Breaking the Grenville–Sveconorwegian link in Rodinia reconstructions

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Abstract

The Grenville, Sveconorwegian, and Sunsas orogens are typically inferred to reflect collision between Laurentia, Baltica, and Amazonia at ca. 1.0 Ga, forming a central portion of the Rodinia supercontinent. This triple-junction configuration is often nearly identical in otherwise diverse Rodinia reconstructions. However, available geological data suggest that although the Grenville and Sveconorwegian provinces shared a similar tectonic evolution from pre-1.8 to ca. 1.5 Ga, they record distinctly different tectonic

histories leading up to, during, and possibly following Grenville–Sveconorwegian orogenesis. Moreover, paleomagnetic data suggest the two continents were separated at peak orogenesis, further invalidating any direct correlation. A number of possible interpretations are permissible with available geological and paleomagnetic data, of which a 'classic' triple-junction configuration appears least likely. In contrast to the commonly inferred intertwined Proterozoic evolution of Baltica and Laurentia, the possibility remains that they were unrelated for a billion years between 1.5 and 0.45 Ga.

Introduction

Periodic aggregation and dispersal of continents has likely exerted a controlling influence on the formation and preservation of crust, mantle dynamics and the evolution and diversification of life on our planet (Nance, et al., 2014). However, apart from the most recent supercontinent – Pangea – supercontinent reconstructions are fraught with uncertainty, to the point that their very existence has been questioned (e.g., Evans, 2013). In the absence of faunal evidence, reconstructions are generally based on available paleomagnetic data and correlation of orogenic and/or magmatic/metamorphic events on different continents. Several reconstructions exist for the late Mesoproterozoic Rodinia supercontinent (Fig. 1). Although reconstructions vary widely, they all imply that Laurentia and Baltica remained in close proximity before and during Rodinia assembly. This inference of proximity largely stems from correlation of the late Meso-/early Neoproterozoic Grenville and Sveconorwegian orogens (Gower, et al., 1990), and sparse paleomagnetic data (Li, et al., 2008). In this contribution, we review evidence that the Sveconorwegian Province is highly unlikely to be a correlative of the Grenville Province in Laurentia, consider how paleomagnetic data are consistent with the two orogens being widely separated at the peak of Grenville–Sveconorwegian orogenic activity, and discuss how evidence from late Meso- through Neoproterozoic allochthonous units around the North Atlantic region, albeit circumstantial at present, may provide constraints on Baltica–Laurentia contiguity.

Paleo- through Mesoproterozoic tectonic evolution of the SE Laurentian and SW Baltican margins

Laurentia and Baltica are generally interpreted to have shared a common tectonic evolution starting at ca. 1.85 Ga, characterized by crustal growth and reworking along their SE and SW margins, respectively (Fig. 2A; Condie, 2013, Karlstrom, et al., 2001, Roberts and Slagstad, 2015). Most models of Rodinia assembly suggest that this coevolution ceased when the two margins collided with a third continent (Amazonia) to form the Rodinia-interior Grenville–Sveconorwegian–Sunsas orogenic belt (e.g., Karlstrom, Åhäll, Harlan, Williams, McLelland and Geissman, 2001, Li, Bogdanova, Collins, Davidson, De Waele, Ernst, Fitzsimons, Fuck, Gladkochub, Jacobs, Karlstrom, Lu, Natapov, Pease, Pisarevsky, Thrane and Vernikovsky, 2008). However, although there are numerous similarities between the two margins until ca. 1.5 Ga, the succeeding evolution is less clear. The SE Laurentian margin was characterized by formation of widespread, Mesoproterozoic arc and back-arc systems that were assembled through a series of ca. 1.25–1.12 Ga Elzevirian and Shawinigan accretionary events, prior to emplacement onto Laurentia during the Grenvillian orogeny (Carr, et al., 2000, Culshaw, et al., 2013). Ensuing Grenvillian orogenesis involved northwestward thrusting of these assemblages as ductile nappes at high-metamorphic grades, probably with the development of a wide orogenic plateau, and is generally inferred to represent continent-continent collision with Amazonia starting at ca. 1.1 Ga (Culshaw, et al., 1997, Rivers, 2012, Rivers, 2015). Late-orogenic extension of ductile crust may have been underway by 1050 Ma, and certainly by 1020 Ma, juxtaposing upper-crustal rocks of the orogenic lid with deeper, more ductile rocks (Rivers, 2012). The late-orogenic extension was followed by a late compressional event, the Rigolet phase, at ca. 1005–980 Ma, close to the orogenic foreland.

In contrast, the SW Baltican margin appears to have been mainly in extension until ca. 1.10 Ga, as evidenced by widespread continental bimodal magmatism and sedimentation (Bingen, et al., 2002, Brewer, et al., 2004, Spencer, et al., 2014). Although this extension may have taken place behind an active continental margin, no outboard arc/back-arc terranes were accreted onto Baltica during Sveconorwegian orogenesis. Sveconorwegian orogenesis between ca. 1140 and 920 Ma is characterized by distinct tectonometamorphic events in different parts of the orogen at different times (Bingen, et al., 2008, Bingen and Viola, 2018, Möller, et al., 2015, Slagstad, et al., 2018, Slagstad, et al., 2017). Unlike the Grenville, the tectonic evolution of the western part of the Sveconorwegian orogen was distinctly different to that of its eastern part, close to the foreland. The latter region was characterized by a high-pressure metamorphic event at ca. 990–970 Ma, and has been a main argument for invoking collisional processes correlative with the Rigolet phase in the Grenville (Möller, et al., 2013). This interpretation, however, neglects the western and central parts of the orogen that were characterized by widespread magmatism and high- to ultrahigh-temperature metamorphism – rather different from that observed in the Grenville and more compatible with active-margin processes (Blereau, et al., 2017, Bybee, et al., 2014, Coint, et al., 2015, Slagstad, et al., 2013). Slagstad et al. (2018, 2017) discuss the arguments for an accretionary Sveconorwegian orogen and the contrasts with the Grenville orogen in detail.

Based on the available data from the Grenville and Sveconorwegian provinces, contiguity and continuity of the SE Laurentian and SW Baltican margins after ca. 1.5 Ga is very much in question. Laurentia–Baltica proximity can be inferred until ca. 1.25 Ga (Fig. 2A), consistent with most other interpretations, but we note that this inference is rather poorly constrained.

Li et al. (2008), in a ‘consensus’ Rodinia reconstruction, show significant N–S separation between Baltica and Laurentia at 1100 and 1050 Ma (Fig. 2B), further invalidating correlation between the Grenville and Sveconorwegian orogens, which were both well underway by that time. By 950 Ma, Baltica had drifted north and occupied a latitude similar to Laurentia (Fig. 2C), where it remained until at least 900 Ma. Importantly, however, the longitude is unconstrained, giving rise to many possible permutations, as illustrated in Fig. 2B, C. In an attempt to reduce the number of possible configurations, we discuss the ensuing Neoproterozoic evolution to see if it can place some constraints on the generally hypothesized proximity of the two continents. We consider three different scenarios: (1) proximal Baltica and Laurentia, more or less as traditionally envisaged; (2) Baltica and Laurentia in relative proximity, but with Baltica shifted eastward compared to scenario 1; and (3) significant separation of Baltica and Laurentia with no contiguous margin.

Neoproterozoic tectonic evolution of the North Atlantic region

Interpretation of the tectonic history of the North Atlantic region (Figs. 2, 3) was advanced with the concept of the Valhalla orogen (Cawood, et al., 2010). This orogenic system encompasses a series of accretionary events that compressed and inverted at least two supercycles of basin formation between ca. 1030 and 710 Ma. The remnants of this basin system are now metamorphosed and widely distributed in Early Paleozoic allochthonous units across the circum-North Atlantic region (Fig. 3). Cawood et al. (2010) interpreted the Valhalla orogen to represent an exterior, accretionary orogen along the northeastern margin of Laurentia, following ~90° clockwise rotation of Baltica (Fig. 2A, B).

Tomographic (Slagstad, et al., 2018) and geochronologic (Tucker, et al., 1990) data suggest that the Sveconorwegian orogenic belt continued northwards along the coast of W Norway, and ca. 1066 Ma mafic dikes (Mertanen, et al., 1996) and ca. 1050 Ma extensional structures (Koehl, et al., 2018) in northern Norway may be an expression of tectonic activity outboard of the present-day margin. After ca. 1000 Ma, the Sveconorwegian orogen was dominated by widespread extension (Slagstad, Roberts, Coint, Høy, Sauer, Kirkland, Marker, Røhr, Henderson, Stormoen, Skår, Sørensen and Bybee, 2018, Viola, et al., 2011), with intermittent compression (Bolle, et al., 2018); thus both tectonic style and timing match that of earliest Valhalla orogenesis, consistent with different zircon Hf evolutionary pathways for the Grenville vs. Sveconorwegian/Valhalla orogens (Spencer, et al., 2018).

The last stage of extension in the Sveconorwegian orogen is recorded by mafic dikes at ca. 850 Ma (Walderhaug, et al., 1999), and extensional structures in northern Norway as young as ca. 800 Ma (Koehl, Bergh and Wemmer, 2018) suggest that the entire present-day coastline of Norway was affected by far-field tectonic forces (Fig. 2D). An extensional depositional environment with intervening compressional phases was active until at least ca. 590 Ma (Cutts, et al., 2010, Kirkland, et al., 2016), covering large tracts of Baltica (Sparagmite Basin, Nystuen, 1987), Laurentia (Spencer, et al., 2015), exotic entities including the Pearya terrane (Estrada, et al., 2018, Malone, et al., 2017, Trettin, 1987), domains of northeastern Russia (Lorenz, et al., 2012), the Moine and Dalradian supergroups (Kirkland, et al., 2008, Strachan, et al., 2013), the Kalak Nappe Complex in northern Norway (Kirkland, et al., 2007), Krummedal succession on Greenland (Kalsbeek, et al., 2000), and terranes on Svalbard (Johansson, et al., 2005) (Fig. 2E). This series of linked basins received detrital input from the eroding Sveconorwegian orogen and other, older and younger continental sources. Sedimentation was interrupted by compressional orogenic events e.g., the Renlandian (980–910 Ma), Knoydartian (840–830 Ma) (Cawood, Strachan, Cutts, Kinny, Hand and Pisarevsky, 2010), and Snøfjord events (Kirkland, et al., 2006), probably related to intermittent active-margin advance, consistent with formation along a long-lived, active margin until at least ca. 700 Ma. These units are exclusively found in Early Paleozoic allochthons, and their relationship to their current basements is unknown.

Discussion

Scenario 1 is essentially the same as that suggested by Slagstad et al. (2017), where the Grenville and Sveconorwegian orogens reflect different settings along the same continental margin, akin to the Himalaya (collision) and Indonesian (arc) orogens on the southern Asian margin (Fig. 2D, G). The North Atlantic allochthons cannot be readily incorporated into this scenario, but since the relationship between the allochthons and their basement is essentially unconstrained, this does not rule out this scenario.

Recognizing the accretionary nature of the Sveconorwegian orogen and assuming a more easterly but relatively Laurentia-proximal location of Baltica at ca. 1.0 Ga, allows a second scenario, in which the Sveconorwegian orogen forms part of the early Valhalla orogenic system (Fig. 2E, H). As outlined above, this shift in paradigm permits an internally consistent interpretation that ties the main orogenic events of the North Atlantic region together into a coherent tectonic framework that is valid until ca. 700 Ma.

Late Meso- and early Neoproterozoic accretionary orogens are found on most continents (e.g., Campanha, et al., 2019, Cawood, et al., 2009) and although the allochthonous North Atlantic Neoproterozoic successions can be correlated based on similarities in stratigraphy, metamorphic and magmatic history, and provenance (e.g., Cawood, Strachan, Cutts, Kinny, Hand and Pisarevsky, 2010, Kirkland, Daly and Whitehouse, 2007, Strachan, Prave, Kirkland and Storey, 2013), it is likely that there were several other, coeval active margins with broadly similar tectonic and temporal evolution. Thus, unless the allochthons show some unique feature that allows them to be correlated, e.g., age of deposition, metamorphic and magmatic events, one could argue that they are not correlative (Fig. 2F, I; Corfu, et al., 2007). Complicating things even further is the fact that the Neoproterozoic successions were accreted onto their respective basements during Early Paleozoic orogenesis, and may even have been accreted onto one continent but now be stranded on the margin following subsequent break up. This cryptic tectonic evolution allows for a third and probably most controversial, but nonetheless possible, scenario in which Laurentia and Baltica separated at or before ca. 1.25 Ga and remained separate until Early Paleozoic Caledonian continent-continent collision.

Conclusions

Given our present knowledge about the tectonic evolution of the Grenville and Sveconorwegian orogens, the ensuing Neoproterozoic evolution of the North Atlantic region, and paleomagnetic constraints, a number of different Baltica–Laurentia configurations in Rodinia are possible. These include scenarios where the two continents remain in relative proximity during and after Grenville–Sveconorwegian orogenesis, forming different portions along the same active margin, analogous to the Himalayan–Indonesian portion of the southern Asian margin. Alternatively, a paleomagnetically unconstrained eastward shift of Baltica would allow the Sveconorwegian orogen to represent the early stages of the Valhalla orogen. This scenario accounts for the current distribution of Neoproterozoic successions in Early Paleozoic allochthons around the North Atlantic, but assumes that the allochthons formed in relative proximity to their currently local basement, for which there is no clear evidence. The third scenario is that Baltica and Laurentia separated at or before ca. 1.25 Ga and remained separated until Early Paleozoic Caledonian continent-continent collision. In this scenario, the Neoproterozoic units resting on Baltica may be derived from the Valhalla orogen or unrelated but similar accretionary orogens elsewhere. The least likely scenario, based on geological and paleomagnetic grounds, appears to be the “classic” configuration where the Grenville and Sveconorwegian provinces represent one side of an extensive collisional orogen formed during amalgamation of the Rodinia supercontinent.

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Figures

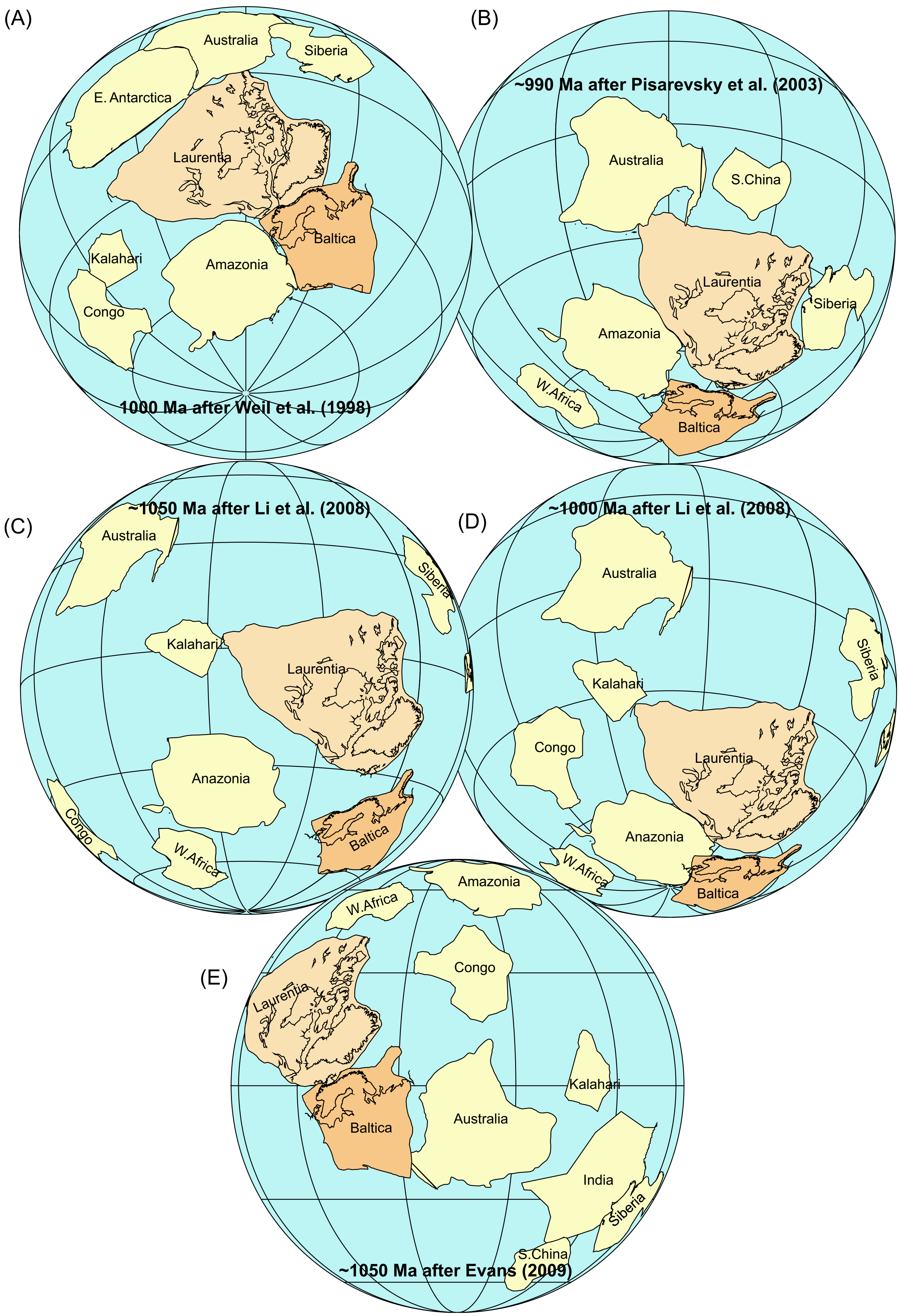
Figure 1. Examples of simplified Rodinia models at ca. 1 Ga, highlighting the positions of Baltica and Laurentia. Early Rodinia models (Dalziel, 1991, Hoffmann, 1991, Moores, 1991) suggested a connection between present-day Canada and Australia and southwest USA and East Antarctica, referred to as SWEAT. Baltica was reconstructed adjacent to either Greenland or Labrador. Later, Weil et al. (1998) presented a paleomagnetic synthesis that generally supported the SWEAT configuration

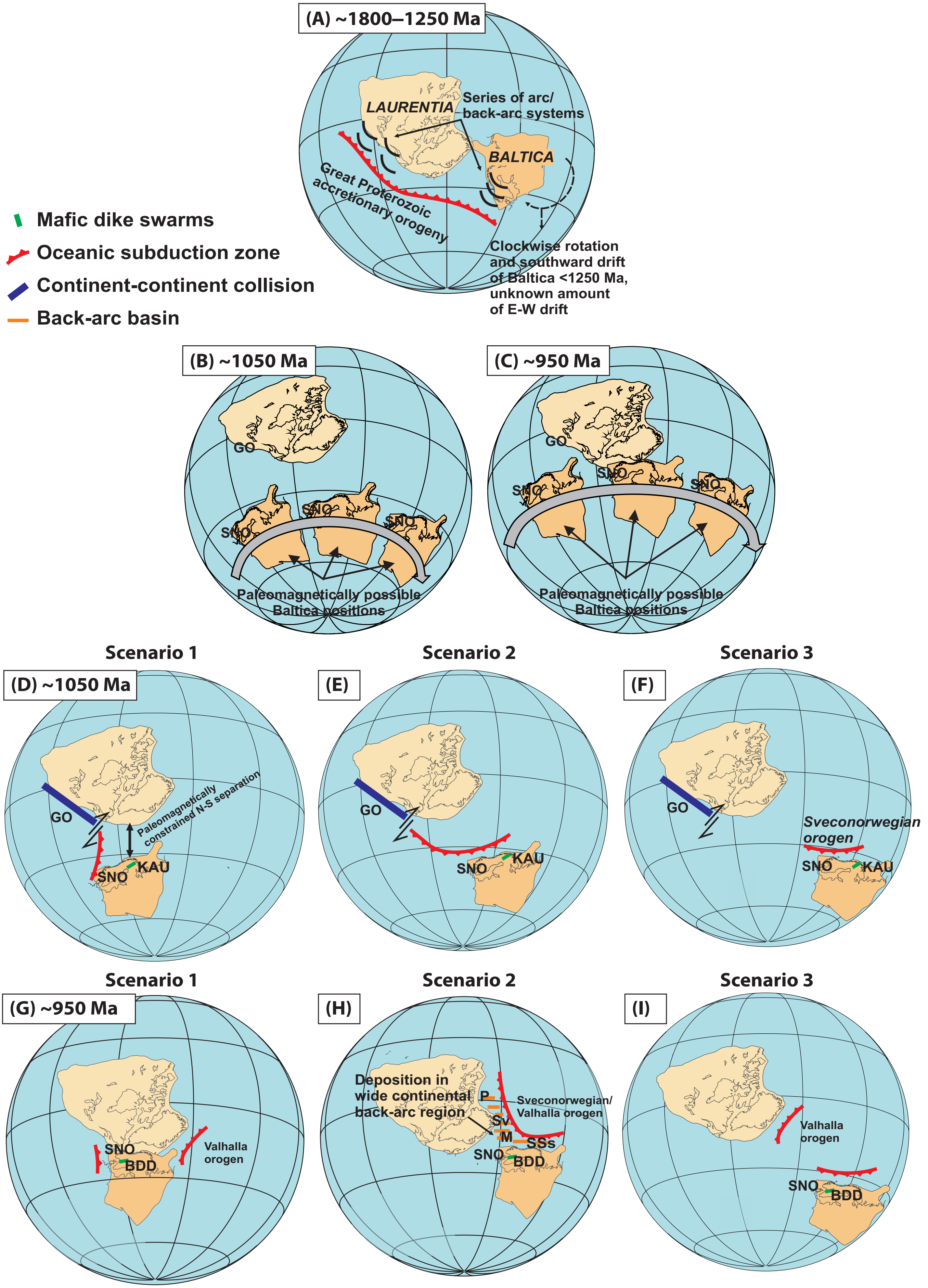
(A). More recent Rodinia reconstructions have revised the SWEAT configuration, proposing a configuration in which Australia was connected with western USA instead of Canada – referred to as the AUSWUS configuration (Karlstrom, et al., 1999). Later, Wingate et al. (2002) and Pisarevsky et al. (2003) questioned the robustness of the previous models on the basis of new paleomagnetic data and proposed the AUSMEX configuration, with Australia adjacent to the southernmost part of Laurentia (B). Li et al. (2008) proposed yet an alternative configuration, somewhat similar to the SWEAT models (C, D). The most radical suggestion is perhaps Evans's (2009) model, who placed Amazonia at the northern margin of Rodinia, leaving the southern Grenville–Sveconorwegian margin facing a major ocean (E). Despite the differences between the models, the Grenville–Sveconorwegian correlation has rarely been questioned.

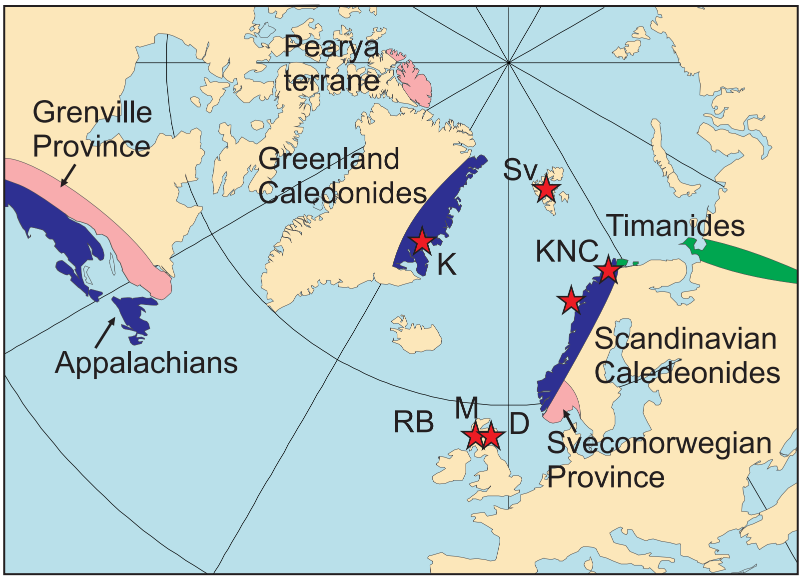
Figure 2. (A) 'Classic' pre-Grenvillian, Mesoproterozoic reconstruction of Baltica and Laurentia, with an extensive, active southern margin. Modified after Karlstrom et al. (2001). (B, C) Various Baltica–Laurentia configurations permitted by the paleomagnetic data at ca. 1050 and 950 Ma. Latitudes are after Li et al. (2008) and various longitudes have been selected to illustrate various possible scenarios, including scenario 1, which is the 'classic' contiguous Baltica–Laurentia configuration (D, G); scenario 2, with Baltica shifted eastward from its classic position (E, H); and scenario 3, with Baltica and Laurentia separated and unrelated to each other. Given a range of geological arguments that the Sveconorwegian orogen did not form as a result of continent-continent collision, and the paleomagnetic data suggesting significant separation of Baltica and Laurentia at the peak of orogenic activity, the 'classic' configuration, with Baltica and Laurentia representing one side of a major collisional orogenic belt interior to Rodinia, seems the least likely. Abbreviations: BDD–Blekinge–

Dalarne mafic dikes; GO–Grenville orogen; KAU–Kautokeino mafic dikes; M–Moine succession; P–Pearya terrane; SNO–Sveconorwegian orogen; SSv–Sørøy-Sværholt succession; Sv–Svalbard terranes.

Figure 3. North Atlantic region with relevant geologic features. Pink blocks correspond to late Meso- to early Neoproterozoic orogens, green to the late Neoproterozoic Timanian orogen, and dark blue to the Paleozoic Caledonian–Appalachian orogen. Red stars indicate areas where evidence of late Meso- through late Neoproterozoic deposition, deformation, and magmatism, interpreted to be related to active-margin processes in a long-lived Rodinia-exterior orogen, have been found in Caledonian allochthonous nappes. Yellow stars indicate similar evidence in autochthonous – with respect to Caledonian tectonism – positions. Abbreviations: ALN–Alnö carbonatite; D–Dalradian succession; EG–Egersund mafic dikes; Ext.–Extensional faulting; FEN–Fen carbonatite; HUN–Hunnedalen mafic dikes; KAU–Kautekeino mafic dikes; K-Krummedal succession; M–Moine succession; RB–Rockall Bank; SAR–Sarfartoq carbonatite; SIL–Sept Isles layered intrusion; SSs–Sørøy and Sværholt successions; Sv–Svalbard terranes.


(A)
Australia
Siberia
E. Antarctica
Laurentia
Baltica
Kalahari
Amazonia
Congo
1000 Ma after Weil et al. (1998)
(B)
~990 Ma after Pisarevsky et al. (2003)
Australia
S.China
Laurentia
Siberia
Amazonia
W.Africa
Baltica
(C)
~1050 Ma after Li et al. (2008)
Australia
Siberia
Kalahari
Laurentia
Anazonia
Congo
W.Africa
Baltica
(D)
~1000 Ma after Li et al. (2008)
Australia
Siberia
Kalahari
Congo
Laurentia
Anazonia
W.Africa
Baltica
(E)
Amazonia
W.Africa
Congo
Laurentia
Baltica
Australia
Kalahari
India
Siberia
S.China
~1050 Ma after Evans (2009)


(A) ~1800–1250 Ma
LAURENTIA
Series of arc/
back-arc systems
BALTICA
Great Proterozoic
accretionary orogeny
Clockwise rotation
and southward drift
of Baltica <1250 Ma,
unknown amount
of E-W drift
Mafic dike swarms
Oceanic subduction zone
Continent-continent collision
Back-arc basin
(B) ~1050 Ma
GO
SNO
SNO
SNO
Paleomagnetically possible
Baltica positions
(C) ~950 Ma
GO
SNO
SNO
SNO
Paleomagnetically possible
Baltica positions
Scenario 1
(D) ~1050 Ma
GO
Paleomagnetically
constrained N-S separation
SNO
KAU
Scenario 2
(E)
GO
SNO
KAU
Scenario 3
(F)
GO
Sveconorwegian
orogen
SNO
KAU
Scenario 1
(G) ~950 Ma
SNO
BDD
Valhalla
orogen
Scenario 2
(H)
Deposition in
wide continental
back-arc region
P
Sv
M
SSs
Sveconorwegian/
Valhalla orogen
SNO
BDD
Scenario 3
(I)
Valhalla
orogen
SNO
BDD


Pearya
terrane
Grenville
Province
Greenland
Caledonides
Sv
Timanides
KNC
K
Appalachians
Scandinavian
Caledeonides
M
RB
D
Sveconorwegian
Province