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# Late Neoproterozoic palaeogeography: the Laurentia-Baltica puzzle

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**Abstract:** Palaeomagnetic and geological data constrain a variety of Laurentia-Baltica reconstructions that have been proposed for the late Neoproterozoic. The presence of palaeomagnetic data that suggests both high and low latitude positions for both continents around the end of the Neoproterozoic prevents the development of a single palaeogeographic model and two alternative animated models are presented.

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## Introduction

There is a broad scale agreement on the relative and absolute distribution of continental blocks during the Phanerozoic (e.g., Reeves and de Wit, 2000; Li and Powell, 2001; Torsvik et al., 2001; Stampfli and Borel, G.D., 2002; Muttoni et al., 2003; McElhinny et al., 2003). The long-lived supercontinent Gondwana collided with Laurussia in the Late Carboniferous, and was joined in the Permian by the Siberian craton and blocks of the Central Asia, to form Pangaea. The Mesozoic breakup of Pangaea caused the opening of Atlantic, Indian and Southern Oceans, and the accretion of East Asian cratons and continental fragments led to the amalgamation of Eurasia.

Precambrian reconstructions however, are much more controversial. The wide variety of possible models (e.g., Hoffman, 1991; Dalziel, 1997; Piper, 2000; Hartz and Torsvik, 2002; Pisarevsky et al, 2003; Pesonen et al., 2003) reflects the general poor level of knowledge of Precambrian geological history, as well as the often large time gaps between, and relatively limited number of, reliable palaeomagnetic poles for the major cratons and blocks. The latest Proterozoic and early Cambrian are the most crucial time intervals in further understanding and refining these reconstructions with the lack of data hindering the extrapolation of Gondwana fragments to their precursor configurations within Rodinia. Recent geochronological, palaeomagnetic and geological data, outlined below, has led to some progress in the understanding of latest Neoproterozoic-Cambrian global palaeogeography. Although these data are not yet sufficient to build a rigorous series of unequivocal palaeogeographic reconstructions, they at least permit a qualitative evaluation of those reconstructions which remain viable as well as indicating those which are invalid.

## Neoproterozoic Laurentia-Baltica fits

Opening of the Palaeozoic Iapetus ocean, marking the final breakup of Rodinia, is generally modelled as involving three major continental blocks – Laurentia (including Greenland, Rockall plateau, and blocks of present-day Scotland), Baltica, and Amazonia (e.g. Cawood et al., 2001). However, the reconstruction of the pre-Iapetus configuration of these blocks is debated. In particular, a variety of late Neoproterozoic Laurentia-Baltica reconstructions have been proposed ( Figure 1 ). These include western Scandinavia against the Rockall-Scotland-SE Greenland segment of Laurentia (Figure 1a; e.g., Winchester, 1988; Hoffman, 1991; Park, 1992; Starmer, 1996; Weil et al., 1998; Grelling and Smith, 2000; Pisarevsky et al., 2003), as well as progressively more northern positions (in present-day coordinates) for western Scandinavia with respect to Laurentia (Figs. 1b, 1c). In Figure 1b the position of Baltica was constrained by the northern position of Amazonia with respect to Laurentia, which was suggested on the basis of apparent geological similarities between Neoproterozoic strata of Scotland and the Arequipa massif in South America (Dalziel, 1994, 1997). This suggestion, however, contradicts Palaeozoic palaeomagnetic data (Forsythe et al., 1993). Recently this reconstruction has been dismissed on the basis of comparative isotopic studies between Laurentian and Amazonia (including the Arequipa-Antofalla basement; Loewy et al., 2003, and references their in). Baltica lay in an even more northerly position in the reconstruction of Dalziel (1992; Fig. 1c) but he subsequently (Dalziel, 1997) dismissed this in favour of the inferred geologically constrained reconstruction in Figure 1b. Some Neoproterozoic Laurentia-Baltica reconstructions (e.g., Karlstrom et al., 1999) use the pre-Grenvillian (roughly pre-1000 Ma) fit (Fig. 1d) based on pre-Neoproterozoic palaeomagnetic data (Poorter, 1981; Stearn and Piper, 1984; Buchan et al., 2000; Pesonen et al., 2003) and on the comparison of pre-Neoproterozoic crustal blocks and orogenic belts in both cratons (e.g., Gaal and Gorbatschev, 1987; Winchester, 1988; Gower et al., 1990). In particular, this reconstruction enables an overall linear trend of the Mesoproterozoic Sveconorwegian belt of Baltica with the similarly aged Grenville belt of east Laurentia (Gower et al., 1990). The relevance of this reconstruction to the Neoproterozoic, pre-Iapetian opening continental configurations has been criticised by Larson and Stigh (2000; see also Åhall and Karlstrom, 2000) as it ignores the inferred Mesoproterozoic break-up of Baltica from Laurentia proposed by Park (1992) and Starmer (1996). Hartz and Torsvik (2002) proposed a “Baltica upside down” reconstruction (Fig. 1e) based mainly on the palaeomagnetic data from the Finnmark province of Norway and northern parts of the Kola Peninsula in Russia (see also Torsvik, and Rehnström, 2001). This fit is poorly justified. It contradicts the correlation of the Precambrian crustal blocks and orogens between northeastern Laurentia and western Baltica (e.g., Winchester, 1988; Hoffman, 1989; Gorbatschev and Bogdanova, 1993; Park et al., 1994; Åhall and Connelly, 1998; Gower, 1996; Karlstrom et al., 1999). Furthermore, the absence of any traces of the Grenvillian orogeny along the eastern margin of Baltica, and data from lithostratigraphic and provenance studies in the Urals (e.g. Willner et al., 2003) are also inconsistent with this model. The Uralain margin of Baltica contains evidence for a thick passive margin sedimentary succession of Mesoproterozoic to mid-Neoproterozoic (Riphean) age which changed to an active margin setting in the late Neoproterozoic (ca. 620 Ma, early Vendian; e.g. Nikishin et al., 1996; Willner et al., 2001, 2003; Maslov and Isherskaya, 2002; Puchkov, 2003 and references therein). This data completely refutes the “upside down” model (Fig. 1e) which predicts an intracontinental rift basin setting for the Urals until Iapetian opening at ca. 550 Ma followed by a passive margin setting until at least 500 Ma. In particular, it requires a thick Cambrian passive margin succession, yet, Cambrian deposits are virtually absent in Urals (Maslov et al. 1997 and references therein).

## Recent geochronological and palaeomagnetic constraints

### *Baltica*

Torsvik et al. (1995a) 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. This age was criticised by Harland (1997) and Evans (2000) as not reliable by present standards. 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 of northern Norway. They concluded that the time range of the Vagangian glacial horizons is 630-560 Ma and this provides a conservative estimate of the age of the palaeopole. Recently, Bingen et al (2005), has established that the Moelv Tillite, also part of the Varangian glacials, must be younger than 620 ±14 Ma based of the age of the youngest detrital zircons from a clastic sediment underlying the glacial horizons.

Storetvedt (1966) and Poorter (1972a) studied the 616 ± 3 Ma (Bingen et al., 1998) Egersund dykes from southern Norway, obtaining palaeopoles of 28.0˚S, 232.0˚E and 22.4˚S, 230.8˚E, respectively ( Table 1 ). Eneroth and Svenningsen (2004) studied the Sarek dykes, which have yielded a U-Pb zircon age of 608 ± 1 Ma (Svenningsen, 2001). Although the structural setting of these rocks in the Seve Nappes means that the calculated palaeopole may not be representative for cratonic Baltica, their overall estimation of an equatorial palaeolatitude for Baltica at this time is reasonable. Eneroth and Svenningsen (2004) also argue that the shallow remanence A of the 665 Ma dolerites of the Särv Nappe in southern Sweden may be late Neoproterozoic (Vendian), as the data pass a fold test. Although Bylund and Zellman (1980), the original authors of the Särv Nappe study, interpreted their result as reflecting a Silurian overprint, Bylund (pers. comm., 2004) accepts that the data may be primary and reflect a low-latitudinal position of Baltica in the late Neoproterozoic. A steep inclination in palaeomagnetic data from mafic dykes in the northernmost part of Baltica, in the Sredni Peninsula and in the southern part of the Varanger Peninsula, suggest a high latitude position for Baltica in the Neoproterozoic (Shipunov, 1988; Shipunov and Chumakov, 1991; Torsvik et al., 1995b). However, Guise and Roberts (2002) recently established a 378 ± 2 Ma 40Ar-39Ar plateau age for the one of these dykes (Komagnes dyke). In addition, Popov et al. (2002) mentioned the similarity of Komagnes/Sredni poles to Jurassic poles from Baltica suggesting the younger remagnetisation has potentially affected the region. Thus, the age of the steep magnetisation in the palaeomagnetic data from Sredni and Varanger Peninsulas is uncertain and cannot be used to constrain the Neoproterozoic location of Baltica.

**Table 1. Vendian and Early Cambrian palaeomagnetic poles**

| | Object | Palaeopole ºN | Palaeopole ºE | dp/dm º | P lat º | Q | Age Ma | Reference |
|---|---|---|---|---|---|---|---|---|
| BALTICA | | | | | | | | |
| 1 | Nyborg Form., Norway | -24.3 | 268.5 | 17.1/24.9 | 32.9 | 4 | 630 - 560 | Torsvik et al. 1995b; Gorokhov et al. 2001 |
| 2 | Egersund Dykes, Norway | -28.0 | 232.0 | 15.0/18.0 | 46.0 | 3 | 616 ± 3 | Storetvedt 1966; Bingen et al. 1998 |
| 3 | Egersund Dykes, Norway | -22.4 | 230.8 | 16.4/21.4 | 42.1 | 4 | 616 ± 3 | Poorter 1972a; Bingen et al. 1998 |
| 4 | Fen Complex | -56.0 | 330.0 | 7.0/10.0 | -30.0 | 4 | 583 ± 15 | Meert et al. 1998 |
| 5 | Winter Coast sediments, Russia | 25.3 | 312.2 | 2.3/3.7 | 23.7 | 7 | 555 ± 3 | Popov et al. 2002; Martin et al. 2000 |
| 6 | Zolotitsa sedi- | 31.7 | 292.9 | 1.6/2.7 | 21.9 | 7 | 550 ± 5 | Popov et al. 2005 |

Several palaeomagnetic studies have been carried out in the Fen Carbonatite Complex of the South Norway and associated rocks (Poorter, 1972b; Storetvedt, 1973; Piper, 1988; Meert et al., 1998). These results were summarised by Meert et al. (1998) who suggest a mean pole of 56.0˚S, 330.0˚E, and who also provided a 40Ar-39Ar age of 583 ± 15 Ma for the complex (Table 1). All these palaeopoles are quite concordant but Meert et al. (1998) noted the need for caution as the primary, Neoproterozoic age for the magnetic remanence has not been established and also that the data resembled the Permo-Triassic field directions for Baltica with the Fen Complex located close to the Oslo Rift, a site of widespread igneous activity of similar age.

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 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). Popov et al. (2002) also noted the palaeopole of Piper (1981) from the Alnø Carbonatite Complex, an inferred correlative of the Fen Complex and dated at 584 ±13 Ma (Anderson, 1996), which is relatively close to the Winter Coast pole and far from the Fen pole (Meert et al., 1998), but the quality of the data is poor. Walderhaug et al. (2003) restudied the Alnø Complex and briefly mentioned a steep primary magnetisation. They also reported a 40Ar-39Ar age for the complex of 589 Ma but as the details of the paleomagnetic and age data are yet to be fully published, the quality of this information cannot be critically evaluated.

Lewandowski and Abrahamsen (2003) published a palaeopole of 40.0˚S, 357.0˚E from the Lower Cambrian Nesko Sandstone of Bornholm Island that has an age of around 545-530 Ma based on biostratigraphy (Table 1). Despite its resemblance of the well-known Permian poles of Europe, they argue for the primary nature of this remanence on the basis of its better grouping than the overprint remanence from other formations of the area. Torsvik and Rehnström (2001) reported a palaeopole of 56.0˚N, 296.0˚E from the Lower Cambrian Torneträsk Formation in northern Sweden suggesting a medium to high palaeolatitude for Baltica at that time (Table 1). Primary remanence of the pole was not demonstrated and it is also close to the Jurassic part of the Eurasian Apparent Polar Wander Path (e.g. Smethurst et al., 1998).

Palaeomagnetic poles have been determined on a diverse range of late Neoproterozoic to Cambrain rock units from Baltica and overall suggest a low latitude position (cf. Eneroth and Svenningsen, 2004). However, only the poles from the Winter Coast (Popov et al., 2002) and the Nyborg Formation (Torsvik et al., 1995a) have a clearly established primary remanence with only the former also having a precise age. In all other cases, late Paleozoic or Jurassic remagnetization cannot be excluded.

## Laurentia

Murthy et al. (1992) studied six dykes of the Long Range swarm of Labrador. Three of them yield a coherent direction for the remanence with a palaeopole at 10.8˚N, 334.3˚E, whereas three others gave different and diverged directions, interpreted as anomalous. The coherent remanence is probably primary as it is supported by a baked contact test. Meert et al. (1994) reinterpreted this data, suggesting the anomalous direction from dyke 1, dated at 615 ± 2 Ma by Kamo et al. (1989) to be primary, but did not justify why they rejected the coherent data which included the baked contact test. The coherent direction was suggested by Torsvik et al. (1996) as representative for Laurentia at 550 Ma on the basis of the K-Ar dates available at that time (Murthy et al., 1992). However, Kamo and Gower (1994) have subsequently obtained an age of 615 Ma based on U-Pb baddeleyite and zircon from dyke 4. They argued that the coherent direction is representative for Laurentia at that time. The anomalous direction from the one dyke used by Meert et al (1994) may record a large secular variation or excursion of the geomagnetic field and we do not consider this direction to be valid in constraining the position of Laurentia.

Palaeomagnetic data from the Cloud Mountain basalts (Deutsch and Rao, 1977), part of the Lighthouse Cove Formation of Williams and Stevens (1969), revealed a palaeopole at 5ºS, 352ºE close to that of their inferred intrusive source, the Long Range Dykes (e.g. Bostock, 1983). Murthy et al. (1992) also studied the Double Mer Formation in northern Labrador, which is close to that from the Long Range Dykes, but the age of the formation is uncertain. Double Mer sediments postdate the Grenvillian deformation and some workers (Gower, 1988 and references therein) correlate them with the Cambrian Bradore Formation of Newfoundland, but alternative correlations are also possible (Gower, 1988).

Symons and Chiasson (1991) reported a palaeopole of 46.3˚N, 301.4˚E from the Callander alkaline complex of northern Ontario (Table 1), Canada, supported by a baked contact test. This result suggests a high-latitude position of Laurentia. There are several dates of the Callander Complex, which were summarized by Symons and Chiasson (1991) who estimated the age at 575 ± 5 Ma. This is supported by a U-Pb age of 577 ± 1 Ma (S. Kamo, pers. comm., 2004).

The palaeomagnetic study of the 564 ± 9 Ma Catoctin Volcanic Province (Meert et al., 1994) revealed two stable components of magnetization (Table 1). These are Catoctin A, with a steep inclination at 43.0˚N, 308.0˚E and Catoctin B, with a shallow inclination at 4.0˚N, 13.0˚E. Both components are bipolar. There is evidence for the primary nature of both components (see also discussion of Pisarevsky et al., 2000, Meert and Van der Voo, 2001, and Pisarevsky et al., 2001 for details).

Tanczyk et al. (1987) also found a two-component magnetisation in the Sept Iles Intrusion (Table 1). The rigorous baked contact test proved the primary nature of the shallow remanence (A, 20.0ºS, 321.0ºE) of the main intrusion dated at 565 ± 4 Ma (Higgins and van Breemen, 1998). Cross-cutting dykes of unknown age carry a steep remanence component B (Tanczyk et al., 1987, 59.0˚N, 296.0˚E). Kirschvink et al. (2003) confirmed the presence and primary nature of the Sept Iles A component in the main intrusion as well as the presence of the B component in the cutting dykes. They also dismissed the possibility of introducing of a regional tilt corrections that has been applied in some re-interpretations for the Sept Iles remanence components (e.g. Symons and Chiasson, 1991; Meert et al., 1994; Torsvik et al., 1996).

The 573 ± 32 Ma Buckingham lavas in Quebec yielded a palaeopole of 9.5˚N, 340.8˚E (Dankers and Lapointe, 1981), close to that determined for the Long Range dykes (Table 1). Palaeomagnetic data from the sediments of the Rainstorm Member of the Johnnie Formation in Nevada (Van Alstine and Gillett, 1979) revealed a similar remanence direction at 10.0˚N, 342.0˚E (Table 1). The age constraints for this formation are imprecise. However, recent correlation of the Rainstorm Member with late Neoproterozoic strata in different parts of the world suggest a Varangian/Marinoan (~ 620 Ma) age (Corsetti and Kaufman, 2003; Wernicke and Hagadorn, 2000; Abolins et al., 1999; Hodych et al., 2004). If so, the palaeomagnetic data from the Johnnie Formation are broadly coeval to those from the Nyborg Formation (Torsvik et al., 1995a).

The 550 Ma Skinner Cove Formation in western Newfoundland (Cawood et al. (2001) contains a low latitude remanence of 15˚S, 337˚N, which is primary as evidenced by an intraformational conglomerate test (McCausland and Hodych, 1998). The unit occurs within the Humber Arm allochthon (Williams and Cawood, 1989), but is inferred not to have been transported far and to have lain at, or near, the Laurentian margin (Cawood et al., 2001; Hodych et al., 2004). A similar pole was obtained from the Lower Cambrian Bradore Formation (~530-520 Ma, Cawood et al., 2001) in St. John Bay, western Newfoundland (Rao and Deutsch, 1976) which is not included in Table 1 due to low reliability index. Several other Early to Middle Cambrian palaeomagnetic results from Laurentia also have lower reliability index, but all show low palaeolatitudes (Black, 1964; Spall, 1968; Rao and Deutsch, 1976; Watts et al., 1980).

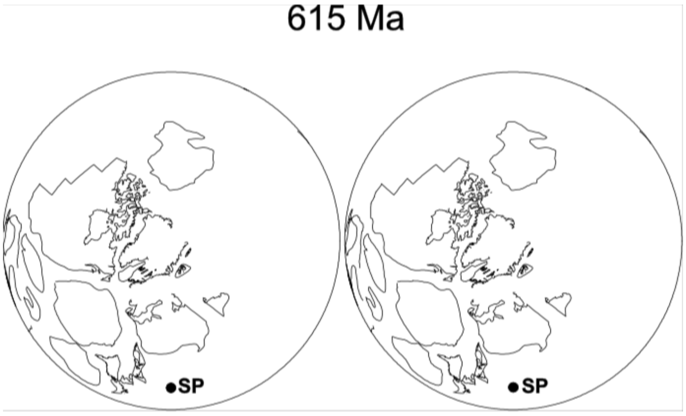
## Discussion

The Vendian – Early Cambrian palaeomagnetic results from Laurentia suggest a complicated palaeogeographic pattern. On one hand, there is a group of three reliable poles (Callander, Catoctin A and Sept Iles B) indicating a similar high-latitude position of Laurentia at 580 – 560 Ma. These poles do not resemble any younger poles, so later remagnetization is unlikely. On the other hand, at least two other palaeomagnetic results for the same time span (Sept Iles A and Catoctin B) are equally, if not more likely to be primary and these require a low latitude position for Laurentia. From our point of view, the baked contact test in Sept Iles intrusion is the most rigorous and hence this data is the most reliable in constraining the position (low-latitude) of Laurentia. Also the Sept Isles results of Tanczyk et al. (1987) are confirmed by an independent study of Kirschvink et al. (2003). However, these poles overlap with the group of slightly younger Cambrian and some Ordovician poles. The same is true for the Long Range (615 Ma) pole. One possible explanation for the data set is a loop in the Apparent Polar Wander Path over this time period, similar to the Grenville loop for the end Mesoproterozoic (Pisarevsky et al., 2003 and references therein). However, the time and latitudinal succession of the different poles from high latitude (Callander) to low-latitude (Sept Isles A) then possibly back to high-latitude (Sept Isles B) before returning to low-latitude (Skinner Cove) cannot be explained by a single Apparent Polar Wander Path loop.

If all the Vendian – Early Cambrian palaeomagnetic results from Laurentia are primary and their ages are correctly assigned, then they cannot be explained by normal plate tectonics processes. The simplest explanation is that some of these data are not relevant, being either the result of remagnetization or incorrect deciphering of the palaeomagnetic signal (e.g. Meert and Van der Voo, 2001; Hodych et al., 2004). However, recently McCausland et al. (2003) reported the preliminary results from two other Quebec intrusions – Mont Rigaud stock, dated by U-Pb zircon at 563±14 Ma (Malka et al., 1996) and the Mutton Bay complex, which has given a K-Ar age of 578 Ma (Doig and Barton, 1968). These results indicate the near-polar position for Laurentia during the emplacement of the Mutton Bay complex, but low-to-equatorial palaeolatitudes during the intrusion of the Mont Rigaud stock.

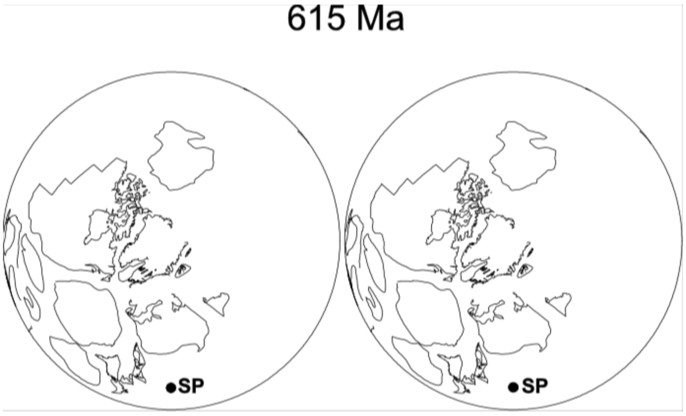
True Polar Wander (e.g., Kirschvink et al., 1997; Kirschvink et al., 2003) could explain the apparent discrepancy between high and low-latitude Laurentian poles. It is also possible that late Neoproterozoic to early Cambrian time was characterized by an anomalously large non-dipole component of the Earth's magnetic field (e.g., McCausland et al., 2003). In any case, we conclude that at present late Neoproterozoic and Early Cambrian palaeomagnetic data from Baltica and Laurentia are not self-sufficient for the creation of a reliable plate tectonic reconstruction and a unique model for Iapetus opening. The only pair of the coeval palaeopoles from both continents is the 616 Ma Egersund dykes pole (Storetvedt, 1966; Poorter, 1972a) and 615 Ma Long Range dykes pole (Murthy et al., 1992). This pair, shown in ( Figure 1 ), clearly shows that only the reconstruction involving the juxtaposition of the western Scandinavian component of Baltica against the Rockall-Scotland-SE Greenland segment of Laurentia is valid at this time. Based on this Laurentia-Baltica configuration we created two computer animations ( Figure 2 ) for the time interval between 615 and 540 Ma in 5 m.y. step intervals with alternate high-latitude and low latitude positions for Laurentia at ~ 580-560 Ma. Following the recommendation of Winchester (1988), we included a palinspastic reconstructions of northwestern Scandinavia and eastern Greenland that removes several hundreds kilometres of Caledonian shortening in both cases. Similar margin restorations have been used by a number of authors including Soper et al. (1992), Park et al. (1994), Fairchild and Hambrey (1995) and Higgins et al. (2001). Such palinspastic restorations are necessary to avoid strong overlap of the continental blocks during the spherical rotations. The approximate position of the pre-Caledonian continental boundaries were calculated in accordance with the studies of Andreasson (1994) for Scandinavia, and of Higgins and Leslie (2000) for East Greenland.

**Figure 1. Palaeoreconstructions**



Alternative palaeoreconstructions of Laurentia and Baltica at ~615 Ma.

**Figure 2. Palaeogeographic animations**



Two sets of palaeogeographic animations for the high-latitude (left) and low-latitude (right) models between 615 and 540 Ma. SP – South Pole.

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