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Laurentia-Baltica-Amazonia relations during Rodinia assembly

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ABSTRACT

Laurentia, Baltica and Amazonia are key building blocks of the end Mesoproterozoic to early Neoproterozoic supercontinent Rodinia. Integration of available data sets enables development of a dynamic model for the Proterozoic interaction of these continental fragments in which Amazonian collision with Laurentia is linked to rifting and rotation of Baltica from Laurentia to collide with Amazonia's northern margin. The geological record of the three blocks indicates a long history extending through the Paleoproterozoic and Mesoproterozoic involving continental growth onto Archean cratonic cores through convergent plate interaction and accretionary orogenesis. This history requires the existence of a long lived and probably large oceanic tract outboard of these continental fragments; the Mirovoi Ocean. Prior to 1265 Ma, Laurentia and Baltica formed a single tectonic plate. Sometime after this, but prior to 990 Ma, these blocks broke into two plates through opening of the triangular shaped Asgard Sea between northeast Laurentia and northern Baltica. After opening of the Asgard Sea the southern margin of Baltica lay at right-angles to east Laurentia. Thus, during final closure of the Mirovoi Ocean and collisional orogenesis, the western margin of Amazonia collided with the east Laurentian margin while the southern margin of Baltica collided with the northern margin of Amazonia. Laurentia, Baltica and Amazonia maintained this configuration until the final breakup of Rodinia with the opening of the Iapetus Ocean at the end of the Neoproterozoic.

1. Introduction

The Rodinia supercontinent formed at the end of the Mesoproterozoic – beginning of Neoproterozoic through collisional assembly of most of the Earth's Archean and Proterozoic continental fragments (Hoffman, 1991; Li et al., 2008). This process of continental amalgamation is recorded in a series of orogenic belts of which the Grenville Orogen of eastern North America (Laurentia) is considered the archetypal example (Rivers, 2015, and references therein). The subsequent development of rift and passive margin successions, most notably around the margins of Laurentia, provides a record of the breakup of Rodinia (Bond et al., 1984). In detail however, there is uncertainty in the absolute and relative position of the continental fragments that enveloped Laurentia (e.g., Evans, 2013, and references therein), due to the incomplete nature of the geological and paleomagnetic record, and reworking of Rodinian successions by subsequent tectonic events, such as during the Appalachian and Cordilleran orogenic cycles. Even for the well-studied East Laurentian region, and its record of interaction with Baltica and Amazonia, a variety of paleogeographic models have been proposed for the configuration and interaction of these cratonic blocks. For example, the Sveconorwegian Orogen in southern Baltica (present co-ordinates) is generally inferred to have formed through continental collision with Amazonia during Rodinia assembly and be contiguous with the Grenville Orogen (Bingen et al., 2008c; Gower et al., 1990; Park, 1992) but recently formation of the orogen in an accretionary setting on the margin of Rodinia has been proposed (Slagstad et al., 2013a). The assembly of Amazonia and Laurentia has been related to both oblique or orthogonal collision, dependent in part on the relative positions of these cratons before and after collision (e.g., Dalziel, 1997; Elming et al., 2009; Evans, 2013; Johansson, 2009; Park, 1992; Pisarevsky et al., 2014; Pisarevsky et al., 2003; Tohver et al., 2004b). Some models have questioned whether Amazonia was the colliding element or even if there was collisional orogenesis (Dalziel et al., 2000; Evans, 2009; Santos et al., 2008). Differences between models reflect evolving data sets as well as a focus on particular regions or data types (e.g., paleomagnetic, geochemical, geochronological). This paper integrates available data on the late Mesoproterozoic to early Neoproterozoic records of Laurentia, Baltica and Amazonia, and although uncertainties remain, proposes a dynamic model in which Amazonian collision with Laurentia is linked to rifting and rotation of Baltica from Laurentia to collide with Amazonia's northern margin (present coordinates).

2. Geologic Framework

Interactions between Laurentia, Baltica and Amazonia are recorded in a series of rock units formed and deformed during extensional and compressional interactions, and largely preserved within, or adjacent to, the orogenic belts that developed on the margins of these continental fragments during the Mesoproterozoic to early Neoproterozoic (Figs. 1, 2). These orogenic belts are the Grenville Orogen in eastern Laurentia, the Valhalla orogen in north-eastern Laurentia, the Sveconorwegian Orogen along the south-western margin of Baltica, and the Sunsas and Putumayo orogens along Amazonia's south-western and northern margins. The late Mesoproterozoic opening of the Asgard Sea also caused the development of the north-eastern and eastern (Timanian – Central and South Uralian) passive margin of Baltica (see also the Pechora Sea of Puchkov, 2005), which was folded and deformed during the late Neoproterozoic Timanian orogeny. Figure 3 outlines the inferred timing of extensional and compressional events, which are in turn related to opening and closing of oceanic tracts related to dispersal and coming together of the main continental blocks and associated magmatic arcs.

2.1. East and southeast Laurentia – Grenville Orogen

The Grenville Orogen (Figs. 1, 2) and adjoining Yavapai/Mazatzal and Granite-Rhyolite provinces preserve a long lived, late Paleoproterozoic to late Mesoproterozoic (from at least ~1.8 Ga) history of igneous activity emplaced into continental margin, island arc and back-arc settings (Condie, 2013; Davidson, 2008; Karlstrom et al., 2001; Karlstrom and Bowring, 1993; Slagstad et al., 2009) in response to subduction of the outboard Mirovoi oceanic lithosphere (e.g., Fig. 1). Orogenic events within this long lived accretionary arc system include the Labradorian (~1680-1660 Ma), Pinwarian (~1520-1450 Ma, Elzevirian (1245-1220 Ma) and Shawinigan (1200-1140 Ma) orogenies and are ascribed to pulses of stabilization involving back-arc closure and arc accretion along, and outboard of, the Laurentian margin (Carr et al., 2000; Corriveau and van Breeman, 2000; Gower and Krogh, 2002; Rivers and Corrigan, 2000). Lithospheric extension within the external segments of the Grenville Orogen and adjacent Laurentian foreland are recorded by emplacement of mafic dykes at 1275 Ma, 1250 Ma and 1235 Ma and accumulation of the rift-related Wakeham and Seal Lake supracrustal successions of sedimentary and bimodal igneous rocks at ~1270-1245 Ma (Rivers, 1997, and references therein). The latter stages of this activity overlap with the Elzevirian orogeny and related to slab rollback (Hynes and Rivers, 2010).

High-grade metamorphism and deformation extending along the Grenville Orogen in the north-eastern US and Canada commenced around 1090 Ma and continuing until 980 Ma, and are taken to mark the onset of continental collision (Gower and Krogh, 2002). This tectonothermal event is termed the Grenville orogeny and is broken into the Ottawan (1090-1020 Ma) and Rigolet phases (1000-980 Ma) (Hynes and Rivers, 2010; McLelland et al., 2001; Rivers, 1997). The Ottawan is a high temperature event focused within the transported allochthonous rocks of the orogen, whereas the lower temperature Rigolet phase is developed in the autochonous inboard units of the orogen. Post-tectonic magmatism along with exhumation and cooling of the orogen extended until around 950 Ma (Gower and Krogh, 2002, and references therein; Tohver et al., 2006). The timing of tectonothermal events in the southern Grenville Orogen, exposed within the Llano Uplift of Texas, are earlier than those to the north. Convergent plate interaction in the southern Grenville terminated with deformation and metamorphism of the succession between ~1150 Ma and 1120 Ma, which is related to arc accretion onto the Laurentian margin and collision of an outboard continental block, and was followed by some late tectonic to post tectonic magmatism extending to 1080 Ma (Mosher, 1998; Mosher et al., 2004).

The collisional suture between Laurentia and Amazonia (Fig. 2) is inferred to lie within the Grenville basement inliers of the southern Appalachian Orogen (e.g., Hynes and Rivers, 2010; Loewy et al., 2003), which is the late Neoproterozoic to Paleozoic orogen lying outboard of, and locally overprinting, the Grenville Orogen. The whole rock lead isotopic signature of the inliers display a relatively ^{207}Pb-rich array, overlapping the Stacey and Kramers (1975) crustal evolution line (Loewy et al., 2003). Amazonia samples also fall on this line consistent with derivation of the two regions from a common source. In contrast, the lead signature of Laurentian crust lies below the average crustal evolution curve. The suture between Laurentian and Amazonian crust is inferred to lie between the southern Appalachian inliers and those to the north and the main Grenville province (Hynes and Rivers, 2010). Based on detailed geochemical and geochronological studies within the Blue Ridge inlier in the southern Appalachians (Aleinikoff et al., 2000; Tollo et al., 2006; Tollo et al., 2004), three magmatic stages of anorthosite–mangerite–charnockite–granite (AMCG) emplacement occurred at ~1185-1145 Ma, ~1120-1110 Ma and ~1080-1030 Ma. High-temperature, ductile deformation occurred between ~1080 Ma and 1050 Ma with no evidence for earlier deformation. This tectonothermal record contrasts with that of the main Grenville Orogen to the north (Fig. 3). Thus, the southern Appalachian basement inliers are inferred to represent a fragment of the colliding Amazonian craton that was left attached to Laurentia during breakup of Rodinia associated with the formation of the Iapetus Ocean. Opening of Iapetus took place on the eastern margin of Laurentia in the late Neoproterozoic to early Paleozoic (Cawood et al., 2001).

The Proterozoic paleomagnetic record for Laurentia is of variable quality. The pre-1.45 Ga paleomagnetic record is fragmentary, but is reasonable for the period 1.45-1.0 Ga (e.g., Elming et al., 2014; Pisarevsky et al., 2014). There is a >200 Ma gap in reliable Laurentian paleomagnetic data between ~1000 and ~790 Ma, followed by another ~100 Ma gap between ~720 and 615 Ma (e.g., Pisarevsky et al., 2008; Pisarevsky et al., 2003). Later (>615 Ma) Ediacaran Laurentian paleopoles are controversial (e.g., Halls et al., 2015; McCausland et al., 2011), but they all suggest that Rodinia had already broken up (Pisarevsky et al., 2008). Consequently paleopositions of Laurentia are paleomagnetically well constrained for the initial (>1000 Ma) stages of the Rodinian assembly, and for the time of Rodinian breakup, but poorly constrained for the final stage of the Rodinian assembly (1000-920 Ma).

2.2. Northeast Laurentia – Valhalla Orogen

The Valhalla Orogen (Cawood et al., 2010; Cawood et al., 2015) is preserved in northeast Laurentia (Fig. 2) and in correlative successions along northern Laurentia and possibly extending as far as Siberia (Cawood et al., 2016; Likhanov et al., 2015; Malone et al., 2014). It is characterized by two cycles of l**atest Mesoproterozoic to mid-Neoproterozoic (1030–710 Ma) sedimentation and orogenic activity that is currently exposed in Scotland, Shetland, East Greenland, Svalbard, and Norway. These blocks largely occur within, and are reworked by,** the Neoproterozoic to Paleozoic Caledonian Orogen, which is the along strike extension of the Appalachian Orogen. The first cycle of sedimentary units are siliciclastic dominated and include the Krummedal in East Greenland and equivalent units (e.g. Morar, Yell Sound, Brennevinsfjorden, Svaerholt). On the basis of the age of the youngest detrital zircon grains and cross-cutting igneous bodies these units accumulated between 1030-980 Ma (Cutts et al., 2009; Friend et al., 2003; Kirkland et al., 2006; Kirkland et al., 2007; Kirkland et al., 2008; Watt et al., 2000). The units were deformed and metamorphosed up to amphibolite facies, locally migmatized, and intruded by granites during Renlandian orogenesis between 980 Ma and 920 Ma (Cawood et al., 2010; Kalsbeek et al., 2008; Leslie and Nutman, 2003; Vance et al., 1998; Watt and Thrane, 2001). The igneous bodies display calc-alkaline affinities (Burns et al., 2004; Johansson et al., 2000; Kirkland et al., 2007) and are considered to have formed in a magmatic arc along and outboard of the NE Laurentian margin during subduction of oceanic lithosphere (Asgard Sea, Cawood et al., 2010; Cawood et al., 2015; Cawood et al., 2016). A second cycle of tectonothermal activity involving initial sedimentation from 910-870 Ma (Cawood et al., 2004; Friend et al., 2003; Kirkland et al., 2007) followed by igneous activity, deformation and metamorphism, focused mainly in Scotland, occurred during the Knoydartian orogeny, which extended until 730 Ma (Cawood et al., 2010; Cawood et al., 2015; Friend et al., 2003), and is also inferred to have occurred in a supra-subduction zone environment.

Little deformed, extension-related rift sedimentation overlies Laurentian basement inboard of the Valhalla Orogen. This includes the ~1000 Ma Torridon Group in Scotland, which is approximately time-equivalent strata to the Krummedal succession in East Greenland, and the unconformably underlying ~1100 Ma Sleat and ~1200 Ma Stoer groups (Kinnaird et al., 2007; Rainbird et al., 2001; Turnbull et al., 1996). In western Svalbard, within the orogen, Balashov et al. (1996) reported U–Pb zircon evaporation ages of 1160 ± 40 Ma for mafic and felsic igneous rocks of the Eimfjellet Group, which separates metasedimentary rocks of the underlying Isbjörnhamma and overlying Deilegga groups. The igneous rocks display within plate geochemistry suggesting igneous activity and enveloping sedimentary rocks developed in an extension related setting.

The Valhalla Orogen lies on the Laurentian margin approximately along strike from the Grenville Orogen. However, unlike the Grenville orogen in which end Mesoproterozoic to early Neoproterozoic orogenesis (Grenvillian) in related to continent-continent collision and thus took place internally within an assembling Rodinia, the Valhalla Orogen is considered to be an external accretionary orogen that developed on the margin of Rodinia (Cawood et al., 2010; Cawood et al., 2016; but see Lorenz et al., 2012, for alternative explanation). The change in the character and setting of orogenesis between the two regions is related to the late Mesoproterozoic clockwise rotation of Baltica with respect to Laurentia (Cawood et al., 2010). Comparison of time equivalent paleomagnetic poles for Laurentia and Baltica indicate that from 1770 Ma to 1265 Ma northeast Laurentia (East Greenland) occupied an internal location within the Nuna supercontinent and lay adjacent to the north-eastern margin of Baltica (Fig. 1; e.g., Pisarevsky and Bylund, 2010). By ca. 990 Ma, Baltica occupied a position which is rotated 95° clockwise with respect to Laurentia with its Scandinavian margin facing Scotland, the Rockall Bank and southeast Greenland, and Laurentia and Baltica maintained this configuration until opening of the Iapetus ocean at the end of the Neoproterozoic (Cawood and Pisarevsky, 2006; Cawood et al., 2010; Pisarevsky et al., 2003). Unfortunately, unlike Laurentia, Baltica is not well constrained by paleomagnetic data between 1250 and 950 Ma (Elming et al., 2014; Pisarevsky et al., 2014). Out of three published poles for this interval, two (Bamble Intrusions and Laanila Dykes) are imprecisely dated (Elming and Pesonen, 2010; Mertanen et al., 1996). The third pole from ca. 1120 Ma Salla dyke (Salminen et al., 2009) is supported by a contact test, but unfortunately the remanence direction of the unbaked host rock is close to the dyke direction, which somewhat undermines the reliability of this test. In addition, this pole is based on just one dyke, so the geomagnetic secular variations are not averaged. If the Salla pole applied, it suggests an unreasonably large ocean, at least 6000 km wide, between Laurentia and Baltica at 1120 Ma (Fig. 4; Pisarevsky, 2016). In view of the issues with the Baltican poles we have not used them in our reconstructions, which are based on the relatively simple model for the Asgard Ocean opening (Cawood et al., 2010).

2.3. Northeast Baltica – Timanides and pre-Urals

The north-eastern margin of Baltica (Fig. 2), and along strike equivalent units in the Central and South Urals to the east (termed the pre-Urals), record a long history of rift and passive margin sedimentation. The oldest units, which lie inboard of the late Neoproterozoic Timanide Orogen, include siliciclastic-dominated sedimentation within the Mezen' Rift (aulacogen) that unconformably overlies Baltica basement (Bogdanova et al., 2008). Microfossils indicate Ectasian (mid-Mesoproterozoic) to Tonian (early Neoproterozoic) ages (Veis et al., 2004). The outboard Timanide succession is up to 10000 m thick and consists of a siliciclastic-dominated succession with some interstratified carbonates (Puchkov, 2010). Age of sediment accumulation is poorly constrained. Rb-Sr and K-Ar dates on the intrusions suggest a pre-1.1 Ga age of the lower part of succession (Puchkov, 2010) and acritarchs from the mid to upper parts of the succession extend the age of sedimentation to the mid-Neoproterozoic (late Riphean, Siedlecka et al., 2004, and references therein). This succession is interpreted to record an initial history of Mesoproterozoic intracratonic extension and rift-related sedimentation and magmatism (Mezen' Rift and lower Timanide succession) followed by, in the latest Mesoproterozoic to early Neoproterozoic, development of a passive-margin succession containing cratonic-derived siliciclastic sedimentary rocks (Maslov, 2004; Maslov et al., 1997; Maslov and Isherskaya, 2002; Nikishin et al., 1996; Siedlecka et al., 2004). The rifting could be related to the 1385-1380 Ma Mashak igneous event in southern Urals (Puchkov et al., 2013). In the late Neoproterozoic, the Uralian and Timanian margins were inverted during ocean closure and emplacement of an outboard upper plate arc system onto the passive margin, to form the pre-Uralide–Timanide orogen around 540 Ma (Kuznetsov et al., 2015, and references therein).

2.4. Southwest Baltica – Sveconorwegian Orogen

The Sveconorwegian Orogen lies along the SW margin of Baltica (Figs. 1, 2) and is divided by Bingen et al. (2008c) into 5 lithotectonic units, which from east to west are: Eastern Segment, representing a para-autochthonous unit of Baltica, and four outboard terranes, including the Idefjorden, Kongsberg, Bamble and Telemarkia terranes that were accreted to Baltica during the Sveconorwegian orogeny. The Eastern Segment consists largely of deformed granitoids, mainly of late Paleoproterozoic age (Bingen et al., 2005). The outboard terranes contain latest Paleoproterozoic and Mesoproterozoic volcanic and plutonic rocks and associated metasedimentary rocks that are interpreted to have formed during pulses of convergent plate magmatism, lithospheric extension, and a series of tectonothermal events (e.g., 1640-1520 Ma Gothian,1520-1480 Ma Telemarkian, 1470-1420 Ma Hallandian–Danopolonian orogenies; Åhäll et al., 2000; Åhall and Connelly, 1998; Bingen et al., 2008a; Connelly and Åhäll, 1996).

Bingen et al. (2008b; 2008c) divided the Sveconorwegian orogeny into four phases on the basis of the spatial and temporal distribution of tectonothermal events. The oldest is the Arendal phase from 1140-1080 Ma, which is ascribed to ocean closure and collision of the Idefjorden and Telemarkia terranes, producing the Bamble and Kongsberg blocks. This phase involved an early pulse of granulite facies metamorphism between 1140 and 1125 Ma, focused in the Bamble terrane, and a later second pulse of amphibolite facies metamorphism extending to 1080 Ma and related to thrusting of Bamble onto Telemarkia. The 1050-980 Ma Agder phase constitutes the main pulse of the Sveconorwegian orogeny and involves high-pressure metamorphism and exhumation of the Idefjorden terrane, and crustal thickening, plutonism and metamorphism, up to granulite facies, in the Telemarkia Terrane. The 980-970 Ma Falkenberg phase reflects final compressional assembly with eclogite facies metamorphism of the Eastern Segment. The final Dalane phase extends from 970 to 900 Ma and includes post-collisional magmatism (including AMCG plutons), extension and metamorphic core complex formation, as well as high-temperature granulite facies metamorphism at 930-920 Ma in the Telemarkia terrane.

The Sveconorwegian Orogen is generally considered to constitute the extension of the Grenville Orogen into SW Baltica (Gower et al., 1990; Karlstrom et al., 2001; Karlstrom et al., 1999) and hence orogenesis is also related to continental collision with Amazonia and related South American blocks (Bingen et al., 2008c). This interpretation has recently been challenged by Slagstad et al. (2013a) who argue that the Sveconorwegian is an accretionary orogen with a history distinct from the adjoining Grenville Orogen (but also see comment and reply, Möller et al., 2013; Slagstad et al., 2013b). Slagstad et al. (2013a) identified a large, little deformed, calc-alkaline batholith, termed the Sirdal magmatic belt, dated at 1070-1020 Ma (see also Coint et al., 2015) within the Telemarkia terrane that they related to ongoing convergence on the margin of Rodinia. Similarly, Bybee et al. (2014) agued on the basis of isotopic data from anorthosite and co-magmatic pyroxene megacrysts within the 950-920 Ma Rogaland Anorthosite Province (Telemarkia terrane) that these rocks formed in a long-lived Andean-type margin. The promotion of contrasting collisional and accretionary orogenic models to account for the tectonothermal record of the Sveconorwegian Orogen reflect the complex history and contrasting datasets with the region displaying a high-grade metamorphic and deformational record similar to collisional orogens but a geochemical record that at least locally records magmatic arc convergent plate margin activity. As outlined in the discussion, these conflicting datasets can be resolved and incorporated into a model which looks at the formation of the orogen within the overall context of Baltica, Laurentia and Amazonia interrelationships.

2.5. Southwest Amazonia – Sunsás Orogen

The Sunsás Orogen (also referred to as the Sunsás-Aguapeí Orogen) formed along the western margin of the Amazonian craton (Fig. 2) during the Mesoproterozoic (1300-1070 Ma; Litherland et al., 1989; Santos et al., 2008). The Sunsas Orogen represents the youngest in a semi-continuous history of accretion of new crust onto the western margin of the

Amazon craton from 2000 Ma to 1300 Ma (Maroni-Itaciúnas, Ventuari-Tapajós, Rio Negro-Juruena, Rondonia-San Ignacio belts) during successive periods of arc magmatism (Bettencourt et al., 2010; Tassinari et al., 2000; Teixeira et al., 2010). The orogen includes thick metasedimentary units (Aguapei, Nova Brasilândia and Sunsas groups) that accumulated sometime after ~1200 Ma, as constrained by the age of the youngest detrital zircons (Santos et al., 2000), and prior to tectonothermal activity during the Sunsas orogeny dated at 1120-1080 Ma (Boger et al., 2005; Tohver et al., 2004a; Tohver et al., 2004b). Effects of orogenesis are variable ranging from little deformed upright folding and low grade metamorphism to multiply deformed rock units displaying metamorphosed medium pressure and temperature upper amphibolite and granulite facies assemblages (Boger et al., 2005; Tohver et al., 2004b). Accumulation of the metasedimentary units sometime between 1200-1120 Ma overlaps with development of strike-slip shear zones in the adjoining Amazon craton (1190-1130 Ma), which led Tohver et al. (2004b) to propose that craton and sedimentary units could have been juxtaposed after sediment accumulation, during the Sunsas orogeny. Combined with data from the Sunsas belt in Bolivia, this has led to a model for orogenesis related to accretion of outboard cratonic blocks (e.g. Paragua block and the Arequipa-Antofalla basement) to the Amazon craton (Boger et al., 2005). But an alternative origin for the Paragua block was proposed by Santos et al. (2008) in which it represents a fragment of the Rondonia-Juruena Province preserved within the Sunsas Orogen. Tohver et al. (2004b; 2002) noted that relative to the main Grenville orogeny in NE Laurentia, orogenesis in the Sunsas belt as well as deformation within the adjoining Amazon craton, occurred earlier with no temporal equivalent to the main Grenville orogeny (see also Santos et al., 2008).

A suite of post-tectonic, tin-bearing granites were emplaced into the margin of the Amazon craton, including the Sunsas Orogen, between 1000-975 Ma (Bettencourt et al.,

1999) and the orogen and environs underwent exhumation and cooling during the early Neoproterozoic (1000-910 Ma; e.g., Teixeira et al., 2010; Tohver et al., 2006).

The timing of the Sunsas orogeny and deformation within the adjoining Amazon craton largely predates that for the main Grenville orogeny in eastern Laurentia (Fig. 1). This lead Tohver and co-authors (2004b; 2005; 2002) to propose that the Sunsas Orogen formed during oblique sinistral strike-slip collision between the Laurentia and Amazonia that commenced in the vicinity of the Llano uplift in southern Laurentia. Amazonian paleomagnetic data available at that time and their comparison with Laurentian ~1200-1000 Ma paleopoles supported this model, but the paleopole from the Aguapei sills (Elming et al., 2009), which were dated at 980 Ma (Ar-Ar), required Amazonia to undertake an anticlockwise half-pirouette as it moved along the Laurentian margin. Evans (2013) using a more restricted paleomagnetic dataset, that excluded the 980 Ma pole for the Aguapei sills as remagnetized and an alternative polarity for the 1200 Ma Nova Floresta pole (Tohver et al., 2002), proposed Amazonia originates from a position to the northeast of Laurentia and underwent 90^o of clockwise rotation prior to final orthogonal collision with the central East Laurentian margin. Recently, D'Agrella-Filho et al. (2016) undertook further study on the Aguapei sills and re-dated them at 1439 ± 4 Ma (U-Pb baddeleyite). Consequently the 980 Ma reconstruction of Elming et al. (2009) is no longer supported by the available data and the model of the oblique sinistral strike-slip collision between Amazonia and Laurentia (Tohver et al., 2004b; Tohver et al., 2005; Tohver et al., 2002) does not require the anticlockwise rotation of Amazonia.

2.6. North Amazonia – Putumayo Orogen

The Putumayo Orogen (Ibanez-Mejia et al., 2011) extends along the northern margin of the Amazon Craton (Fig. 2). It is preserved in a series of basement inliers within the northern Andes of South America (e.g., Ramos, 2010, and references therein) as well as in the Oaxaquia terrane of Mexico, which has been placed between Baltica and Amazonia in the Rodinian reconstructions (Fig. 2) (Keppie and Ortega-Gutiérrez, 2010; Pisarevsky et al., 2003). The orogen consists of Mesoproterozoic igneous and volcano-sedimentary protoliths deformed and metamorphosed during the late Mesoproterozoic to earliest Neoproterozoic (Cardona et al., 2010; Cordani et al., 2005; Cordani et al., 2000; Fuck et al., 2008; Ibanez-Mejia et al., 2015; Ibanez-Mejia et al., 2011). Geochronological and geochemical data on igneous rocks within the orogen indicate protracted igneous activity in the period ~1.3-1.1 Ga (and possibly as old as 1.47 Ga), which is inferred to have formed in magmatic arc and back arc systems either along, or flanking, the margin of the northern Amazon Craton (Cardona et al., 2010; Cordani et al., 2005; Ibanez-Mejia et al., 2015; Keppie and Ortega-Gutiérrez, 2010; Weber et al., 2010). Associated metasedimentary rocks have an arkosic composition with inferred depositional ages that approximate the ages of the dominant youngest detrital zircon population (Ibanez-Mejia et al., 2011), consistent with accumulation adjacent to a magmatic arc (cf., Cawood, 1991; Cawood et al., 2012).

Deformation, metamorphism, and local migmatization of the arc systems occurred at ~1165-1145 Ma (Cordani et al., 2005), 1100-1070 Ma (Olmecan orogeny in Oaxaquia, Solari et al., 2003; Weber et al., 2010) and 1050-1010 Ma (Cordani et al., 2005; Ibanez-Mejia et al., 2011). These events are ascribed to accretionary orogenesis associated with amalgamation of arc systems and their accretion onto the northern Amazonian margin (Ibanez-Mejia et al., 2011). Subsequent widespread deformation and metamorphism to granulite facies (750^{o}C and 8 kbar) occurred between 1010-970 Ma and is termed the Putumayo orogeny in the northern Andes (Ibanez-Mejia et al., 2015; Ibanez-Mejia et al., 2011) and the Zapotecan orogeny in Oaxaquia terrane of Mexico, which would be accreted to northern Amazonia at that time (Solari et al., 2003). This event has been linked to collision between northern Amazonia and

Baltica (Cardona et al., 2010; Ibanez-Mejia et al., 2011; Keppie et al., 2001; Keppie et al., 2004; Weber et al., 2010). Argon-argon ages in the range 970-920 Ma from the Colombian basement inliers are related to regional exhumation and cooling of the orogen (Cordani et al., 2005).

3. Tectonic Evolution

Any viable model that attempts to account for the tectonic evolution of, and interactions between, Laurentia, Baltica and Amazonia during Rodinia assembly must be able to account for the timing and distribution of compressional and extensional events outlined in figure 3. Key elements of this history are that east Laurentia, southwest Baltica, and southwest and north Amazonia all show evidence for an extended history of convergent plate interaction that commenced as early as the Paleoproterozoic and extended until the late Mesoproterozoic. This implies the existence of a long lived and probably large oceanic tract outboard of these continental fragments in pre-Rodinian time (Mirovoi ocean, Fig. 1; McMenamin and McMenamin, 1990). Periods of extension during this overall history of plate convergence are related to slab-rollback resulting in either back arc basin opening or inboard extension on the craton margin, whereas compressional events are related to advancing accretionary orogenesis (cf., Cawood et al., 2009) in which the upper plate overrides the lower plate resulting in arc amalgamations and/or accretion of outboard arcs to the continental margin (Hynes and Rivers, 2010; Ibanez-Mejia et al., 2011). Subduction was terminated through ocean closure resulting in continental-continental collision, which stabilized and isolated these previous continental margin assemblages into the interior of the assembled Rodinia supercontinent. The timing of accretionary orogenesis varies from margin to margin reflecting margin specific histories of arc amalgamation, but some overlap of events (e.g., Shawinigan and early orogenesis on north Amazonian margin, Fig. 3) suggest these events may have been part of global kinematic plate adjustments (cf., Cawood et al., 2009).

The timing and duration of inferred terminal orogenesis also varies between orogens. This is perhaps surprizing as these events are related to collision between Laurentia and Amazonia as well as Baltica and Amazonia and a similar timing between opposing colliding cratons would be expected. Thus, the timing of Sunsas orogenesis in Amazonia is discrete from orogenesis in Laurentia, although it does overlap with the end of deformation in the Llano uplift and the start of the main Ottawan orogenic pulse in the central and northern Grenville. But orogenesis within the basement inliers of the Appalachian orogen, which may represent fragments of Amazonia (Loewy et al., 2003, 2004) left behind in North America when the Iapetus Ocean opened at the end of the Neoproterozoic, does overlap with the main Ottawan phase of Grenville orogenesis (Fig. 3).

Early phases of the Sveconorwegian orogeny (Aredal) are older than the main Grenville event but overlap deformation in Amazonia. The main phase of the Sveconorwegian (Agder) does however overlap in part with the Grenville orogeny, notably the late Ottawan and Rigolet phases, and the later part of the Agder also overlaps with the Putumayo/Zapotecan orogeny on the northern Amazonian margin (Fig. 3). But the early Agder also corresponds with the time of inferred convergent plate margin activity (Sidal magmatic belt), which overlaps with final accretionary orogenesis on the northern Amazonian margin.

Throughout the Mesoproterozoic to early Neoproterozoic, the northeast Laurentian and northern Baltica margins show a history discrete from the other regions, and involve initial intra-plate extension followed by rifting and passive margin development, which in northeast Laurentia was followed by oceanic lithosphere subduction beneath the margin and accretionary orogenesis (Fig. 3). The contrasting histories of these regions with respect to east Laurentia, west Amazonia and southwest Baltic reflects the clockwise rotation of Baltica with respect to Amazonia in the Mesoproterozoic. This resulted in the opening of the Asgard Sea between northern Baltica and northeast Laurentia, and the oroclinal bending of Southwest Baltica (and the Sveconorwegian Orogen) with respect to east Laurentia (and the Grenville Orogen). The exact timing of opening of the Asgard Sea and oroclinal bending of Baltica with respect to Laurentia is poorly constrained. Paleomagnetic data only limit these events to start after 1265 Ma (e.g. Cawood 2010). Prior to this time the earlier Mesoproterozoic and older orogenic belt of southeast Laurentia and southwest Baltica formed a continuous linear belt (Buchan et al., 2000; Gower et al., 1990; Karlstrom et al., 2001). The lack of biostratigraphic control on the inferred rift and passive margin sedimentary rocks in the Timanide and Valhalla orogens means that the timing of the rift to drift transition associated with opening of the Asgard Sea is not known. If subduction along the Greenland margin is inferred to have commenced around 990 Ma (based on inferred affinities of igneous rocks in the Valhalla Orogen) then the Asgard Sea must have been opened by this time. On figure 3, we speculate that opening and rotation in part overlapped with inferred convergent plate margin activity in the Sveconorwegian Orogen; i.e. opening of the Asgard Sea was compensated by convergence along the southern margin of Baltica as represented by the Sirdal magmatic belt dated at 1070-1020 Ma (Coint et al., 2015; Slagstad et al., 2013a). The timing of this activity is also synchronous with the main Ottawan phase of the Grenville collisional orogenesis suggestive of a causative relationship. Prior to rotation, Laurentia and Baltica constituted part of a single plate, Nena (Northern Europe – North America, Gower et al., 1990). But with opening of the Asgard Sea they formed two separate plates (Laurentia and Baltica). The plate boundary would initially have run along the spreading centre associated with the Asgard Sea but at least for Laurentia the plate boundary would have switched to the subduction zone outboard of the Greenland margin at the beginning of the Neoproterozoic.

Figure 5 provides a series of schematic cross sections across the margins of eastern Laurentia, north-eastern and south-western Baltica, and south-western and northern Amazonia. Prior to 1150 Ma the margins of southeast Laurentia, southwest Baltica and southwest and north Amazonia were dominated by convergent plate interaction associated with closure of the Mirovoi Ocean. Magmatic arcs lie along these cratonic margins as well as in peri-cratonic settings outboard of the margins (e.g. Composite Metasedimentary Belt of northern Grenville, Coal Creek arc of Llano uplift, terranes of southern Baltica, basement inliers in Cordilleran Andes). Tectonothermal activity during this timeframe (e.g. Elzevirian, Shawwinigan, Llano, and unnamed event in Columbian Andes inliers) occurs during ongoing convergent plate margin activity and is related to tectonic switching from retreating to advancing accretionary orogens associated with coupling between the down going and overriding plate (cf., Cawood et al., 2009), and likely resulting in closing of back arc basins and accretion of marginal arcs to cratonic margins. During this time period Baltica and Laurentia constitute a single plate but lithospheric extension, perhaps driven by outboard slab rollback, results in intracratonic rifting and subsidence, as evidenced by the Mezen’ rift, Stoer, Sleat, Wakeham and Seal Lake groups, dyke emplacement, and the metasedimentary and igneous succession in western Svalbard.

Full continental collision between Amazonia and east Laurentia commenced around 1080 Ma and corresponds with the Ottawan phase of the Grenville orogeny in East Laurentia and tectonothermal activity in the Blue Ridge basement inliers of the Appalachian Orogen, which are inferred to constitute the leading edge of Amazonia. Earlier tectonothermal activity within the Amazon Craton and marginal Sunsas belt (Fig. 3) is related to localized accretion of outboard cratonic fragments (Boger et al., 2005), although Tohver et al. (2004b) proposed this activity reflected initial collision of Amazonia with southern Laurentia prior to sinistral transpressional motion between the two cratons. Mosher et al. (2004) ascribed the latter phases of orogenic activity in the Llano uplift, southern Laurentia, to collision of an outboard continent but noted that there was no evidence for transcurrent motion along the margin. In southwest Baltica, the early phases of the Sveconorwegian orogeny, the Arendal phase, also predate the main Grenville event and their restricted regional distribution is consistent with this phase related to localized accretion of the Idefjorden and Telemark terranes.

Final closure of the Mirovoi Ocean between southwest Baltica and north Amazonia is represented by the Sirdal magmatic belt and magmatism and tectonothermal activity in Amazonia. Early phases of this activity resulted in suturing or arcs and continental fragments prior to final continental collision between Baltica and Amazonia (possibly with Oaxaquia in between, Fig. 2) represented by the Putumayo/Zapotecan orogeny and the latter Agder phase of the Sveconorwegian orogeny. Rotation of Baltica with respect to Laurentia is inferred to also have occurred at the end of the Mesoproterozoic, although the precise timing of rotation and corresponding opening of the Asgard Sea is poorly constrained. Importantly, the rotation of Baltica meant that the Sveconorwegian Orogen lay at right angles to the Grenville Orogen in Laurentia and thus this paleogeographic relationship provides a configuration in which collisional orogenesis on the northern and western margins of Amazonia is related to suturing to Baltica and Laurentia, respectively (Figs. 2 and 5).

4. Ocean closure and continental collision through two sided subduction: implications

The record of convergent plate margin activity and accretionary orogenesis between the south-east Laurentian and south-west Amazonia margins and between the north Amazonia and south-western Baltica margin indicate that closure of the this part of the

Mirovoi Ocean took place within an overall framework of two-sided subduction (Fig. 5). This process of Rodinia assembly has important implications for understanding the rock record (Cawood et al., 2013; Spencer et al., 2013) and contrasts with preceding and succeeding supercontinent cycles. Two-sided subduction results in colliding margins being dominated by magmatic arc assemblages and lacking older basement and overlying passive margin successions on one of the opposing margins. Hence, collision in a two-sided subduction system results in the reworking of relatively young convergent plate margin rock units, whereas one-sided subduction results in reworking of older basement units associated with a passive margin. Collision zones are sites of crustal thickening and zones of high topographic relief, and as such are the major sources of sediment influx into the oceans. Erosion of relatively juvenile crust during two-sided subduction associated with the collision of Laurentia, Baltica and Amazonia may account for the absence of seawater $^{87}Sr/^{86}Sr$ anomaly and zircon Hf excursion associated with Rodinia assembly (Cawood and Hawkesworth, 2014; Cawood et al., 2013). In contrast Gondwana, which is inferred to have been assembled largely by one sided subduction (Collins and Pisarevsky, 2005) resulting in thickening, reworking and erosion of ancient cratonic lithosphere and resulted in a positive seawater Sr excursion and a shift of Hf values to more negative values (Cawood et al., 2013; Spencer et al., 2013). The paucity of preserved ancient passive margins associated with Rodinia assembly but their relative abundance in association with Gondwana (Bradley, 2008) is also consistent with two-sided subduction during Rodinia assembly.

5. Conclusions

Laurentia, Baltica and Amazonia are key building blocks of the end Mesoproterozoic to early Neoproterozoic supercontinent Rodinia. There is however, uncertainty in their absolute and relative position with respect to Rodinia. Integration of all available data sets has enabled the development of a dynamic model for the Proterozoic interaction of these in which Amazonian collision with Laurentia is linked to rifting and rotation of Baltica from Laurentia to collide with Amazonia's northern margin (Figs. 1-3). The geological record of the three blocks indicates a long history extending through the Paleoproterozoic and Mesoproterozoic of continental growth onto Archean cratonic cores through convergent plate interaction and accretionary orogenesis. This history requires the existence of a long lived and probably large oceanic tract outboard of these continental fragments; the Mirovoi Ocean. Periods of extension during plate convergence likely reflect slab-rollback with back arc basin opening or inboard extension on the craton margin. Compressional events are related to advancing accretionary orogenesis in which the upper plate overrides the lower plate resulting in arc amalgamations and/or accretion of outboard arcs to the continental margin. Prior to 1265 Ma, Laurentia and Baltica formed a single tectonic plate. Sometime after this, but prior to 990 Ma, these blocks broke into two plates through opening of the Asgard Sea between northeast Laurentia and northern Baltica. Spreading within the sea died out to the south such that Baltica was rotated through 95^{o} in a clockwise sense with respect to Laurentia and moved some 1000 km to the south. Thus, after opening of the Asgard Sea the southern margin of Baltica lay at right-angles to east Laurentia, whereas prior to opening preserved orogenic tracts in the two continents constituted single linear along strike continuations. This oroclinal bending of originally linear and contiguous belts in east Laurentia and southern Baltica meant that during final closure of the Mirovoi Ocean and collisional orogenesis, the western margin of Amazonia collided with the east Laurentian margin while the southern margin of Baltica collided with the northern margin of Amazonia. Laurentia, Baltica and Amazonia maintained this configuration until the final breakup of Rodinia with the opening of the Iapetus Ocean at the end of the Neoproterozoic. The site of Iapetus opening did not correspond exactly with the site of initial collision resulting in fragments of Amazonia being left behind in east Laurentia and are now exposed in the basement inliers of the southern Appalachian Orogen.

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6. Figure Captions

Figure 1. Laurentia and Baltica at c. 1270 Ma. More detailed reconstruction in lower left shows positions of these and other continents (after Pisarevsky et al., 2014). Abbreviations: Au – Australia; Am – Amazonia; Ba – Baltica; La – Laurentia; MR – Mezen' rift; RB – Rockall Bank; SG – Stoer Group; Si – Siberia; SN – Sveconorwegian Orogen; WA – West Africa.

Figure 2. Laurentia, Baltica and Amazonia at 990 Ma. More detailed reconstruction in lower left shows positions of these and other continents (after Cawood et al., 2016). Abbreviations: Au – Australia; Am – Amazonia; Ba – Baltica; Hf – Hebridean foreland; K – Krummedal succession; La – Laurentia; M – Moine succession; Pt – Putumayo Orogen; Ox – Oaxaquia terrane; Rb – Rockall Bank; RP – Rio de la Plata; Sh – Shetland Islands; Si – Siberia; Sn – Sveconorwegian Orogen; Ss – Sunsas Orogen; Sv – Svalbard; WA – West Africa.

Figure 3. Schematic time-stratigraphic plot of key late Mesoproterozoic to early Neoproterozoic events along the west and north margins of Amazonia, east and northeast Laurentia, and north and south Baltica. See text for discussion and sources of data. Abbreviations: ABI – Appalachian basement inliers; PTM – post-tectonic magmatism; Wake – Wakeham.

Figure 4. Reconstruction of Laurentia and Baltica at ca. 1120 Ma (after Pisarevsky, 2016) based on the Salla Dyke paleopole (Salminen et al., 2009) . Laurentia is rotated to absolute framework by 70.03˚ clockwise around Euler pole at 36.27˚N, 102.34˚W. Baltica is rotated to Laurentia by 121.53˚ clockwise around Euler pole at 24.65˚N, 50.49˚W.

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Figure 5. Series of schematic cross sections between Laurentia, Baltica and Amazonia for the periods pre-Rodinia assembly (>1.2-1.15 Ga), during Rodinia assembly (~1.08 Ga), and for the assembled Rodinia (~1.0-0.95 Ga).

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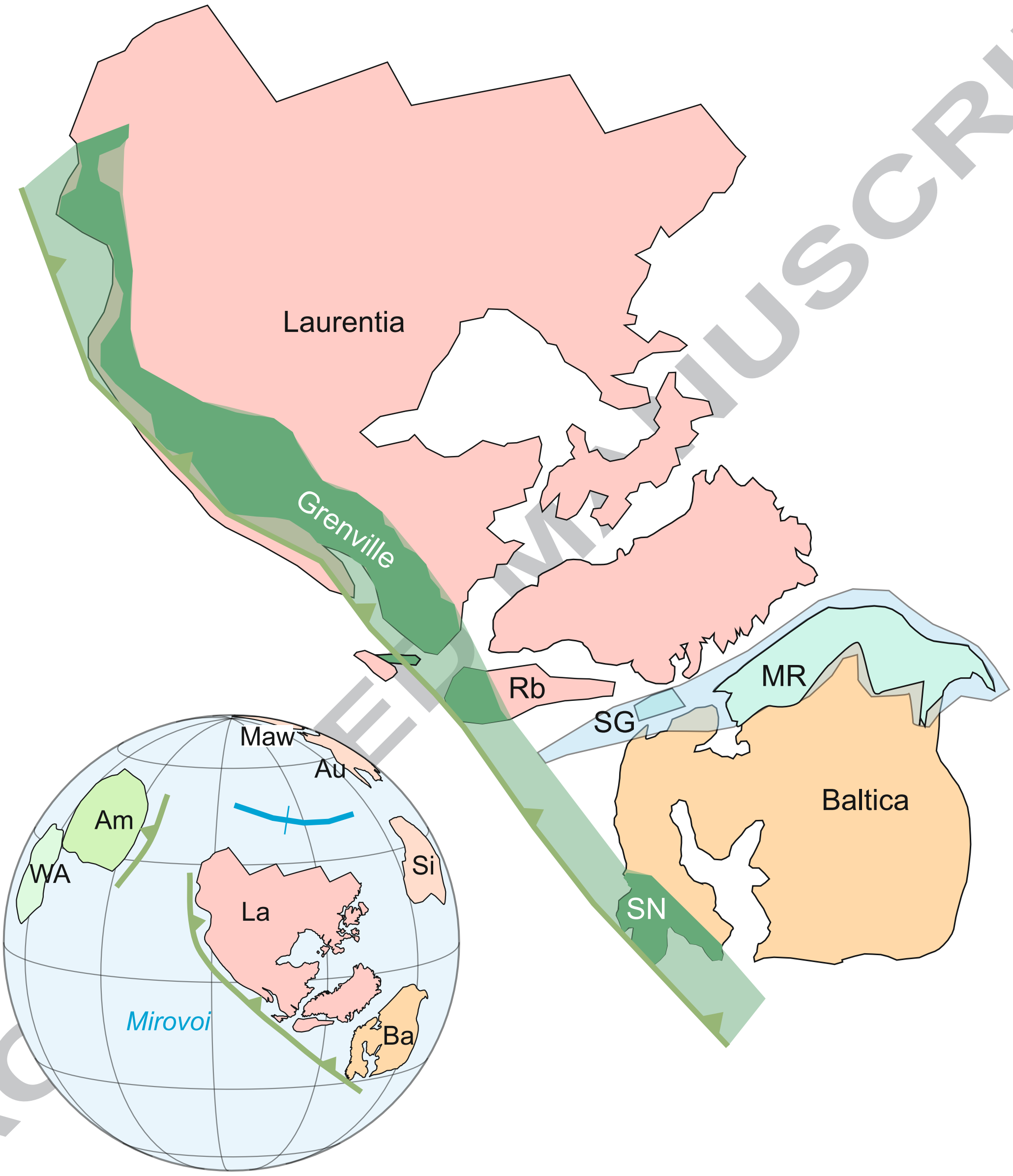
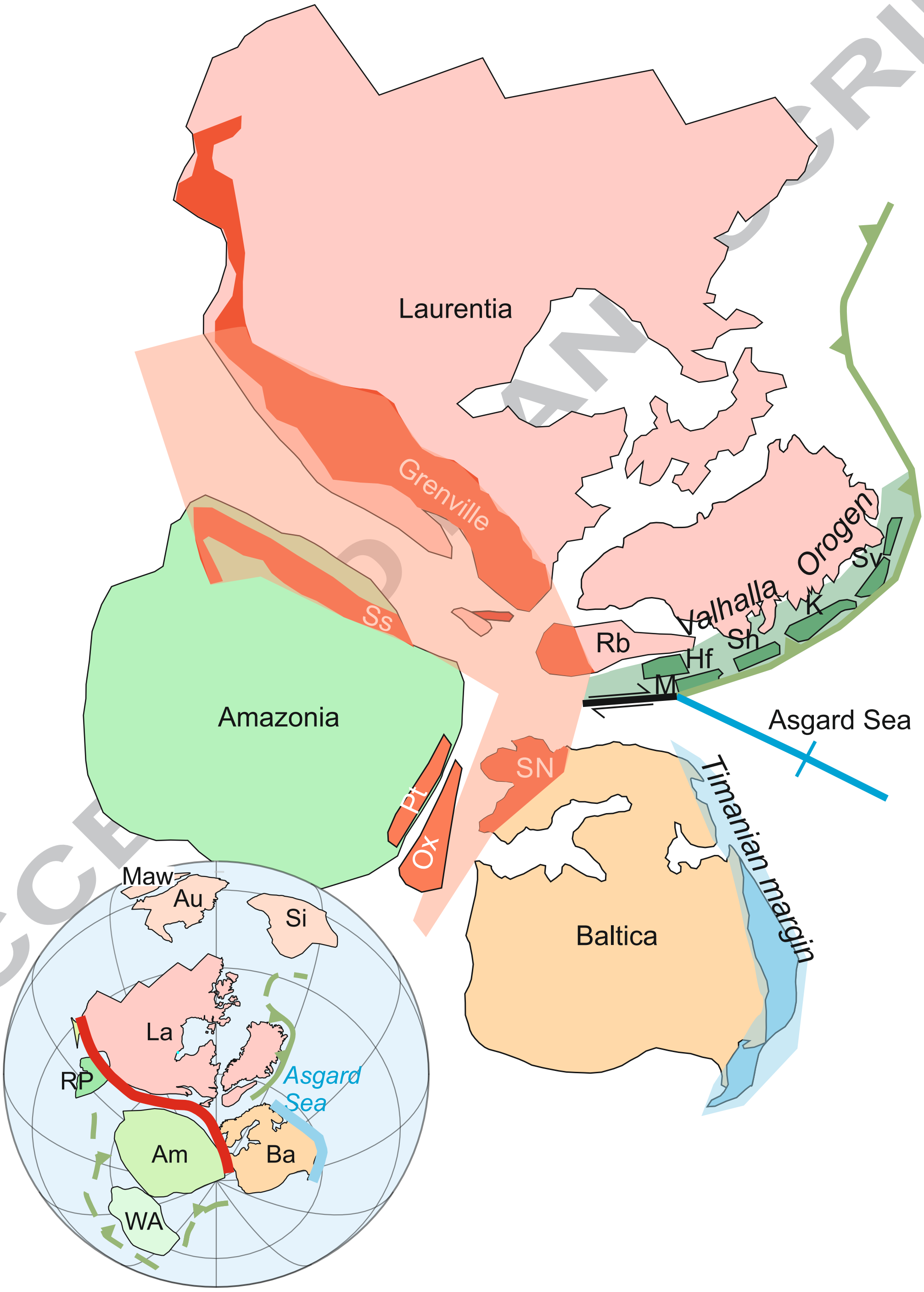
Cawood & Pisarevsky - Fig. 1



Cawood & Pisarevsky - Fig. 2



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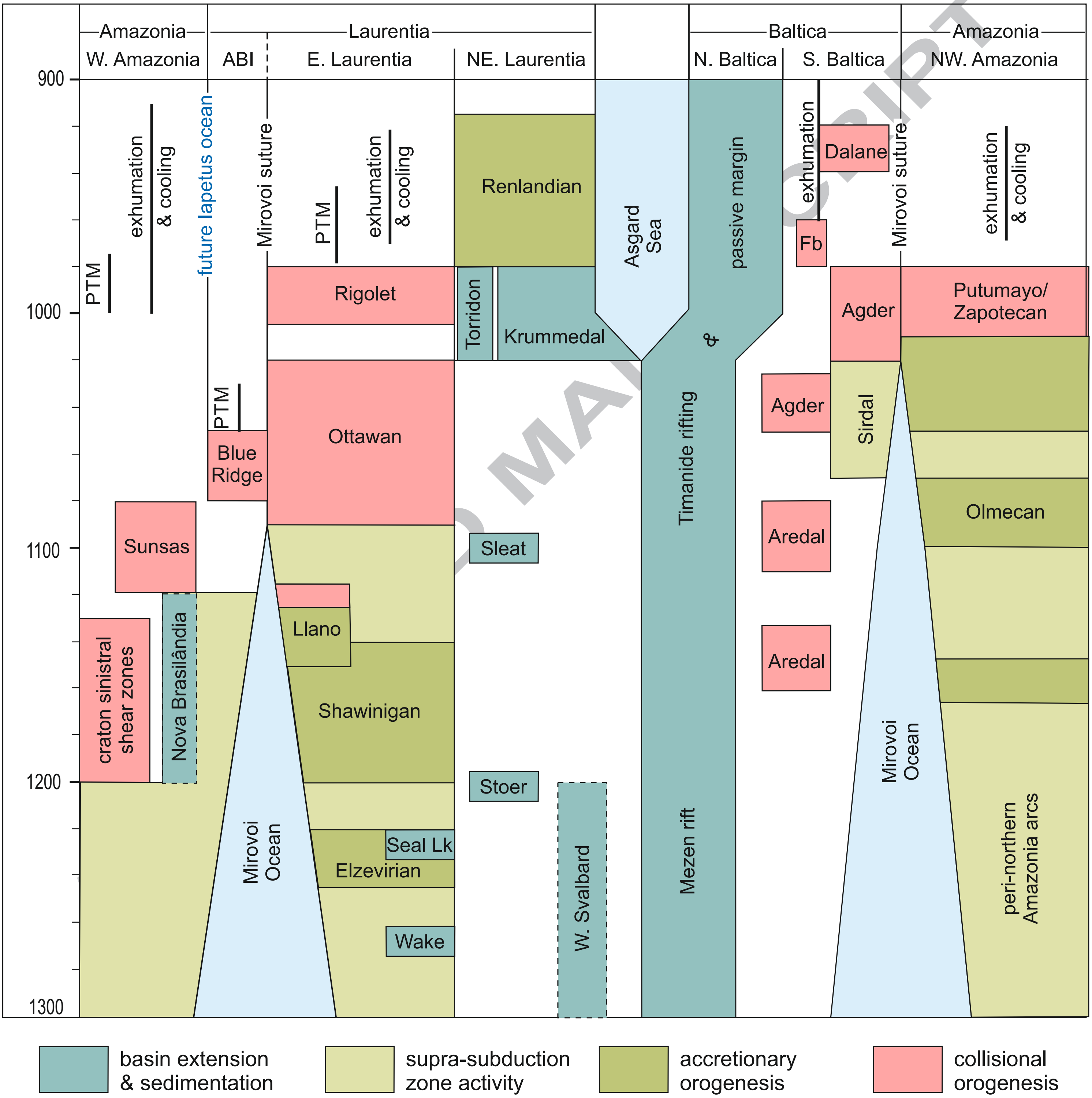

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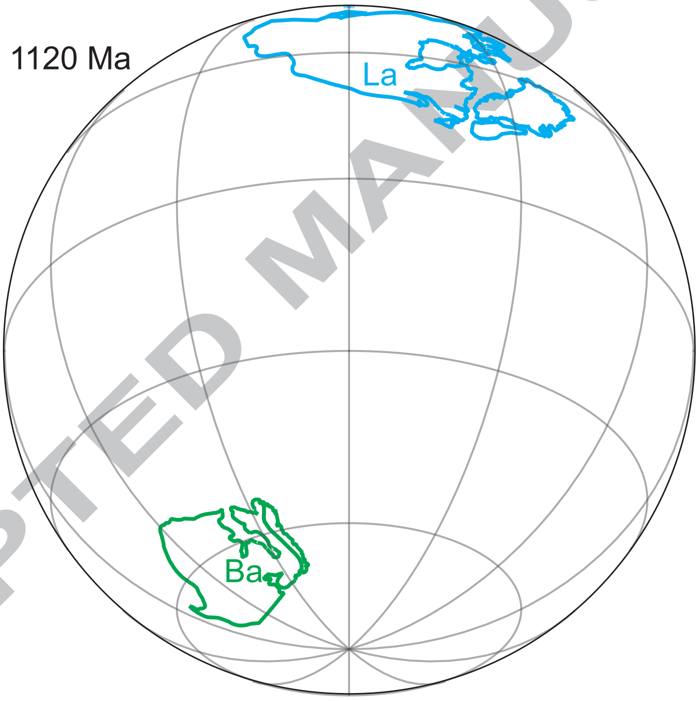

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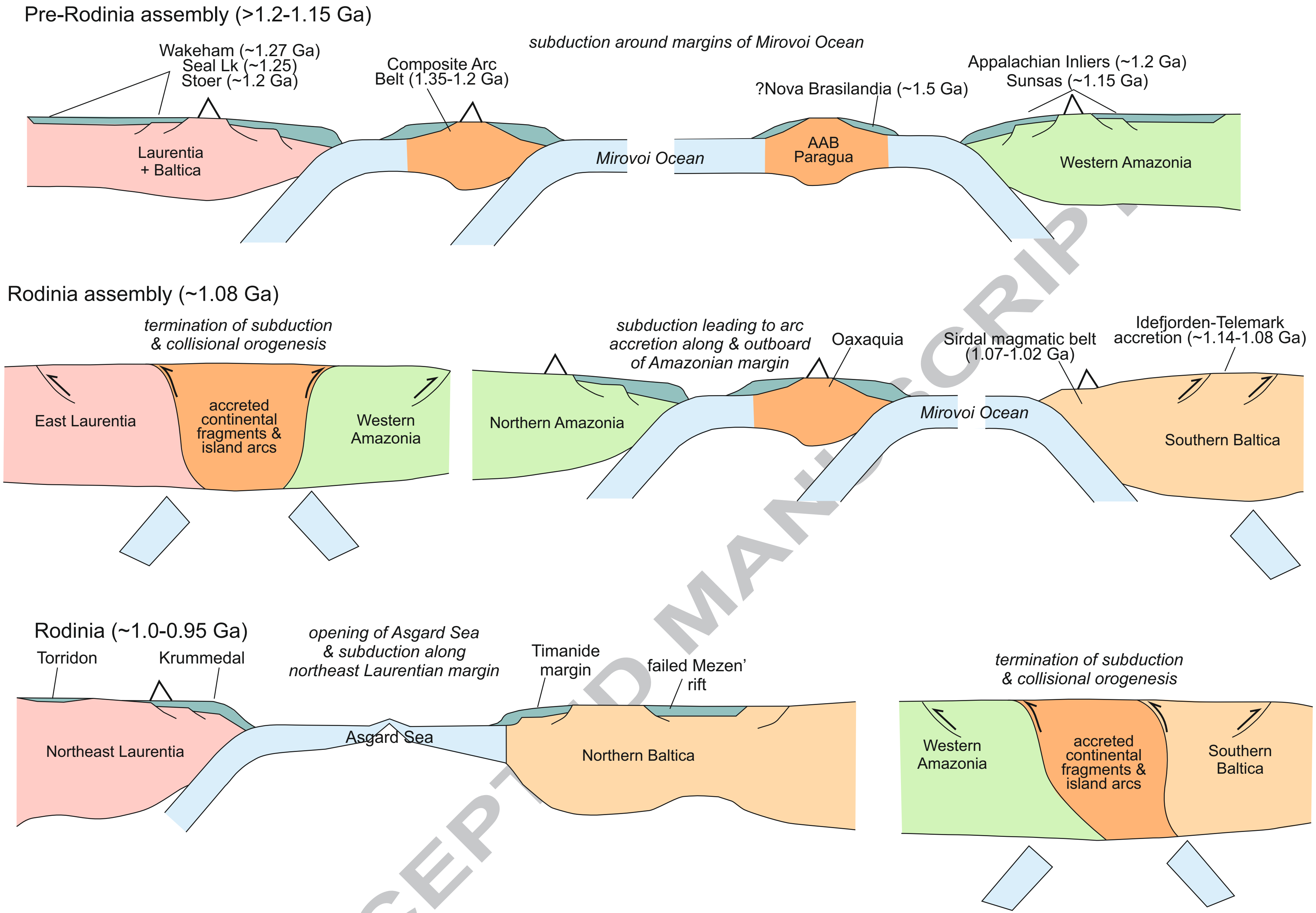

Highlights:

- Laurentia, Baltica and Amazonia are key building blocks of Rodinia
- Opening of Asgard Sea in end Mesoproterozoic drove rotation of Baltica
- Amazonia collision with Laurentia linked to rotation of Baltica
- Rotation resulted in collision of N Amazonia with S Baltica