In this paper we outline geological and palaeomagnetic constraints on the orientation and position of Baltica within its Neoproterozoic Rodinian progenitor.

Reconstructing Baltica

Opening the Iapetus Ocean marks the final breakup of Rodinia and involved, according to most models, the rifting of east Laurentia from the conjugate margins of Baltica in the north and Amazonia in the south (current coordinates; Cawood *et al*. 2001). A variety of relative and absolute positions and orientations have been proposed for these blocks (Fig. 1).

In most Neoproterozoic reconstructions, western Baltica is placed in its current orientation (right way up) against NE Laurentia in a variety of positions that vary up to 3000 km along strike (Dalziel 1992; Weil *et al*. 1998; Cawood *et al*. 2003; Pisarevsky *et al*. 2003). In the reconstruction of Cawood *et al*. (2003), the northwestern margin of Baltica lies adjacent to eastern Greenland and results in an overall linear trend for Mesoproterozoic and older belts such as the Sveconorwegian and Grenville (Fig. 1a). This reconstruction was based in part on pre-Grenvillian (roughly pre-1000 Ma) palaeomagnetic data (e.g. Buchan *et al*. 2000) integrated with a comparison of pre-Neoproterozoic crustal blocks and orogenic belts (Gower *et al*. 1990; Åhall & Connelly 1998). Similar reconstructions have been proposed for the Mesoproterozoic (e.g. Gower *et al*. 1990; Karlstrom *et al*. 2001). The reconstruction of Pisarevsky *et al*. (2003; see also Hoffman 1991; Park 1992; Weil *et al*. 1998), involving western Scandinavia against the Rockall–Scotland–SE Greenland segment of Laurentia (Fig. 1b), results in a sharp bend in the trend of the Grenville–Sveconorwegian orogen and is based on the superposition of early Neoproterozoic-aged loops in the Grenville and Sveconorwegian apparent polar wander paths (see Stearn & Piper 1984). In the reconstructions of Dalziel (1992, 1994, 1997), the position of Baltica with respect to Laurentia is constrained by the position of Amazonia (Fig. 1c and d). Dalziel argued that the Scottish promontory of Laurentia lay within the ancestral Arequipa embayment of South America, which was included within the western margin of Amazonia. Proposed geological similarities between the two regions, including the presence of Neoproterozoic glacial deposits, were cited as further support for this set of reconstructions.

Hartz & Torsvik (2002) proposed a reconstruction in which Baltica was inverted from its standard right-side-up position (Fig. 1e) with the Uralian margin of Baltica adjacent to the east Greenland segment of Laurentia prior to opening of the Iapetus Ocean. They argued that this model was plausible on the basis of available geological data and importantly removed the need for 180° rotation of Baltica after Iapetus opening (Torsvik *et al*. 1996; Meert *et al*. 1998; Torsvik & Rehnström 2001; Siedlecka *et al*. 2004; see also Cocks & Torsvik 2005).

Validating Baltica–Laurentia reconstructions

Although the reconstructions outlined in Figure 1 are nominally based on palaeomagnetic and/or geological constraints, only one can be correct. Each reconstruction has predictable consequences with respect to available data against which they can be validated. In particular, the upside-down and the various right-way-up reconstructions have distinct palaeogeographical implications for the Neoproterozoic margins of Baltica that must also be compatible with the history of the conjugate NE Laurentian margin.

Geological constraints

Both the eastern Uralian and northeastern Timanide margins of Baltica (Fig. 2) record a initial history of Mesoproterozoic intracratonic extension and rift-related sedimentation and magmatism followed by, in the latest Mesoproterozoic to early Neoproterozoic, development of a passive-margin succession containing cratonic-derived siliciclastic sediments (Nikishin *et al*. 1996; Maslov *et al*. 1997; Maslov & Isherskaya 2002; Siedlecka *et al*. 2004). In the late Neoproterozoic, at *c*. 620 Ma, the Uralian and Timanide margins were inverted during terrane accretion and collision, including the accretion of the Novaya Zemlya microcontinent, which resulted in a change in sediment

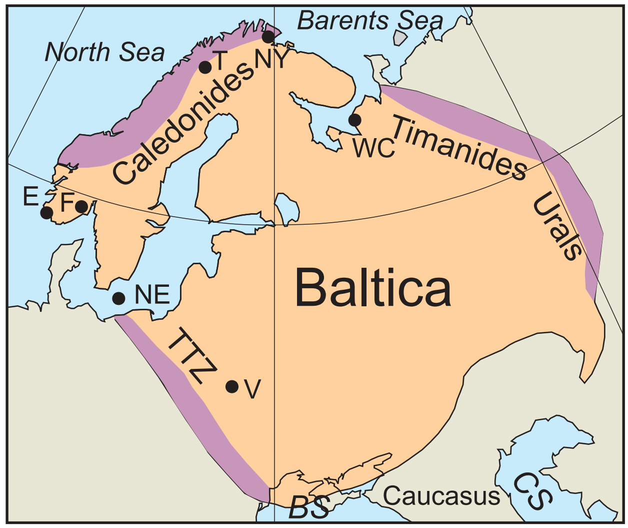

Fig. 2. Simplified map of Baltica showing distributions of the Timanide, Uralian, Scandinavian and Teisseyre–Tornquist Zone (TTZ) margins. Also shown is the location of palaeopoles for Baltica noted in Table 1. E, Egersund; F, Fen Complex; NE, Nekso Sandstone; NY, Nyborg Formation; T, Torneträsk Formation; V, Volhynia lavas and tuffs; WC, Winter Coast, Zolotitsa, Verkhotina; BS, Black Sea; CS, Caspian Sea.

provenance with input from the orogenic hinterland (Willner *et al*. 2001; Maslov & Isherskaya 2002; Roberts & Siedlecka 2002). This convergent regime continued until the end of the Neoproterozoic (Grazhdankin 2004; Larionov *et al*. 2004) and possibly into the early Palaeozoic with obduction of the Enganepe ophiolite at 500 Ma in the Polar Urals (Scarrow *et al*. 2001).

The western Baltoscandian margin, preserved in the lower to upper Caledonian thrust nappes (Fig. 2), records dyke intrusion between 670 and 600 Ma followed by a developing continental-margin sedimentary sequence with the rift-to-drift transition and ocean opening occurring at the end of the Neoproterozoic, around 600–580 Ma (Bingen *et al*. 1998; Greiling *et al*. 1999; Siedlecka *et al*. 2004). It remained an open passive margin until Palaeozoic nappe emplacement. Outcrops of older Neoproterozoic sediments in western Scandinavia are fragmented and generally interpreted to represent non-marine environments (Winchester 1988). Combined with the paucity of strata between *c*. 1000 and 800 Ma (Nystuen & Siedlecka 1988), this is consistent with an intracratonic setting (see Cawood *et al*. 2004).

Unravelling the Neoproterozoic record of the southern margin

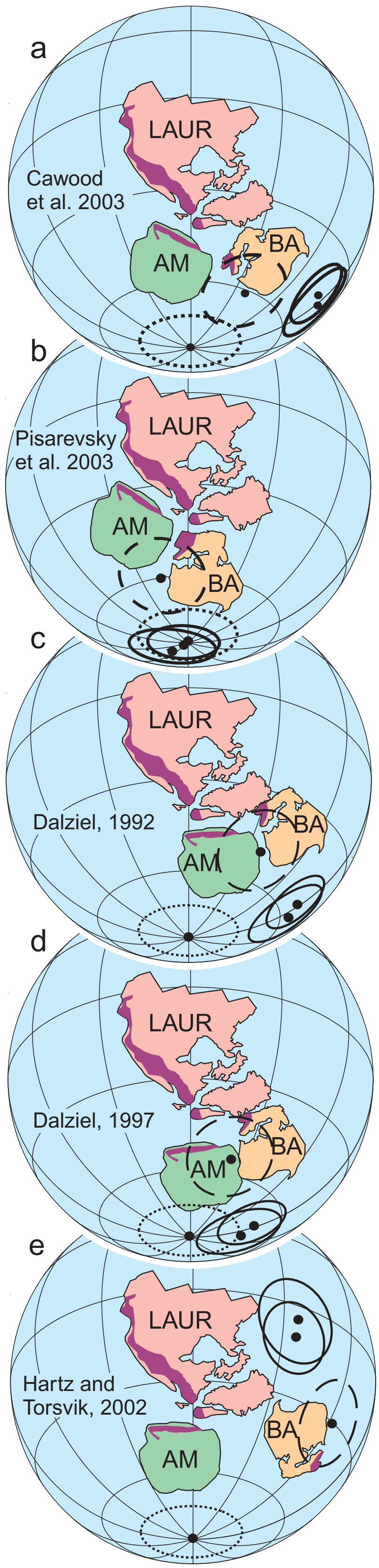

Fig. 1. A selection of late Neoproterozoic reconstructions for the position of Baltica (BA) with respect to Laurentia (LAUR), which is fixed about the pole of Hodych *et al*. (2004), and Amazonia (AM). (**a**) From Cawood *et al*. (2003); (**b**) from Pisarevsky *et al*. (2003) with the East Greenland and Scandinavian Caledonides margins distended to take into account the effect of Palaeozoic orogenic foreshortening (e.g. Winchester 1988); (**c**) from Dalziel (1992); (**d**) from Dalziel (1997); (**e**) from Hartz & Torsvik (2002). Lines of longitude and latitude are in 30° increments. Palaeopoles: dotted-line circle, pole for Laurentia based on Hodych *et al*. (2004); continuous-line circle, poles for Egersund dykes from Storetvedt (1966) and Poorter (1972); dashed-line circle, unpublished pole for Egersund dykes cited by Meert & Torsvik (2003).

of Baltica is hindered by locally intense late Palaeozoic Hercynian–Variscan deformation and a thick sedimentary cover (Pre-Caspian basin; Khain 1985; Lobkovsky *et al*. 1996). However, Lobkovsky *et al*. (1996) noted the possibility of late Precambrian rifting and early Palaeozoic sedimentary deposition in a relatively deep-water environment in the Pre-Caspian area, which is consistent with a passive margin regime (see Nikishin *et al*. 1996). Kostyuchenko *et al*. (2004) marked the area east of the Azov Sea (near Black Sea) as a Riphean passive margin. Rifting and opening of the Tornquist Sea along the southwestern margin of Baltica (Teisseyre–Tornquist Zone, Fig. 2) probably commenced in the late Neoproterozoic, and is indicated by widespread 560–550 Ma magmatism (Compston *et al*. 1995; Nosova *et al*. 2005) and the rift-related basin development (Poprawa *et al*. 1999).

The protracted history of the eastern and northern margins of Baltica, facing an open ocean from the early Neoproterozoic, which converted to an accretionary margin at the end of the Neoproterozoic, is incompatible with the juxtaposition of these regions against northeastern Laurentia, as portrayed in the reconstructions of Hartz & Torsvik (2002) and Cawood *et al*. (2003). The east Laurentian margin records a history of Neoproterozoic rift-related sedimentation and magmatism with development of a passive continental margin succession, at least in the Appalachian segment, not occurring until the early Cambrian at around 530 Ma (Cawood *et al*. 2001).

Only those models in which the Caledonian margin of Baltica is against Laurentia are geologically plausible (Fig. 1b–d). Right-way-up reconstructions are also consistent with the evolution of the southern margin of Baltica abutting Amazonia, prior to rifting and opening of the Tornquist Sea at the end of the Neoproterozoic. We note, however, that in the Scandinavian Caledonides the late Neoproterozoic age of the rift-to-drift transition appears to be earlier than along the East Laurentian conjugate. Cawood *et al*. (2001) proposed that the East Laurentian margin may preserve a multistage rift history with initial separation from Baltica by 570 Ma followed by the rifting off of Amazonia before 550 Ma, and finally by separation of micro-continental ribbons, which resulted in the preserved, younger Cambrian rift-to-drift transition.

Recently Dalziel and coworkers (e.g. Loewy *et al*. 2003) have argued against his earlier reconstructions (Fig. 1c and d), partly on the basis of Pb-isotopic data, which suggest that Amazonia lay off the central to southern Appalachians, and hence Baltica is no longer constrained by this block to a northerly location against Laurentia. Furthermore, palaeomagnetic and geological data for Late Mesoproterozoic rock units from Amazonia (Tohver *et al*. 2002, 2004) suggest it may have interacted first with the Llano segment of Laurentia's Grenville margin before being strike-slipped along the margin to lie off the northern to central segment of the Grenville Province in a position similar to that depicted in Figure 1b.

Palaeomagnetic constraints

Reliable late Neoproterozoic to early Palaeozoic palaeomagnetic data provide constraints on the position and orientation of Baltica and on its position relative to Laurentia, and complement the geological data (Table 1). In particular, the presence of time-equivalent late Neoproterozoic palaeomagnetic data from both Laurentia and Baltica allows a direct comparison of their position and orientation.

Murthy *et al*. (1992) obtained palaeomagnetic data from six dykes of the *c*. 615 Ma Long Range swarm in Labrador. Three yielded a coherent direction for the remanence with a palaeopole at 11°N, 334°E, whereas the other three gave different and

Table 1. *Late Neoproterozoic and Early Cambrian palaeomagnetic poles from Laurentia and Baltica*

Object	Pole (°N)	Pole (°E)	dp/dm (deg.)	*Q*	Age (Ma)	References
Baltica						
Nyborg Formation, Norway	−25	269	17/25	4	630–560	Torsvik *et al*. (1995); Gorokhov *et al*. (2001)
Egersund dykes, Norway	−28	232	15/18	3	616 ± 3	Storetvedt (1966); Bingen *et al*. (1998)
Egersund dykes, Norway	−22	231	16/21	4	616 ± 3	Poorter (1972); Bingen *et al*. (1998)
Fen Complex, Norway	−56	330	7/10	4	583 ± 15	Meert *et al*. (1998)
Winter Coast sediments, Russia	25	312	2/4	6	555.3 ± 0.3	Martin *et al*. (2000); Popov *et al*. (2002)
Zolotitsa sediments, Russia	32	293	2/3	6	550 ± 5	Popov *et al*. (2005)
Verkhotina sediments, Russia	32	287	2/3	5	550 ± 1	Popov *et al*. (2005)
Zolotitsa sediments, Russia	28	290	4/4	6	550 ± 5	Iglesia Llanos *et al*. (2005)
Volhynia lavas and tuffs, Russia	34	306	–	4	551 ± 4	Compston *et al*. (1995); Nawrocki *et al*. (2004)
Nekso Sandstone, Denmark	−40	357	4/7	–	545–530	Lewandowski & Abrahamsen (2003)
Torneträsk Formation, Sweden	56	296	12/15	4	545–520	Torsvik & Rehnström (2001)
Laurentia						
Long Range dykes (5 dykes)	19	355	15/21	5	615 ± 2	Murthy *et al*. (1992); Kamo & Gower (1994)
Cloud Mountain basalt	−5	352	2/4	3	605 ± 10	Stukas & Reynolds (1974); Deutsch & Rao (1977)
Callander Complex	46	301	6/6	5	575 ± 5	Symons & Chiasson (1991)
Catoctin volcanics A	43	308	9/9	5	564 ± 9	Meert *et al*. (1994); Aleinikoff *et al*. (1995)
Catoctin volcanics B	4	13	10/10	5	564 ± 9	Meert *et al*. (1994); Aleinikoff *et al*. (1995)
Sept Iles intrusion A	−20	321	5/9	5	565 ± 4	Tanczyk *et al*. (1987); Higgins & van Breemen (1998)
Sept Iles dykes B	59	296	10/10	4	<565 ± 4	Tanczyk *et al*. (1987); Higgins & van Breemen (1998)
Buckingham lavas	10	341	7/10	4	573 ± 32	Dankers & Lapointe (1981)
Johnnie Formation	10	342	5/10	4	570 ± 10	Van Alstine & Gillett (1979); Hodych *et al*. (2004)
Skinner Cove Formation	−15	337	9/9	4	550 ± 3	McCausland & Hodych (1998); Cawood *et al*. (2001)

Q is the quality factor after Van der Voo (1990) and ranges from zero to seven, with the later representing the highest-quality data. Volhynia lavas and tuffs are mean of two poles. Nekso Sandstone result is calculated by non-traditional methods and cannot be assessed by Q factor. Long Range Dykes were recalculated by Hodych *et al*. (2004). dp/dm: semi-axes of the 95% cone of confidence about the mean pole.

divergent directions that those workers considered to be anomalous. Hodych *et al*. (2004) have recently reinterpreted these data, arguing that if two of these anomalous directions are inverted and integrated with the original three coherent dykes, the mean direction has relatively low scatter that can be explained by secular variations of the geomagnetic field about a pole at 19°N, 355°E (Table 1). Palaeomagnetic data from probable extrusive equivalents of the Long Range dykes (Cloud Mountain basalts of Lighthouse Cove Formation) reveal a similar pole at 5°S, 352°E but with a lower reliability index (Deutsch & Rao 1977).

Two palaeomagnetic studies of the *c*. 616 Ma Egersund dykes (Bingen *et al*. 1998) have yielded pole locations at 28°S, 232°E (Storetvedt 1966) and 22°S, 231°E (Poorter 1972). Figure 1 shows the location of the Long Range and Egersund poles with respect to the various Baltica–Laurentia reconstructions. Only in the Dalziel (1992, 1997) and Pisarevsky *et al*. (2003) reconstructions do the poles overlap within error. Meert & Torsvik (2003) cited a new pole for the Egersund dykes at 48°S, 200°E that is similar to, but does not overlap, the two previous results for the dykes (Fig. 1). This pole is based on unpublished data and its reliability is not known.

The upside-down orientation of Baltica originally proposed by Torsvik *et al*. (1996, and references therein) was based on palaeomagnetic data for inferred Neoproterozoic dykes in northern Russia (Sredni Peninsula) and northern Norway (Varanger Peninsula) south of the Trollfjorden–Komagelva Fault Zone. However, Guise & Roberts (2002) have shown that the Norwegian dyke is of Devonian age and Popov *et al*. (2002) noted the similarity of the palaeomagnetic pole to those for Baltica in the Jurassic (e.g. Smethurst *et al*. 1998; McElhinny & McFadden 2000), suggesting remagnetization. The age of the Russian dyke is also uncertain (Shipunov 1988; Shipunov & Chumakov 1991). In the upside-down Baltica reconstruction, Laurentia is placed in a high-latitude position at 615 Ma based on selective use (see also Meert *et al*. 1994) of just one of the six dykes originally studied by Murthy *et al*. (1992, dyke 1). Justification for the use of this single dyke was that it was the only one to be precisely dated (Meert *et al*. 1994). However, Kamo & Gower (1994) subsequently obtained a U–Pb baddeleyite and zircon age of 615 Ma from dyke 4 of Murthy *et al*. (1992). The integrated pole proposed by Hodych *et al*. (2004) incorporates two polarities, suggesting it is a better approximation of the true pole than those calculated from either just three unipolar dykes (Murthy *et al*. 1992) or one dyke (Meert *et al*. 1994; Torsvik *et al*. 1996).

Only if the pole calculated from the single Long Range dyke (dyke 1) is combined with the unpublished pole for the Egersund dykes reported by Meert & Torsvik (2003), is it possible to have a high-latitude upside-down Baltica and Laurentia reconstruction that is palaeomagnetically viable (Fig. 3a). However, it is crucial to note that this solution is not unique and a right-way-up Baltica adjoining Laurentia is equally viable even within this restricted and selective dataset (Fig. 3b).

Laurentian poles with ages between *c*. 600 and 560 Ma form two groups of roughly similar reliability (Table 1): one supports a low-latitude position of Laurentia, and the other supports a high-latitude position (Pisarevsky *et al*. 2000; Meert & Van der Voo 2001; Pisarevsky *et al*. 2001). If all these late Neoproterozoic palaeopoles are primary and their ages are correctly assigned, then they are difficult to explain through normal plate tectonic mechanisms, and processes such as true polar wander or a more rapid style of plate tectonics may need to be invoked (e.g. Evans 2003). An alternative explanation is that some of these data are not correct, being either the result of remagnetization or incorrect deciphering of the palaeomagnetic signal (e.g. Meert & Van der Voo 2001; Hodych *et al*. 2004).

A reliable palaeomagnetic pole for Baltica at the end of the Neoproterozoic is currently limited to the 583 ± 15 Ma Fen Carbonatite Complex of southern Norway, which has a mean pole of 56.0°S, 330.0°E (Table 1). Meert *et al*. (1998) urged caution in interpreting the pole as primary until confirmed by additional data, because of its similarity to Permian–Triassic poles for Baltica. However, applying this pole in a Baltica upside-down orientation and comparing it with the high-latitude component of the time-equivalent Laurentian data (Meert *et al*. 1998, fig. 5) implies that the northern Iapetus Ocean had started to open by this time. Similarly, if Baltica is placed in its right-way-up orientation based on the Fen pole and Laurentia is constrained to a low-latitude position then some separation between the two blocks is also required.

Torsvik *et al*. (1995) determined a palaeomagnetic pole of 24.3°S, 268.5°E from the Nyborg Formation (Table 1), an interglacial unit associated with the Varangian glaciation in northern Norway. They used a Rb–Sr whole-rock date of 653 ± 7 Ma, recalculated from Pringle (1973), as the age for the pole but this is not considered to be reliable (Harland 1997). Gorokhov *et al*. (2001) carried out a new Rb–Sr study on clay fractions from the Stangenes (pre-glacial), Nyborg (interglacial) and Stappogiedde (post-glacial) formations. They concluded that the time range of the Varangian glacial horizons is between 630 and 560 Ma and this provides a probable time range for age of the palaeopole. Recently, Bingen *et al*. (2005) have established that the Moelv Tillite, generally correlated with the Varangian glacial horizons, must be younger than 620 ± 14 Ma based of the age of the youngest detrital zircons from a clastic sediment underlying the glacial horizons. The Nyborg pole indicates a low- to mid-latitude position (33°) for Baltica but its broad age range prevents detailed comparison with data from Laurentia. Svenningsen (1994) noted that evaporitic dolomites are widespread in the Scandinavian Caledonides below the hiatus under the Varanger tillites. This lithology is indicative of low to moderate palaeolatitudes based on comparison with modern subtropical evaporites.

Popov *et al*. (2002) recently reported a high-quality palaeopole of 25.3°N, 312.2°E from the late Neoproterozoic strata from the Winter Coast, White Sea region, Russia (Table 1). This section is marked by the occurrence of Ediacara fauna (Fedonkin 1981) and dated at 555.3 ± 0.3 Ma by a U–Pb zircon age on volcanic ash layers interstratified with the sediments (Martin *et al*. 2000). The primary nature of their Z remanence component is supported by reversal, stratigraphic and consistency tests. Z-type remanence was recently reported from West Ukraine by Nawrocki *et al*. (2004) and from two other locations in the Winter Coast area by Popov *et al*. (2005) (Table 1). A further palaeomagnetic study of the latest Neoproterozoic sequence from the Winter Coast, some 70 km west of the Popov *et al*. (2002) site, revealed a multi-component remanence (Iglesia Llanos *et al*. 2005). The direction of the most stable component is similar to the earlier Winter Coast results. Coherent results from several locations and rock types suggest that the palaeogeographical position of Baltica at 555–550 Ma is very well constrained palaeomagnetically (Table 1).

Palaeomagnetic data from the *c*. 550 Ma Skinner Cove Formation of Laurentia (McCausland & Hodych 1998) allow direct comparison with the time-equivalent Winter Coast data from Baltica. Although the Skinner Cove Formation lies within an

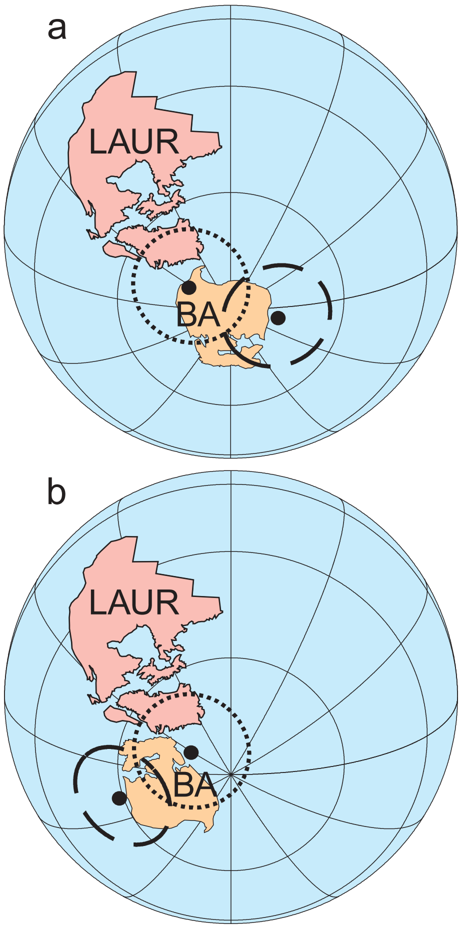

Fig. 3. Permissible positions for Laurentia and Baltica based on the palaeopole from dyke 1 of the Long Range swarm (dotted-line circle; Murthy *et al*. 1992) and an unpublished pole from the Egersund dykes (dashed-line circle) cited by Meert & Torsvik (2003). (**a**) and (**b**) show that both right-way-up and upside-down configurations are possible.

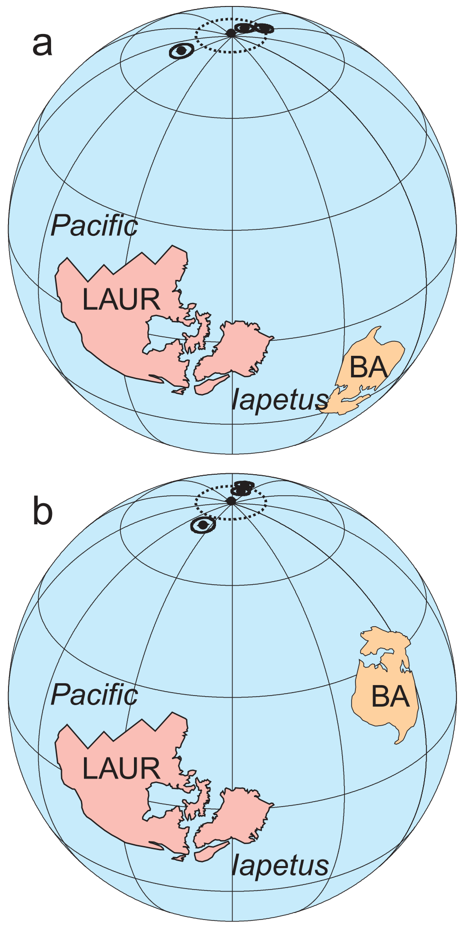

Fig. 4. Reconstructions of Laurentia and Baltica at 550 Ma constrained by palaeomagnetic data from Skinner Cove (dotted-line circle; McCausland & Hodych 1998); Winter Coast (continuous-line circle; Popov *et al*. 2002); Zolotitsa and Verkhotina (continuous-line circle; Popov *et al*. 2005). (**a**) and (**b**) represent two polarity options. An additional pole from the Winter Coast, located some 70 km west of the section sampled by Popov *et al*. (2002) and from a similar late Neoproterozoic stratigraphic sequence also yielded similar results (Iglesia Llanos *et al*. 2005). In both options Baltica is rotated some 90° with respect to its earlier inferred location adjacent to Baltica (compare Fig. 1b and e, respectively). To account for this rotation Baltica is separated from Laurentia through opening of the Iapetus Ocean. The actual width of Iapetus Ocean is not constrained from the palaeomagnetic data (i.e. palaeomagnetic data do not constrain relative latitudinal position of Baltica with respect to Laurentia).

allochthonous thrust sheet (Cawood *et al*. 2001), it still provides an accurate latitudinal constraint for Laurentia (Hodych *et al*. 2004). In either a right-way-up or upside-down configuration, Baltica at 550 Ma has had to rotate *c*. 90° from its position adjoining Laurentia, suggesting that by this time it must have separated from Laurentia (Fig. 4).

Early Cambrian data from Baltica are controversial, as poles of apparently similar ages give different results (e.g. Torsvik & Rehnström 2001; Lewandowski & Abrahamsen 2003). The Torneträsk pole (Torsvik & Rehnström 2001) is probably more reliable, as the presence of both polarities is demonstrated. However, neither of these results has been proven to unequivocally represent a primary remanence and both show similarities to younger parts of the European apparent polar wander path; Permian for the Nekso pole (Lewandowski & Abrahamsen 2003) and Jurassic for the Torneträsk pole (Torsvik & Rehnström 2001). Lewandowski & Abrahamsen (2003) used contoured stereographic plots to deal with scatter within their dataset, preventing the calculation of the palaeomagnetic quality factor (Van der Voo 1990) and limiting the application of the result. There are no coeval reliable counterparts from Laurentia for comparison.

Discussion

Baltica formed during the Neoproterozoic breakup of Rodinia. Available geological and palaeomagnetic data support a right-way-up orientation of Baltica within its Rodinian progenitor, with its western Scandinavia margin aligned along the Rockall–Scotland–SE Greenland segment of Laurentia. In particular, the rift-to-drift history of the Baltoscandian margin is similar to the history of the east Laurentian margin, which is supported by palaeomagnetic data from the time-equivalent *c*. 615 Ma Long Range and Egersund dykes from Laurentia and Baltica, respectively (Storetvedt 1966; Poorter 1972; Hodych *et al*. 2004). This configuration results in a sharp bend in the trend of the

Mesoproterozoic Grenville–Sveconorwegian orogen and is similar to one based on overlapping the loops in the earliest Neoproterozoic Sveconorwegian and Grenville apparent polar wander paths (Weil *et al*. 1998; Pisarevsky *et al*. 2003). The persistence of this configuration during most of Neoproterozoic is in accord with the Rodinia hypothesis. However, the Baltica–Laurentia configuration need not have remained static throughout this period and we note that the east Greenland and Scotland segments of Laurentia show evidence for a series of phases of intracratonic extension followed by compressional deformation between 1000 and 700 Ma requiring some intracratonic movement of these blocks within Rodinia (Cawood *et al*. 2004). The geological and palaeomagnetic data also show that an upside-down orientation for Baltica with respect to Laurentia is not viable.

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