

# Baltica upside down: A new plate tectonic model for Rodinia and the Iapetus Ocean

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## ABSTRACT

**We propose that Baltica was geographically inverted throughout the Neoproterozoic and therefore suggest reassessment of the classic Wilson Cycle paleoreconstruction depicting an Atlantic-type early Paleozoic (Iapetus) ocean between western Norway and East Greenland. Our new reconstruction dismisses the need for 180° rotation of Baltica after breakup of Iapetus and presents more plausible geologic correlations between Baltica, Laurentia, and Gondwana than those accompanying previous fits. In our reconstruction, the breakup that led to the formation of the Iapetus Ocean was initiated at a junction between a rift (Laurentia-Gondwana), a right-lateral fault (Laurentia-Baltica), and a trench (inverted Baltica-Gondwana), thereby linking the late Precambrian Iapetus opening to the Timanian and Avalonian orogenies between Gondwana and an inverted Baltica.**

**Keywords:** Iapetus, Wilson Cycle, Precambrian, Avalonia, Rodinia, Baltica, paleomagnetism.

## CLASSIC NEOPROTEROZOIC BALTICA-LAURENTIA FIT AND ITS PROBLEMS

The Wilson Cycle (Wilson, 1966), i.e., the orthogonal opening and closing of an early Paleozoic Atlantic-type ocean (the Iapetus Ocean; Harland and Gayer, 1972) revolutionized plate tectonic thinking and has represented one of the mainstays of pre-Mesozoic plate reconstructions. Current models intimately link early Paleozoic or late Precambrian opening of the Iapetus Ocean to breakup of the Rodinia supercontinent (e.g., Hoffman, 1991; Torsvik et al., 1996; Dalziel et al., 2000). The paleogeography of Rodinia (Fig. 1A) is continuously debated, but the classic model (Dewey, 1969; Harland and Gayer, 1972; Wilson, 1966) of Atlantic-type rifting of northern Iapetus between western Baltica (Scandinavian side) and northeast Laurentia is inferred in all plate reconstructions. The existence of ca. 1 Ga Grenvillian-Sveconorwegian rocks on the Atlantic-facing margins of Laurentia and Baltica has been used as key evidence to link the continents together in the late Precambrian along their present-day Atlantic margin. In this type of fit, the geographic location of the late Precambrian Laurentia-Baltica boundary would have been mimicked almost exactly by the ca. 0.42 Ga Caledonian orogeny and thus requires that Atlantic rifting imitated the proto-Atlantic (Iapetus) rifting (Fig. 1A) (Dalziel et al., 2000; Hoffman, 1991; Torsvik et al., 1996, 2001). Considering the long span of time and the vast rotational and latitudinal movements of Baltica between the late Precambrian breakup and the Caledonian Laurentia-Baltica continental collision, reutilization of precisely the same plate junction is remarkable. This issue has not been previously addressed, largely because most available evidence to promote or refute the late Precambrian juxtaposition of southwestern Baltica and eastern Laurentia has been founded in age and geochemical links between large crystalline complexes. For example, traditional linking of the 1.2–0.9 Ga Sveconorwegian (Scandinavia) and Grenville (eastern North America) orogenies can be questioned by large differences in the structural histories and diachroneity of events between rocks in the two areas (Johansson et al., 2001). Furthermore, the Grenvillian events in East

Greenland are defined by 1.0–0.93 Ga allochthonous granites (Watt and Thrane, 2001), and no documented autochthonous Grenvillian-Sveconorwegian deformation exists along the northern margins of East Greenland and western Norway, as some workers have proposed to justify a tight Wilson-type Rodinia fit (Fig. 1A) (Dalziel et al., 2000).

The late Precambrian basin evolution in these two regions also varies considerably with respect to tectonic setting, depositional age and environment, basin thickness, lithology, and igneous activity (Kumpulainen and Nystuen, 1985), and the overall conclusion must be that the Precambrian geology of East Greenland and that of Scandinavia are not as compatible as implied in traditional late Precambrian reconstructions.

Another worrisome aspect of the Wilson-type fit is the apparent diachroneity and different styles of rifting within the Iapetus Ocean. Southern Iapetus, along eastern North America, probably opened from south to north during the latest Vendian (570–550 Ma) (Cawood et al., 2001). However, paleomagnetic, paleontologic, and geologic evidence shows that by 580 Ma Baltica was inverted in the Southern Hemisphere, implying that the northern Iapetus Ocean opened earlier (ca. 600 Ma) than the Southern Iapetus (Meert et al., 1998; Torsvik and Rehnström, 2001; Torsvik et al., 1996).

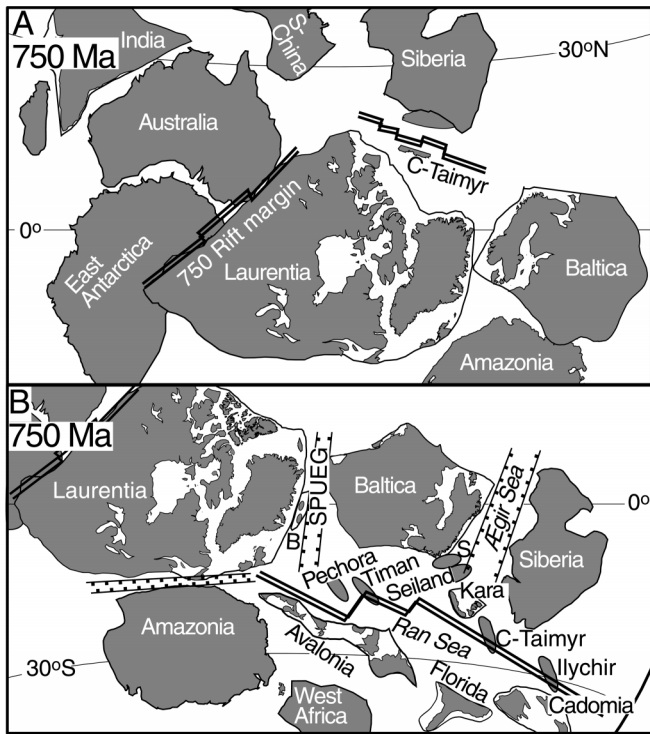
In order to complete the Wilson Cycle, in which the same landmasses rifted and collided twice along the same margin, these forms of evidence imply that Baltica “instantly” rotated 180° to an inverted position as Iapetus opened, and then rotated 180° again as the ocean closed in the early Paleozoic (Torsvik et al., 1996).

## NEW NEOPROTEROZOIC BALTICA-LAURENTIA FIT

Collectively, the described paleomagnetic complications and the unsatisfactory geologic correlations call for an alternative pre-Iapetus Baltica-Laurentia fit. By using existing paleomagnetic and geologic data, we thus propose a less ambiguous fit, suggesting that Baltica was already in an inverted position (relative to the present day) prior to the opening of Iapetus.

Paleolongitude is undefined from paleomagnetic data. In addition, notably when dealing with Precambrian rocks, the hemisphere choice for paleomagnetic data is ambiguous. Because the paleomagnetic re-

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**Figure 1.** Two alternative reconstructions of Rodinia. **A:** Typical ca. 750 Ma Rodinia reconstruction. Positions of India, Australia, south China, Laurentia, and Baltica are paleomagnetically defined (data listed in Torsvik et al., 2001), and relative fits of East Antarctica, Amazonia, and Siberia are those of Dalziel et al. (2000). **B:** Revised ca. 750 Ma SPUEG (southern peri-Urals–East Greenland) reconstruction of eastern Rodinia. In this reconstruction (1) Laurentia's position is similar to that shown in A but slightly farther to north on basis of upgraded Neoproterozoic database for Laurentia, (2) Amazonia and West Africa (no paleomagnetic data) are shown in Hoffman-type (Hoffman, 1991) reconstruction, (3) Baltica is geographically inverted, and (4) we have added small continental fragments and arcs within Ægir Sea and Ran Sea (cf. text). Laurentia: 21.1°N, 154.4°E (north pole; smoothed spline); Baltica: 28.5°S, 17.0°E (north pole; smoothed spline); peri-Gondwana arcs (in Avalonia, Cadomian, and Florida) are positioned in possible outboard position relative to Amazonia and West Africa. In Neoproterozoic, parts of northern Norway and Kola Peninsula were not part of Baltica; they are indicated as terrane blobs in the Ran Sea south of Baltica. Sève Nappe Complex (S) and Seiland igneous province are Caledonian terranes of Baltic affinity. Barentia (central and eastern Svalbard) is positioned east of Baltica on the basis of stratigraphic correlation, and Kara block correlates directly with events and deposition typical for Ægir Sea (e.g., Pechora) and is thus placed in this region. Ilychir is an ophiolite complex in western Siberia (cf. text). Reliable Siberian paleomagnetic data exist only for 1100 Ma and 650 Ma, but these data do not corroborate a north Canada–Siberia link (Fig. 1A); we thus use the 650 Ma data set (listed in Smethurst et al., 1998) to tentatively place Siberia in Ægir Sea during the Neoproterozoic. Double lines mark ca. 750 Ma seafloor spreading and faults mark intercontinental rifting.

cord for Baltica is broken for a considerable length (between ca. 750 and 580 Ma), we thus have no knowledge whether Baltica's 750 Ma pole is a south or north pole; therefore, Baltica can be placed either in the Southern or Northern Hemisphere. The archetypal Atlantic-type Baltica-Laurentia reconstruction in Figure 1A is based on paleomagnetic data, and in this example, a mean 750 Ma pole of 28°S, 17°E for Baltica was assumed to be a south pole (Torsvik et al., 1996). Conversely, Figure 1B assumes the opposite polarity but, owing to Baltica's equatorial position, this polarity mandates a direct inversion of Baltica so that southeast Baltica (the southern peri-Urals) faces Laurentia prior

to rifting (we refer to this southern peri-Urals–East Greenland pre-Iapetus reconstruction as the SPUEG fit; Fig. 1B). Inverting Baltica prior to the opening of the northern Iapetus Ocean obviously dismisses the need for rapid post-breakup rotation of Baltica; the new fit also provides both a framework for discussing alternative geologic correlations and a new plate tectonic model for the entire region.

### Neoproterozoic Basin Evolution Along Pre-Iapetus Margins

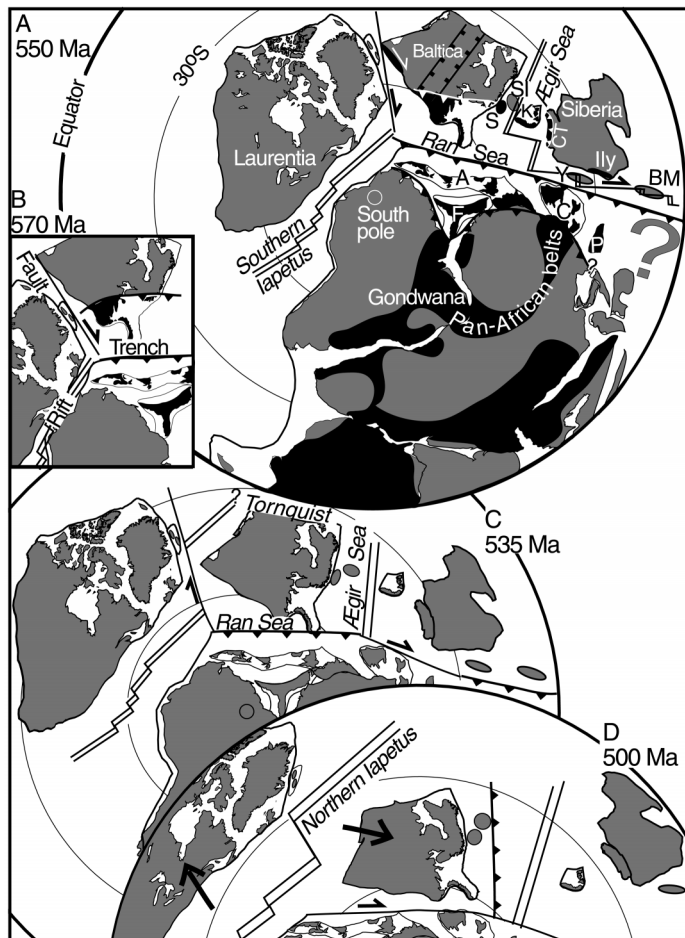
In contrast to the Neoproterozoic–Vendian geologic noncorrelation between western Baltica (Scandinavia) and East Greenland, there are remarkable correlations between East Greenland and Russian Baltica (southern peri-Urals). Late Mesoproterozoic to earliest Neoproterozoic metasedimentary rocks are intruded by early Neoproterozoic granites ranging in age from ca. 1 to 0.93 Ga in both East Greenland (Watt and Thrane, 2001) and the southern peri-Urals (Khain, 1985; Maslov et al., 1997). In both areas, the intrusions are considered anorogenic, and the subsequent early Neoproterozoic basins are typical marine rifts, filled with shales, sandstones, and limestones (Fig. 1B) (Henriksen and Higgins, 1976; Khain, 1985).

A huge late Neoproterozoic epicontinental sag basin (in which the 5 km upper Eleonore Bay Supergroup was deposited) covered East Greenland with sandstones, shales, limestones, and dolomites, and correlate on a bed-to-bed basis for more than 1000 km in East Greenland and directly across to Svalbard (Haller, 1971; Henriksen and Higgins, 1976). Barentia (central and eastern Svalbard) is thus inferred to have been located offshore East Greenland at the time of deposition (Fig. 1B). The Eleonore Bay Supergroup compares very well to the sedimentary fill in the synchronous sag basin in the southern peri-Urals (the Karatau Group); the fill also consists of thick shallow-marine sandstones, shales, and carbonates that can be traced for more than 1000 km along the rim of Baltica (Maslov et al., 1997; Nikishin et al., 1996).

Lower Vendian marine deposits of the peri-Urals (Maslov et al., 1997) also generally correlate with those in East Greenland (Haller, 1971) until the end of deposition of middle Vendian marine tillites. Rocks above the tillites do not correlate; the most pronounced difference is that the inferred global cap carbonates (Hoffman et al., 1998) overlying Vendian glacial deposits in Gondwana and Laurentia were not deposited on Baltica (Kumpulainen and Nystuen, 1985). A regional late Vendian unconformity occurring in both the southern peri-Urals (Maslov et al., 1997) and East Greenland (Haller, 1971) probably marks the separation of the two plates. In East Greenland, the discrete unconformity is overlain by Lower Cambrian lithic sandstone and a Cambrian–Ordovician carbonate platform (Haller, 1971). In contrast, only minor Cambrian rift basins formed in the southern peri-Urals, which generally were eroded during the Cambrian Timanian–Baikalian orogeny prior to widespread deposition of Upper Cambrian to Lower Ordovician coarse clastic deposits (Maslov et al., 1997; Nikishin et al., 1996).

### Neoproterozoic Events in Ran and Ægir Seas, South and East of Inverted Baltica

Inverting Baltica in a SPUEG fit obviously has several implications for the tectonic scenario east and south of Baltica. Several workers have linked the late Vendian to Cambrian Timanian events in northern Baltica with the Avalonian events in the peri-Gondwana region (Gee et al., 2000; Rehnström et al., 2002; Roberts, 2001; Torsvik and Rehnström, 2001), inferring that Baltica inverted after rifting away from East Greenland. However, pre-Iapetus (Neoproterozoic) events in these regions are widely dispersed and unrelated in a Wilson-type fit. In the SPUEG fit, these regions are all located within the realm of ocean east and south of Baltica during the Neoproterozoic (Figs. 1B and 2A), and they coherently record several pulses of magmatic activity related to well-documented rifting and subduction in the Ægir and Ran Seas. The ocean east of inverted Baltica recently was named the Ægir Sea (Torsvik and Rehnström, 2001). We propose that the neigh-



**Figure 2.** Continental distribution on Southern Hemisphere during late Vendian to Cambrian. Rift geometry (seafloor spreading marked by double lines) in peri-Gondwana region generally follows Murphy et al. (1999). A: 550 Ma reconstruction based on paleomagnetic data for Baltica, Laurentia, Gondwana, and Kara (K) listed in Rehnström et al. (2002). Other terranes are placed in accordance with geologic correlations. Gondwana and peri-Gondwana terranes (A, Avalonia, C, Cadomia, F, Florida, P, Perunia) were assembled, whereas Laurentia had rifted off South America (southern Iapetus opening). Northern Baltica terrane amalgamation was completed and central Taimyr (CT) had accreted to south Taimyr. Kara is now north of Siberia, but was independent block during early Paleozoic; placement of Kara in offshore northern Baltica is based on 500 Ma poles. Yenisey (Y) and Baikal-Muya (BM) are Vendian ophiolites in western and southern Siberia. Seiland igneous province (SI) and Săve nappe complex (S) are Caledonian nappes. Areas with ca. 550 Ma orogenic belts are marked by black. Normal faults on Baltica mark Vendian Mid-Baltic rift, a major graben, connected to huge ca. 551 Ma basalt province in Poland (Nikishin et al., 1996). B: Schematic 570 Ma reconstruction, after rift-rift-rift model of Cawood et al. (2001), but illustrating rift-trench-fault geometry with Baltica inverted. C: 535 Ma reconstruction. Continued opening of southern Iapetus Ocean with SPUEG (southern peri-Urals–East Greenland) margins acting as dextral transform fault. Reconstruction modified from Torsvik and Rehnström (2001). D: 500 Ma reconstruction. Southern Iapetus rift passed north of Baltica, initiating seafloor spreading in northern Iapetus Ocean. Trench formed along Aegir margin as Baltica moved eastward along dextral transform fault, reactivating peri-Gondwana trench. Reconstruction is modified from Torsvik and Rehnström (2001).

boring ocean south of inverted Baltica be named the Ran Sea (Ran is the wife of Aegir, god of the ocean in Nordic mythology) (Fig. 2A).

The opening of Ran and Aegir Seas appears synchronous with rifting west of Laurentia and is recorded in Neoproterozoic rift-magmatism, including the 830–700 Ma Seiland igneous province (oc-

curing today as a Caledonian nappe in northern Norway [Krogh and Elvevold, 1990]), 780 Ma bimodal magmatic rocks in Timan (Khain, 1985), and 850–718 Ma ophiolites in central Taimyr and at Ilychir in southwest Siberia (Vernikovskiy, 1997) (Fig. 1B). In the SPUEG fit, these igneous bodies correlate with the 763–740 Ma peri-Gondwana arcs occurring in Avalonia, the Cadomian-Armorican massif of France, and with the Pan-African belts of northern Africa (Murphy et al., 1999) (Fig. 1B).

These early crust-forming events may in part overlap with formation of calc-alkalic arcs related to subduction of Aegir crust along the continent boundaries. These 690–603 Ma arcs dominate the peri-Gondwana region (Murphy et al., 1999), which formed synchronously with arcs in the Ran and Aegir Seas, including the 620–604 Ma metagabbros in the Seiland igneous province (Krogh and Elvevold, 1990), 625 Ma bimodal arcs in Timan and Pechora blocks (Khain, 1985), 618–585 Ma Baikal-Maya ophiolite belt of southern Siberia, and the 600–585 Ma Yenisey Ridge and Ilychir ophiolite belts of western Siberia (Vernikovskiy, 1997) (Fig. 2A).

These events continued into the late Vendian–Early Cambrian collision of microcontinents, including the ca. 580–550 Ma Timanian obduction of the Timan and Pechora blocks onto Baltica (Gee et al., 2000; Roberts, 2001), the 630–573 Ma metamorphism and deformation related to the Baikalian obduction of central Taimyr onto Siberia (Vernikovskiy, 1997), the 637 Ma metamorphic event recorded in the Caledonian Săve nappe complex in northern Scandinavia (Rehnström et al., 2002), and the well-documented Cadomian, Avalonian, and Pan-African events in the Ran Sea (the western peri-Gondwana regions) (Murphy et al., 1999) (Figs. 1B and 2A). These late Vendian–Early Cambrian Timanian-Baikalian-Avalonian-Cadomian events are synchronous with the late Pan-African orogeny leading to the amalgamation of Gondwana (Keppie and Ramos, 1999) and with continued seafloor spreading in the Aegir region as recorded in Caledonian and Siberian nappes (Fig. 2A).

### Breakup to Form Iapetus and Related Events

Breakup of the exterior of Rodinia began as Neoproterozoic seafloor spreading in the Ran Sea, and along Laurentia's western margin (Torsvik et al., 1996), and was synchronous with intercontinental rifting in the Aegir and pre-Iapetus region (e.g., rifting of eastern North America [Cawood et al., 2001]) and narrow rifting followed by deposition of thick marine deposits in the wide epicratonic basin of the SPUEG area (Fig. 1B).

A second rift event, marked by Vendian dikes younging northward along Laurentia's eastern margin (eastern North America and Scotland), is interpreted to reflect pre-Iapetus rifting, leading to northward opening of the Iapetus Ocean by 570 Ma, and continued rifting until 550 Ma (Cawood et al., 2001). In the SPUEG fit, this rift can be traced directly into Baltica, where a remarkably well defined Vendian failed rift split Baltica in two (the Moscov-Mesen-Volyn basins) (Nikishin et al., 1996) (Fig. 2A). The rift continues into the huge Deccan Trap-sized late Vendian Volyn basalt provinces along Baltica's Tornquist margin in Ukraine and Poland (Nikishin et al., 1996). This volcanic province has no apparent continental counterpart, and we suggest that it formed as the mid-Baltic rift crossed the Tornquist margin of Baltica, which bordered either a strong oceanic plate or a rift zone adjacent to an as-yet unknown continent (Fig. 2A). Eventually the mid-Baltic rift failed, and was inverted by the Early Cambrian (Nikishin et al., 1996). Northern Iapetus did not split Baltica, and eventually formed offshore of East Greenland.

### Vendian Rift-Trench-Fault—Final Breakup of Rodinia

In a Wilson-type fit, eastern Rodinia is proposed to break up in a rift-rift-rift triple-junction setting along the southern Iapetus rift (Laurentia separating from Amazonia) at 550 Ma (Cawood et al., 2001),



the northern Iapetus rift (Baltica separating from Laurentia) at 616 Ma, and the early Tornquist Sea (Baltica separating from Amazonia) at 551 Ma (Bingen et al., 1998). The geometric consequence of a 551 Ma rift between southern Baltica and Amazonia is that these plates would have drifted apart (Cawood et al., 2001). Mere separation contrasts with paleomagnetic data showing that Baltica from 580 to 550 Ma already was inverted and drifted south toward Gondwana and that Baltica's northern margin (present-day coordinates) then remained close to the Gondwana margin until the Early Ordovician (Fig. 2, A and B) (Torsvik and Rehnström, 2001). This geometry is corroborated by the Avalonian-Armorican-Cadomian orogenies related to Andean-type southward subduction of oceanic crust (Murphy et al., 1999). The east-trending arm of the triple junction (south of Baltica) thus was a trench in the Vendian–Early Cambrian.

That rift (southern Iapetus)-trench (peri-Gondwana)-rift (northern Iapetus) triple junctions are geometrically impossible suggests that the SPUEG margins (northern Iapetus) were initiated along a right-lateral transform fault (Fig. 2, A–C). This concept is consistent with regional late Vendian to Early Cambrian transcurrent faulting and intercontinental (no ophiolites) Timanian-Cadomian nappe emplacement along the southern peri-Urals margin (Willner et al., 2001) (Fig. 2A).

A rift-trench–right-lateral fault model explains several features in the overall plate tectonic scenario of Laurentia, Baltica, and Gondwana. The model explains why Baltica drifted southward from 580 to 550 Ma (Torsvik and Rehnström, 2001) and directly relates contractional events between Baltica and Gondwana to the opening of the Iapetus Ocean (Fig. 2, A and B). As Baltica's southward drift stopped against Gondwana, southern Iapetus continued to open by displacing Laurentia rapidly northward toward the equator from 550 to 535 Ma (Torsvik et al., 1996), along the transform fault (Fig. 2, C and D). Opening of the southern Iapetus continued along the transform fault until the rift passed north of Baltica, initiating Cambrian seafloor spreading in the northern Iapetus (Fig. 2D). Rifting west of Baltica corresponds with subduction east of Baltica, today recorded in Caledonian nappes (Torsvik and Rehnström, 2001), while the continent was transposed eastward toward its Early Ordovician position east of Avalonia (Torsvik et al., 1996) (Fig. 2D). This displacement is recorded in dextral transtension along the peri-Gondwana trench (Murphy et al., 1999) and along the Timanian suture in northernmost Norway; the displacement coincides with the initiation of counterclockwise rotation of Baltica to its post-Cambrian right-side-up position (Torsvik and Rehnström, 2001).

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