Mesoproterozoic paleogeography: supercontinent and beyond

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Abstract

A set of global paleogeographic reconstructions for the 1770–1270 Ma time interval is presented here through a compilation of reliable paleomagnetic data (at the 2009 Nordic Paleomagnetic Workshop in Luleå, Sweden) and geological constraints. Although currently available paleomagnetic results do not rule out the possibility of the formation of a supercontinent as early as ca. 1750 Ma, our synthesis suggests that the supercontinent Nuna/Columbia was assembled by at least ca. 1650–1580 Ma through joining at least two stable continental landmasses formed by ca. 1.7 Ga: West Nuna (Laurentia, Baltica and possibly India) and East Nuna (North, West and South Australia, Mawson craton of Antarctica and North China). It is possible, but not convincingly proven, that Siberia and Congo/São Francisco were combined as a third rigid continental entity and collided with Nuna at ca.1500 Ma. Nuna is suggested to have broken up at ca. 1450–1380 Ma. West Nuna, Siberia and possibly Congo/São Francisco were rigidly connected until after 1270 Ma. East Nuna was deformed during the breakup, and North China separated from it. There is currently no strong evidence indicating that Amazonia, West Africa and Kalahari were parts of Nuna.

Key words: Mesoproterozoic, global, paleogeography, supercontinent, paleomagnetism.

1. Introduction

There has been a growing interest in the hypothesised pre-Rodinian supercontinent, variously called Nuna, Columbia, or Hudsonland (e.g., Hoffman, 1997; Meert, 2002; Pesonen et al., 2003; Zhao et al., 2002, 2004). One of the main geological arguments used for this hypothesis is in the presence of 2.1–1.8 Ga orogens in a majority of continents (e.g., Zhao et al., 2004), and it was suggested that some or all of these orogens resulted from the assembly of this supercontinent. However, most reconstructions are highly speculative in nature, mainly due to the lack of adequate high quality paleomagnetic data to provide independent constraints.

At the 2009 Nordic Paleomagnetic Workshop in Luleå (Sweden; Elming and Pesonen, 2010), it was concluded that there are about one hundred late Paleoproterozoic to Mesoproterozoic paleopoles (most of them are from Laurentia, Baltica, Siberia and Australia) of 'reasonable' quality and they can be used for late Paleo- to Mesoproterozoic reconstructions. In this study we slightly updated the Luleå data compilation utilising more recently published paleomagnetic and geochronological results (Table 1). Most of the paleopoles in Table 1 are considered to be of high quality, but we have also included some less reliable poles (shown in italics), which were used only as a "second-order" constraints for paleogeographic reconstructions. In most cases these less reliable poles are either poorly dated or have not averaged out secular variation of geomagnetic field and are therefore marked as Virtual Geomagnetic Poles (VGPs). Hereafter we shall call them 'non-key' poles. In the following sections we use (directly and indirectly) about a hundred ca. 1800–1000 Ma poles in an attempt to reconstruct the global distribution of continents and the history of their drift in the late Paleoproterozoic and much of the Mesoproterozoic (mainly the 1770–1270 Ma time internal). The paleogeography of the 1270–1000 Ma time period is enigmatic and has to be analysed separately and published elsewhere. However, we consider few elements of this late Mesoproterozoic paleogeography to provide some clues for understanding of older events.

The paleomagnetic data presented in Table 1 and Figure 1 clearly demonstrate that both temporal and spatial distributions of the 1800–1000 Ma data are very uneven. Even from the paleomagnetically most thoroughly studied Laurentia there are still not enough data for the construction of a reliable Apparent Polar Wander Path (APWP) for the entire period. Paleomagnetic databases for other continents are even less complete, and paleopositions of some continents (e.g. South China, Rio de La Plata, São Francisco, West Africa) are not paleomagnetically constrained at all.

Comparison of lengths and shapes of APWPs is a normal technique for testing supercontinent hypotheses – as long as two continents have travelled together as parts of a single plate, they should have identical APWPs. In the absence of well defined APWPs, as the first approximation, we can use pairs of coeval paleomagnetic poles from two cratonic blocks for a test. If the distance between two paleopoles with ages X and Y of one continent is the same as the distance between two paleopoles with ages X and Y of another continent, we can suggest that these continents could have been parts of the same supercontinent between times X and Y (e.g. Evans and Pisarevsky, 2009), provided that the Geocentric Axial Dipole (GAD) model is valid for Precambrian (Veikkolainen et al., 2012). This is a necessary, but not sufficient condition. If there are more than two such coeval and equidistant pairs of poles, the probability of rigid co-travelling increases. Even in this case the paleomagnetic reconstruction of mutual positions of two continents must still be tested by geological data. In addition, we can use single poles to constrain the paleolatitudes of a given continent, and examine the possibility of it being a part of a supercontinent by comparing both their paleolatitudes and geological linkages. In the following section we mainly use the methods of comparing the APWPs or paired paleopoles between two continents to examine their potential links during the late Paleo- to Mesoproterozoic.

2. Baltica and eastern Laurentia

Paleomagnetic data for the period 1800–1270 Ma are most abundant for Laurentia and Baltica (Table 1, Fig.1). Salminen and Pesonen (2007) demonstrated that paleomagnetic data support the existence of a single Baltica–Laurentia continent from ca. 1760 Ma until ca. 1270 Ma. Their reconstruction was similar, but not identical, to the reconstruction of Gower et al. (1990), which was built by matching pre-Neoproterozoic crustal blocks and orogenic belts of these cratons. The difference between the “geological” reconstruction of Gower et al. (1990) and the “paleomagnetic” reconstruction of Salminen and Pesonen (2007) is within the precision limits of both paleomagnetic and geochronological methods. A similar paleomagnetically-based reconstruction was given by Wu et al. (2005).

Baltica was assembled sometime during1800–1700 Ma (Bogdanova et al., 2008; Elming et al., 2010) by the collision between Sarmatia/Volgo-Uralia and Fennoscandia along the Central Russian collision belt (Fig. 2). Pisarevsky and Bylund (2010) slightly modified the Baltica-Laurentia reconstruction using new paleomagnetic data and proposed that the “best fit” Laurentia- Fennoscandia reconstruction between 1790–1770 Ma and 1270–1260 Ma requires an anticlockwise rotation of Fennoscandia (and the whole of Baltica after 1700 Ma) to Laurentia (Fig. 2). We followed this suggestion in our reconstructions and treat Laurentia and Fennoscandia (Baltica after 1700 Ma) as a single continent until 1270 Ma.

The Mesoproterozoic tectonic history of Baltica is characterised by prolonged accretion from the present-day west (e.g., Gorbatschev and Bogdanova, 1993; Bogdanova et al., 2001; Åhäll and Connelly, 2008; Bingen et al, 2008; Bogdanova et al., 2008). The 1900–1850 Ma Svecofennian orogeny culminated in the formation of the 1850–1650 Ma Transscandinavian Igneous Belt (TIB), which was followed by the 1640–1520 Ma Gothian orogeny, the 1520–

1480 Ma Telemarkian accretionary events, the 1470–1420 Ma Hallandian-Danopolonian orogeny, and eventually by the 1140–970 Ma Sveconorwegian orogeny (Bingen et al., 2008). The SE margin of Laurentia has a similar history with the 1800–1700 Ma Yavapai, 1700–1600 Ma Mazatzal and 1300–900 Ma Grenville orogenies (e.g., Karlstrom et al., 2001).

The exact timing of the post-1270 Ma breakup of Baltica from Laurentia is unclear. Park (1992) suggested that it was related to the 1270 Ma giant McKenzie magmatic event and Elming and Mattsson (2001) suggested that the coeval Central Scandinavian Dolerite complex was a result of such a breakup. Starmer (1996) provided some structural evidence that separation started at ca. 1240 Ma. Ca. 1270 Ma Laurentian and Baltican paleopoles support the integrity at that time. The next oldest non-key Salla Dyke pole from Baltica and the Abitibi and Nipigon poles from Laurentia (Table 1, entries 73 and 77, respectively), however, indicate a wide separation between the two continents at ca. 1120 Ma.

3. Siberia and northern Laurentia

Based on 1050–950 Ma Laurentian and Siberian paleomagnetic data (Table 1, entries 78–89) Pisarevsky and Natapov (2003) suggested that these two continents could have moved coherently during that time if Siberia was located NW of Laurentia and with a significant ‘gap’ between them that was presumably occupied by some yet unknown piece(s) of continental crust. Wingate at al. (2009) reported a new ca 1475 Ma Siberian paleomagnetic pole. This pole, together with a coeval Laurentian pole by Meert and Stuckey (2002), suggests that this distant but fixed position of Siberia relative to Laurentia may be valid between ca. 1500 and 1000 Ma. Such a distant relationship might explain the apparent absence of any traces of the giant 1267 Ma Mackenzie igneous event in Siberia (Gladkochub et al., 2006; Pisarevsky et al., 2008). Notably, these hypotheses assume that the Siberian craton behaved as a rigid coherent continent since the Mesoproterozoic. However, Gurevich (1984) analysed early Paleozoic Siberian paleomagnetic data and suggested that there was a significant (ca. 20°) clockwise rotation of SW Siberia (the Aldan block) with respect to NW Siberia (the Anabar-Angara block) during the opening of the v-shaped Vilyui syneclise in Devonian time. Pavlov et al. (2008) provided more geophysical, geological and paleomagnetic evidence for such a rotation and reported the best estimate of Euler rotation parameters (Aldan is rotated to Angara-Anabar) to be +23° about a pole at 62°N, 117°E. Using these parameters, we modified the shape of pre-Devonian Siberia. This restoration also caused the rotation of the ca. 1050–950 Ma Siberian poles (Pavlov et al., 2000, 2002; Gallet et al., 2000; Table 1, entries 84–89) from the Aldan block (Table 1). These readjustments provide a tighter fit of the ca.1500–950 Ma coeval Siberian and Laurentian poles but still require a distant position of Siberia with respect to Laurentia (Fig. 3). Following this paleomagnetic argument we suggest that between ca. 1500–1270 Ma Laurentia, Baltica and Siberia were in a fixed position with respect to each other, implying that there might have been a supercontinent during that time. Didenko et al. (2013) published two 1730–1720 Ma paleopoles from the Aldan block (Table 1, entries 24–25). These poles suggest an equatorial position for Siberia at 1730–1720 Ma, which is supported by three ca. 1750–1730 Ma non-key Siberian poles (Table 1, entries 21–23). The best fit of these poles with the Laurentian 1740 Ma Cleaver Dykes pole (Table 1, entry 20) suggests a larger distance between the two continents than shown in Fig. 3. We conclude that Siberia had not joined the Laurentia-Baltica system by 1740–1720 Ma.

4. Australia and western Laurentia

1800–1500 Ma Australian paleopoles are relatively abundant (Table 1; Fig. 1), and most are from Northern Australia. There is a general agreement that Australia was assembled by collision of three Archean to Paleoproterozoic building blocks – the North Australian, West Australian and South Australian cratons (NAC, WAC and SAC). However, the timing of this assembly is still debated (e.g. Myers et al., 1996; Betts and Giles, 2006; Schmidt et al., 2006;

Cawood and Korsch, 2008; Li and Evans, 2011). In this study we accept the model of Li and Evans (2011), suggesting the proximity between these three elements since ca. 1800 Ma, but in a configuration different from the present-day one until ca. 650 Ma. There was an intraplate rotation between WAC–SAC and NAC during 650–550 Ma which resulted in the present-day configuration. We also adapted the hypothesis of a clockwise rotation of the SAC at ca. 1500–1300 Ma that resulted in a collision with the WAC during the Albany-Fraser orogeny (Betts and Giles, 2006). It has been suggested that the Gawler craton of the SAC has a continuation into the Mawson Craton in Antarctica (e.g. Fanning et al., 1995; Fitzsimons, 2003; Boger, 2011 and references therein), but the size and shape of the Mawson craton is yet unclear. In our reconstructions we follow this suggestion and use the shape of the Mawson craton as it was shown by Powell and Pisarevsky (2002).

Precambrian connections between western Laurentia and Australia (SWEAT, AUSWUS, AUSMEX, “Missing Link”) have been debated for over two decades (e.g. Moores, 1991; Dalziel, 1991; Brookfield, 1993; Li et al.,1995; Karlstrom et al., 2001; Burrett and Berry, 2000; Wingate et al. 2002). A detailed review of Neoproterozoic (after 1000 Ma) Australia-Laurentia fits was presented by Li et al. (2008a). However, Pisarevsky et al. (2003a) demonstrated that neither of those reconstructions is valid for Mesoproterozoic time (ca. 1200 Ma) according to paleomagnetic data. Analysing 1800–1580 Ma geological and paleomagnetic data from North Australia, Betts et al. (2008, 2009) showed the possibility of a “SWEAT-like” reconstruction with North Australia located close to the north-western tip of Laurentia. With new paleomagnetic analyses Zhang et al. (2012) supported this idea of North Australia being fixed to NW Laurentia in such a SWEAT-like configuration. Here we modify this model, suggesting that though the two continents were in a geographical proximity, their final assembly occurred at 1650–1600 Ma during the Racklan orogeny (Fig. 2; Furlanetto et al., 2013). The reasons for such an interpretation are as follows.

The thick sedimentary Wernicke Supergroup was deposited in the Yukon Territory on the northern part of the western Laurentian margin. The measurable thickness of this succession is ca. 13 km, but the lower contact with the basement is not exposed, so the real thickness can even be larger (Furlanetto et al., 2013). Seismic profile suggest the whole thickness to be up to 20 km with gradually increase to the west (Mitchelmore and Cook, 1994), which is characteristic of a passive continental margin, but also possible for an intracontinental basin. Thorkelson et al. (2005) suggested that the two hypotheses are equally viable, noting, however, that the intensity of the following ca. 1650–1600 Ma Racklan orogeny is more consistent with collisional tectonics along a continental margin than intracratonic deformation. If we accept the passive margin model, the initial rifting event should have occurred after the end of the ca. 1900 Ma Wopmay orogeny (Hildebrand et al., 2010). Cook and Erdmer (2005) suggested that the initiation of the Wernicke Basin formation occurred between 1840–1760 Ma. Thorkelson et al. (2005) suggested that the minimum age of Wernicke sedimentation is constrained by the 1720 Ma Bonnet Plume River intrusions, which apparently cut the Wernicke sediments. However, Furlanetto et al. (2013) challenged this cross-cutting relationship after finding ca. 1640 Ma detrital zircons in the lower part of the Wernicke Supergroup. These authors suggest that the Bonnet Plume River intrusions originated in an offshore volcanic arc terrane (Bonnetia) that was accreted to Laurentia during the ca. 1600 Ma second stage of the Racklan orogeny. If true, this model is supportive of the hypothesis of a late Paleoproterozoic oceanic margin in this part of western Laurentia, since it is hard to imagine a volcanic arc in an intracontinental basin. The timing of initiation of Wernicke sedimentation is still unclear, since the lowermost part of the supergroup is not exposed, but we assume that, at 1770 Ma, there was an oceanic space west of western Laurentia. To the south of the Mackenzie Mts the Muskwa assemblage is a 6 km thick sequence of essentially unmetamorphosed, predominantly fine-grained siliciclastic and carbonate strata with a maximum age of 1766 Ma (youngest detrital zircon) (Ross et al., 2001). Seismic studies show a passive margin fabric (Cook et al., 2004).

There has been a rapidly improved understanding of the Late Paleoproterozoic and Mesoproterozoic tectonic evolution of eastern North Australia in the last decade (e.g. Giles et al., 2002; Betts and Giles, 2006; Fraser et al., 2007; Gibson et al., 2008; Betts et al., 2008, 2009). These studies led to somewhat contrasting tectonic models. Detailed descriptions of these models are beyond the scope of our study. However, there are several common elements in these models relevant to the Australia-Laurentia reconstructions between ca.1800–1600 Ma. In particular, sedimentation in the eastern basins of North Australia is suggested to have persisted until ca. 1600–1550 Ma, when sedimentation ended, which may be related to the westward vergence of the Jana orogeny in the Georgetown, Coen, Yambo, and Dargalong inliers (Betts and Giles, 2006 and references therein). This is roughly reminiscent of the development of the Wernicke Supergroup and to the Racklan orogeny. The tectonic history of the eastern edge of the North Australian craton between ca. 1800–1550 Ma includes several changes of the tectonic regime, which are, in our view, not consistent with a purely intracontinental environment, implied by rigid connection with Laurentia. A geochemical study of the 1685–1640 Ma mafic rocks in the Georgetown Inlier (Baker et al., 2010) led the authors to suggest that these volcanic rocks were associated with a volcanic passive margin. Betts and Giles (2006) suggested a mid-oceanic ridge east of North Australia at 1650–1620 Ma and convergence with western Laurentia at 1610–1570 Ma. All this implies that North Australia faced an ocean (maybe a small remnant sea like the Mediterranian) in the present east at ca. 1800–1550 Ma. It is difficult to estimate the width of this ocean. At some stages it may have been a Mediterranean-type basin (this may explain the variety of tectonic styles within it), which explains a paleomagnetically permitted proximity of North Australia and Laurentia at ca. 1800–1600 Ma. However, it is very unlikely that these continents were at exactly the same mutual position as shown in the 1780–1650 Ma reconstructions of Betts et al. (2008). We propose a series of 1770–1580 Ma paleomagnetically supported reconstructions in which Australian and Antarctic continental blocks approached NW Laurentia from relatively distal positions until assembly at ca. 1600–1550 Ma (Figs.7–10).

Pisarevsky et al. (2003a) demonstrated that Australia and Laurentia were widely separated at ca. 1200 Ma, which means that there was a breakup sometime after 1550 Ma. It is difficult to establish a precise time for this breakup because there are no reliable 1500–1220 Ma paleomagnetic data for Australia. Betts and Giles (2006) loosely constrained this rifting to between 1500–1330 Ma. This breakup can be related to the opening of the Belt-Purcell basin in western Laurentia, constrained by the 1469–1457 Ma Moyie sills intruded into still-wet sediments of the lowermost Prichard Formation of the Belt Supergroup (Elston et al., 2002 and references therein). Goodge et al. (2008) reported a 1441 ± 6 Ma granitoid clast found in the central part of the Transantarctic Mountains with Hf and Nd isotopic compositions similar to the ca. 1500–1300 Ga Laurentian granites. The authors suggested that this supports a Laurentia-East Antarctica (Mawson craton) connection at ca. 1440 Ma. If so, the separation between Australia-Mawson and Laurentia could not have begun before that. In the northern part of western Laurentia the breakup could have been associated with the rift-related 1.38 Ga Hart River magmatism, followed by deposition of the Pinguicula Group (Medig et al., 2010).

5. North China and Australia

The 1780–1760 Ma and 1460–1410 Ma paleopoles from North China (Table 1, entries 11–12 and 53) permit a fixed position of this continent juxtaposed to Australia (Figs.7–13) as was proposed by Zhang et al (2012). We suggest a similar North China-Australia fit. The 1780–1750 Ma andesite-dominated Xiong’er Group at the southern margin of the North China Craton has been suggested to represent an Andean-type continental margin (e.g., Zhao, 2009; He et al., 2010; Zhao and Cawood, 2012). The position of North China after the suggested breakup of Australia and Laurentia is constrained by a new ca. 1350 Ma pole of Chen et al. (2013; Table 1, entry 61).

6. Amazonia and West Africa

Amazonia has two coeval pairs of poles at ca. 1790 Ma and at ca. 1420 Ma (Table 1, entries 14–15, 54–55; Fig. 1). In this study we discuss the SAMBA-type and other reconstructions of this continent (Johansson, 2009; Bispo-Santos et al., 2008; Elming et al., 2009a; Zhang et al., 2012). We also follow the generally accepted hypothesis of Trompette (1994) that West Africa and Amazonia constituted a rigid continent since the Mesoproterozoic, similar to their Gondwanan configuration.

The original SAMBA reconstruction (Johansson, 2009) is based on the similar late Paleoproterozoic–Mesoproterozoic accretionary history of Amazonia and Baltica. In particular, it was suggested that the 1900–1850 Ma Svecofennian orogen in Baltica continues into the 1980–1810 Ma Ventuari-Tapajós province in Amazonia, and that the 1850–1650 Ma TIB and the 1640–1520 Ma Gothian orogen have their continuation into the 1780–1550 Ma Rio Negro–Juruena province (Fig.4). In the SAMBA model the combined Baltica-Amazonia-West Africa continent existed as a rigid body from 1800 Ma until after 900 Ma (Johansson, 2009). Fuck et al. (2008), however, argued that the Ventuari-Tapajós and Rio Negro-Juruena provinces are truncated by the younger Grenville-age orogen in their northern parts (Fig.4), which questions the continuity of Baltican and Amazonian accretionary belts.

Bispo-Santos et al. (2008) argued that their 1789 ± 7 Ma Colider Volcanics paleopole (Table 1, entry 14) requires some distance between Amazonia and Baltica at ca. 1790 Ma. In their reconstruction North China is located between these two continents. D’Agrella-Filho et al. (2012) and Bispo-Santos et al. (2012) published two coeval, closely located and well-dated ca. 1420 Ma Indiavaí and Nova Guarita poles (Table 1, entries 54–55). D’Agrello-Filho et al. (2012) demonstrated that these poles do not support the SAMBA reconstruction at ca.

1420 Ma. Recently Reis et al. (in press) cited a new 1790 Ma pole for the Avanavero intrusion, for which the primary origin of the magnetization is supported by a contact test (Table 1, entry 15). This pole is coeval to the Colider pole, but the angular difference between them is about 48°. Unfortunately, no details of this paleomagnetic study have been provided. Reis et al. (in press) argue that the Avanavero pole supports the SAMBA reconstruction at ca. 1790 Ma, but the authors admit that this requires the integrity of Baltica by 1790 Ma. Meanwhile, Baltica was not yet assembled at that time, and Sarmatia/Volgo-Uralia was separated from Fennoscandia (e.g. Bogdanova et al., 2008; Elming et al., 2010). Reis et al. (in press) give two alternative explanations for the significant angular difference between coeval Avanavero and Collider poles. The first explanation is that the Avanavero pole is primary, but the Colider pole represents a younger remagnetisation. This explanation has some merit, since the Colider pole is not supported by field tests. The second explanation suggests that northern Amazonia (where the Avanavero intrusions are located) was separated from southern Amazonia (location of the Colider, Indiavaí and Nova Guarita sampling areas) at ca. 1790 Ma. Reis et al. (in press) suggest that these two parts of Amazonia were assembled sometime after 1790 Ma.

In Fig.5 we show a paleomagnetic test of the SAMBA reconstruction at 1790 Ma (Fig. 5a–c) and at 1420 Ma (Fig. 5d–f). Figs. 5a and 5d consider the integrity of the Amazonian Craton. In the SAMBA-type configuration Amazonia is juxtaposed against Sarmatia. In this scenario the Avanavero pole is close to Laurentian, Fennoscandian and Sarmatian poles of similar age (Fig.5a; pole numbers are as in Table 1), which makes the SAMBA reconstruction paleomagnetically permitted at ca. 1790 Ma (with some reservations about the quality of the Avanavero pole), but the Colider pole does not support this reconstruction. Therefore, if the SAMBA model is correct, we suggest that the Colider pole is not primary. At 1420 Ma (Fig. 5d), however, both Indiavaí and Nova Guarita poles are >45° away from roughly coeval Laurentian and Baltican poles, indicating that the SAMBA reconstruction is not paleomagnetically permissible at 1420 Ma.

In Figures 5b and 5e the hypothesised displacement between southern and northern Amazonia is illustrated, with the Euler pole of rotation as in Reis et al. (in press). In this scenario the Avanavero and Colider poles match exactly, but the displacement is significant and probably contradicts one of the key arguments for the SAMBA model – it disrupts the linearity of the Ventuari-Tapajós province. At 1420 Ma the displacement makes little difference compared to the first scenario (Fig.5e), because both Indiavaí and Nova Guarita poles are still ca. 45° away after rotation from Laurentian and Baltican poles, so the paleomagnetic test of SAMBA also fails in this case too.

In the third scenario we tried to minimize the displacement between parts of Amazonia allowing the Colider and Avanavero poles to differ with touching circles of confidence (Fig. 5c and f). Even in this case the linearity of the Ventuari-Tapajós province is disrupted, and although Indiavaí and Nova Guarita poles are slightly closer to Laurentian and Baltican poles, there is still a ca. 40° difference.

In our opinion, the SAMBA reconstruction is paleomagnetically permissible (but still doubtful) at 1790 Ma, but at 1420 Ma this reconstruction is unlikely. Paleomagnetic reconstructions for 1210–1150 Ma are also inconsistent with the SAMBA hypothesis (Tohver et al., 2002; Elming et al., 2009a).

7. India

The new palaeopole for the 1466 ± 3 Ma Lakhna dykes (Pisarevsky et al., in press; Table 1, entry 44) rules out a position of India close to North China (e.g., Zhao et al., 2002, 2004; Zhang et al., 2012). Among other possibilities (which are geologically contradictory, see Pisarevsky et al., in press), this pole, supports the position of India juxtaposed against the southern part of Baltica with the Archean Dharwar and Sarmatia cratons located next to each other, suggesting that they formed part of a single proto-craton (Fig. 6). Sarmatia consists of several Archean terranes which become welded together in the latest Archean – earliest Paleoproterozoic (Bogdanova et al., 1996). The Dharwar Craton has a somewhat similar history with its eastern and western parts welded together at ca 2515 Ma (the age of the 'stitching' Closepet Granite, Meert et al., 2010). Late Archean and Paleoproterozoic banded iron formations (BIFs) are widespread both in Sarmatia and Dharwar (Fig. 6; Khan and Naqvi, 1996; Shchipansky and Bogdanova, 1996; Srivastava et al., 2004). Both cratons are bounded by Paleoproterozoic orogenic belts (Fig. 6). The Lipetsk-Losev/East Voronezh Belt probably marks the 2100–2050 Ma accretionary orogen along the eastern margin of Sarmatia, which led to the collision with Volgo-Uralia by 2020 Ma (Schipansky et al., 2007; Bogdanova et al., 2008). Deformation and UHT metamorphism of almost the same age (2040 ± 17 Ma) has been reported from the Satpura Belt, or Central Indian Tectonic Zone (CITZ, Mohanty, 2010). These tectonothermal events reflect some stage of amalgamation of the Dharwar/Bastar/Singhbhum and Bundelkhand/Aravalli cratons. Trends and positions of these two orogens suggest their possible genetic relationship (Fig. 6). Many occurrences of Mesoproterozoic (ca. 1400–1000 Ma) kimberlites and lamproites are reported both from Dharwar and Sarmatia (e.g., Chalapathi Rao et al., 2004; Kumar et al., 2007; Bogatikov et al., 2007). However, many of these bodies are not precisely dated, so no direct correlation is yet possible.

An India-Baltica reconstruction (Fig. 6) aligns the eastern margin of India with the southern segment of the west-south western accretionary margin of Baltica. Several discoveries of Palaeo- to Mesoproterozoic ophiolites with ages between 1850 and 1330 Ma in the Eastern Ghats province of India (Fig. 6; Dharma Rao et al., 2011) suggest a long-lived active margin along the eastern Indian margin. This is supported by the development of foreland basins (Biswal et al., 2003; Chakraborty et al., 2010). Geochemical data also suggest subduction-related environments on the eastern Indian margin at 1460 Ma (Pisarevsky et al., in press).

The alignment of Laurentian, Baltican and Indian long-lived Paleo- to Mesoproterozoic accretionary orogens imply a giant, nearly linear, long-lived Paleo- to Mesoproterozoic accretionary orogen comparable in scale to the present eastern Pacific active margin.

The timing of India's breakaway from Baltica is not well constrained. Palaeomagnetic data (Table 1, entries 73–75, 93–96) suggest that it occurred between ca. 1120 and 1080 Ma (Pisarevsky et al., in press). There is no evidence of Mesoproterozoic rifting found in the western Dharwar Craton. Such evidence could be concealed in the recently (Cenozoic) rifted away Seychelles Block and/or the Antongil Terrane of Madagascar. However, these blocks were strongly tectonically overprinted in the middle and late Neoproterozoic-Cambrian East African orogen (Tucker et al., 2001; Schofield et al., 2010). Similarly, the south-western margin of Sarmatia is mostly covered and probably strongly overprinted by the Cadomian orogeny. Bogdanova et al. (1996) suggested that the 1300–1100 Ma Volyn-Orsha aulacogen (Fig. 6) could represent the failed arm of a triple junction, which implies that the successful rifting could have occurred along the Teisseyre-Tornquist line, which may also represent rifting between Baltica and India. Poprawa and Pacześna (2002) suggested that this rifting could have occurred during the Mesoproterozoic. Nikishin et al. (1996), in their 1350–1050 Ma paleogeographic reconstruction of Baltica, indicate a continental slope along the Teisseyre-Tornquist line, suggesting the passive continental margin, which could be result of the continental breakup. The 1300–1100 Ma mafic sills in the western part of the Volyn-Orsha aulocogen were mentioned by Bogdanova et al. (2008) with reference to unpublished K-Ar and Rb-Sr dates of Aksenov (1998), which indirectly provide some constraints on the timing of the rifting between Baltica and India.

8. Congo/ São Francisco and Siberia

The Congo/ São Francisco craton is traditionally treated as a single entity, owing to the similarity of Archean and Paleo- to Mesoproterozoic rocks and bounding late Neoproterozoic mobile belts (e.g. Teixeira et al., 2000; Trompette, 1994). Ernst et al. (2013) suggested that the Siberian and Congo/ São Francisco cratons were close to each other between 1500 and 1380 Ma. In this case the continuity of general trends of the coeval ca.1500 Ma Kuonamka dyke swarm (Siberia), Curaçá and Chapada Diamantina dyke swarms (São Francisco) and SW Angola sills (Congo) intersect in NE Siberia and provide a possible location for the mantle plume centre (shown in our 1500 Ma reconstruction, Fig.11). There were also coeval 1384 ± 2 Ma Siberian Chieress (Ernst et al., 2000) and Congolesian Kunene (1385 ± 8 Ma, Drüppel 193 et al., 2000; 1385 ± 25 Ma, Mayer et al., 2004; 1371 ± 3 Ma, McCourt et al., 2004), Kabanga-Musongati-Kapalaglula and Kibaran (1370–1380 Ma, Tack et al., 2000) magmatic events, which support the closeness of these continents for at least 120 m.y. Such a reconstruction is also broadly consistent with two non-key poles – the Siberian 1384 ± 2 Ma Chieress pole (Ernst et al., 2000) and the Angolan 1385–1375 Ma Kunene pole (Piper, 1974, redated by Drüppel et al., 2000; Myer et al., 2004; McCourt et al., 2004; Table 1 entries 62–63). These poles are shown in our 1380 Ma reconstruction (Fig.14). The 1236 ± 24 Ma late Kibaran pole (Meert et al., 1994) also support this reconstruction at later times, as shown in our 1270 Ma reconstruction (Fig.15).

9. Kalahari

Only two poorly dated non-key poorly dated poles are available for Kalahari (Table 1, entries 32 and 37). Pesonen et al. (2003) and Jacobs et al. (2008) showed in their 1770 Ma, 1750 Ma and 1200 Ma reconstructions that Kalahari was surrounded by oceans. We follow this suggestion for our 1770–1270 Ma reconstructions where Kalahari is a “lone” continent, the position of which is constrained by the two abovementioned non-key poles.

10. Global paleogeographic reconstructions

Other continents other than those discussed above are paleomagnetically under-represented. For these continents we either used geological constraints to place them in our reconstructions, or in some cases ignored them. All rotation parameters are shown in Table 2.

Cratonic cores of most considered continents were formed by the late Paleoproterozoic, but some (Laurentia, Baltica, Amazonia) experienced significant growths during Mesoproterozoic accretionary orogenies. In our reconstructions we schematically showed these growths by increasing the sizes of these continents for successive younger ages (Figs. 7–15). Some other continents could also have grown (e.g. Jacobs et al., 2008), but their histories are less certain, so we used the same shape for them during the entire time interval considered.

10.1. 1770 Ma (Fig. 7)

Several Archean proto-cratons (Superior, Slave, Hearne, Rae, Nain) were interpreted to have collided at ca. 2000–1800 Ma along the Trans-Hudson, Telon-Taltson and Torngat orogens and formed the core of Laurentia (Hoffman, 1989; Karlstrom et al., 2001). Evidence for the 1780–1720 Ma collision between the Wyoming and Hearne cratons, the Big Sky orogeny (Harms et al., 2004), suggests that the Wyoming Craton was approaching Laurentia by 1770 Ma (Fig. 7). The ca. 1800–1700 Ma accretion of juvenile crust along the S-SE Laurentian margin (in present coordinates – hereafter) resulted in the Yavapai orogeny (Karlstrom et al., 2001).

The Archean Kola and Karelian cratons collided at the end of the 1940–1860 Ma Lapland-Kola orogeny (Lahtinen et al., 2008) and assembled as the core of Fennoscandia (Bogdanova et al., 2008). At ca.1920 Ma the accretionary growth of Fennoscandia begun along its SW margin, culminating in the formation of 1810–1770 Ma NW-trending granitoids in southern Sweden, i.e. the older part of the Transscandinavian Igneous Belt (TIB1, Lahtinen et al., 2008).

The continuous accretionary orogenic events along the S-SE Laurentian margin and SW Fennoscandian margin suggest an active margin regime along the joint Laurentian-Fennoscandian continent (Pisarevsky and Bylund, 2010). This idea is supported by the ca. 1900–1700 Ma Laxfordian orogeny in the northern Scottish blocks of Laurentian affinity (Snyder et al., 1996) and by the active margin conditions in the Makkovik Province of Labrador in the same time interval (Culshaw et al., 2000).

The position of the joined Laurentia and Fennoscandia is constrained by paleopoles from both continents (Table 1, entries 1–8; Fig. 7). Sarmatia/India and Volgo-Uralia approached Fennoscandia during that time.

Two other building blocks of Baltica – Sarmatia and Volgo-Uralia – have a distinct pre-1800 Ma history and are considered as separate continents up to ca. 2.0 Ga, when they amalgamated (Bogdanova, 1993; Bogdanova et al., 2008). Between 1800 and 1700 Ma Fennoscandia and Volgo-Uralia/Sarmatia approached each other and collided along a suture that was subsequently overprinted by the Volyn-Orsha and Mid-Russian aulacogens (Bogdanova et al., 2008). The 1770–1740 Ma Korosten paleopole from Ukraine (Elming et al., 2001; Elming et al., 2010) suggests that Baltica was not yet assembled at that time. In our reconstruction their position is constrained by the Korosten paleopole and coeval Baltican poles (Table 1, entries 2–6; Fig. 7).

Another conglomeration of continents – Australia, Mawson and North China – are loosely constrained by four poles (Table 1, entries 9–12) and geological evidence (see Sections 4 and 5).

A Siberian connection with Congo/São Francisco is suggested on the basis of previuously presented arguments (see Section 8).

The position of Amazonia/West Africa is constrained by two poles (Table 1, entries 13 and 15). However, the Colider pole (Table 1, entry 14) is not supportive of this position (see discussion in Section 6). Accretion continued along the SW margin of Amazonia, expressed by the 1780–1550 Ma Rio Negro – Juruena province.

There are indicators of subduction under the western margin of Kalahari and of a passive regime on its eastern margin (Jacobs et al., 2008), which suggest that this continent was surrounded by oceans.

10.2. 1720 Ma (Fig. 8)

Laurentia’s SE margin grew during the Yavapai accretionary orogeny, and accretion continued during the Mazatzal-Labrador orogeny. The Wyoming Craton collided with the Hearne Craton (the Big Sky orogeny), and Sarmatia-India and Volgo-Uralia moved closer to Fennoscandia. The position of Laurentia-Fennoscandia is constrained by the Cleaver Dykes pole (Irving et al., 2004; Table 1, entry 20), whereas there is no coeval pole for Fennoscandia.

An equatorial position of Siberia is supported by recently published poles from the Aldan block (Didenko et al., 2013; Table 1, entries 24–25) and three non-key VGPs (Table 1, entries 21–23).

The position and orientation of Australia is well constrained paleomagnetically (Table 1, entries 16–19). Accretionary processes continued along the southern margin of the NAC (1740–1715 Ma Strangways orogeny; Betts and Giles, 2006).

The location and orientation of Amazonia/West Africa in uncertain. In this and several further reconstructions we place them into positions interpolated from paleomagnetically constrained 1770 Ma and 1420 Ma reconstructions.

10.3. 1650 Ma (Fig. 9)

The position of the Laurentia-Baltica is constrained by two Baltican poles (Table 1, entries 26–27). Accretion along SE Laurentia (the Mazatzal orogeny), W Baltica (the Gothian orogeny) and India continued.

Australia/Mawson approached western Laurentia at this time (the first phase of the Racklan orogeny). Accretion along the southern margin of the NAC continued (the Liebig Event; Betts and Giles, 2006).

Siberia was moving closer to its paleomagnetically constrained 1470 Ma position, and the position of Kalahari is loosely constrained by two non-key poles (Table 1, entries 32 and 37).

10.4. 1580 Ma (Fig. 10)

The position of the Laurentia-Baltica is constrained by two Baltican poles (Table 1, entries 33–34). The accretion along the SW Laurentian margin temporarily stopped (Karlstrom et al., 2001). However, accretion continued along the western Baltican (the Gothian orogeny) and possibly the SE Indian margins.

At ca. 1600 Ma a collision between the NAC and Laurentia occurred, and their relative positions are also paleomagnetically constrained (Table 1, entries 35–36). Betts et al. (2007) reported a 1600–1500 Ma hot spot track from SAC to NAC. The position of the suggested mantle plume head is shown in this and the next reconstructions.

We speculate that ca. 1600–1580 Ma was the time of the complete assembly of Nuna when two continental assemblies – Laurentia-Baltica-India (West Nuna) and Australia-Mawson-North China (East Nuna) – amalgamated. It is not clear whether Siberia-Congo/São Francisco also joined Nuna at the same time, or if this occurred later, at ca. 1500–1470 Ma (see Section 3).

The position of Kalahari, which we suggest was a “lone”, continent is loosely constrained by a non-key pole (Table 1, entry 37).

10.5. 1500 Ma (Fig. 11)

The position of Laurentia-Baltica is constrained by two Baltican poles (Table 1, entries 38–39). Tectonic activity (Pinwarian orogeny) was renewed along the NE Laurentian margin involving subduction beneath Laurentia (Karlstrom et al., 2001 and references therein; Gower and Krogh, 2002). The 1520–1480 Ma Telemarkian accretion continued along the western margin of Baltica (Bingen et al., 2008).

Nuna moved northward and the NAC moved across the mantle plume (Betts et al., 2007). Another mantle plume possibly reached the surface in NE Siberia, causing the Kuonamka-Curaçá-Chapada Diamantina radial dyke swarm (see Section 8).

10.6. 1470–1450 Ma (Fig. 12 and 13)

During this time interval the position of the Laurentia-Baltica continent is well constrained by paleomagnetic data (Table 1, entries 45–52).

The tectonic regime along the SE margin of Laurentia is generally regarded as ‘anorogenic’ (e.g., Davidson, 2008 and references therein), but there is some evidence for continental arc magmatism and collision of ca. 1500–1400 Ma juvenile crustal blocks (Karlstrom et al., 2001 and references therein). Gower and Krogh (2002) explained the 1460–1230 Ma Elsonian magmatism in the Genville Province by a low angle subduction, possibly associated with an overridden spreading centre. Accretion also continued along the western margin of Baltica (the 1470–1420 Ma Hallandian-Danopolonian orogeny; Bingen et al., 2008).

The westerly source region for of Paleoproterozoic detritus in the Belt-Purcell sedimentary basin near the western margin of Laurentia (Fig. 13) is distinct from known Laurentian crust (e.g. Davidson, 2008 and references therein). The tectonic setting of this basin has been debated (e.g. Hoffman, 1989; Winston and Link, 1993 and references therein), however, most workers argued in favour of an intracontinental origin (e.g. Davidson, 2008). We suggest that the Belt-Purcell basin developed on the failed arm of a rifting system (Fig. 13). Rifting was probably related to the 1469–1457 Ma Moyie sills found in the lower part of the Belt Supergroup (Elston et al., 2002). Traces of ca. 1450–1430 Ma magmatism are also found in Hainan Island (Cathasia), which could have been a part of Laurentia during the late

Paleo- to Mesoproterozoic (Li et al., 2008a,b). In our model two successive rifting arms caused a separation of the Mawson/Gawler part of East Nuna from Laurentia (Fig. 13).

10.7. 1380 Ma (Fig. 14)

The rifting between western Laurentia and Mawson/SAC propagated northward (present coordinates) and eventually caused the breakup between the NAC and Laurentia at ca. 1380 Ma (the age of the Hart River magmatism).

This propagating rifting caused internal movements within East Nuna, in particular the anticlockwise rotation of the SAC with respect to the NAC (Figure 18a of Betts and Giles, 2006) caused the separation of the Mount Isa Inlier (NAC) from the Broken Hill area (SAC) and closure of the gap between SAC and WAC marking the initial stage of the Albany-Fraser orogeny.

On the basis of a new ca. 1350 Ma pole from North China, breakup and rotation of this continent from East Nuna after ca. 1400 Ma is suggested (Table 1, entry 61).

The position of Laurentia-Baltica is supported paleomagnetically (Table 1, entries 56–60). The SE margin of Laurentia was probably still subduction-related (e.g., Rivers, 1997 and references therein; Karlstrom et al., 2001 and references therein; Gower and Krogh, 2002), whereas it is less certain along the western margin of Baltica. Bingen et al. (2008) described the 1340–1140 Ma Pre-Sveconorwegian interval for western Baltica as "an extensional or transtensional regime located in a continental arc, continental back-arc or Basin and Range environment". The eastern Indian margin was probably also active as Dharma Rao et al. (2001) reported a ca. 1330 Ma Kanigiri ophiolitic mélange in that area.

The fixed distal position of Siberia with respect to Laurentia (see Section 3) is also supported by a match between the non-key 1384 ± 2 Ma Chieress VGP and coeval Laurentian poles (Table 1, entries 56–60 and 62).

The Siberian connection with Congo/São Francisco (see Section 8) is supported by the mentioned Chieress pole and the non-key 1385–1375 Ma Kunene pole (Table 1, entry 63).

10.8. 1270 Ma (Fig. 15)

The paleoposition of Laurentia is paleomagnetically well constrained (Table 1, entries 65–71), and the Baltican pole from post-Jotnian Intrusions suggest that Baltica and Laurentia still were still connected (Table 1, entry 64). The Elzevirian orogeny continued along the NE margin of Laurentia (e.g. Davidson, 2008 and references therein).

Although there are no Australian paleomagnetic data for this time, we suggest that Australia was widely separated from Laurentia, as indicated by younger paleopoles from both continents (Table 1, entries.67, 76 and 90).

The slightly younger, 1260–1212 Ma, late Kibaran pole from Congo (Table 1, entry 72) suggests that the Siberian connection with Congo/São Francisco still persisted.

11. Final remarks

After the ca. 2.0–1.8 Ga assemblies of most proto-continents – Laurentia, Fennoscandia, Sarmatia/Volgo-Uralia, Siberia, NAC, WAC, SAC/Mawson, North China, Congo/São Francisco, Amazonia/West Africa, India and Kalahari – some of these collided to form two or three stable continental masses by ca. 1700 Ma. The first landmass, that we preliminary call West Nuna, consisted of Laurentia, Baltica (Fennoscandia/Sarmatia/Volgo-Uralia) and probably India. The second landmass (East Nuna) included North, West and South Australia, the Mawson craton of Antarctica and North China. Although these two land masses may have joined as a single supercontinent by ca. 1.75 Ga as suggested by numerous previous studies (e.g., Zhao et al., 2004, 2004; Evans and Mitchell, 2011; Zhang et al., 2012), such a connection may not have been stable and some minor relative movements might have occurred between them after this time but prior to ca. 1600. We suggest that East and West Nunas likely collided between 1650 and 1580 Ma to form a more coherent Nuna supercontinent. Siberia and possibly Congo/São Francisco joined Nuna at ca. 1500 Ma, if not earlier. The breakup of Nuna occurred between ca. 1450 and 1380 Ma. The first stage of this separation caused internal displacements within East Nuna – rotation of SAC/Mawson with respect to NAC and WAC. North China also broke away from East Nuna. By 1270 Ma a wide ocean had developed between West and East Nunas. West Nuna, Siberia (connected with northern Laurentia by as yet unknown continental blocks) and maybe Congo/São Francisco remained a single continent until ca. 1270 Ma. It is yet unclear whether Amazonia/West Africa and Kalahari were ever parts of Nuna.

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Appendix

An animated history, 1770–1270 Ma – PowerPoint animation available at (link to the PowerPoint file at the Elsevier online version).

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Figure captions

Fig. 1 Time-space distribution of late Paleoproterozoic and Mesoproterozoic paleomagnetic data for different cratons.

Fig. 2. Laurentia-Baltica reconstruction (a) and Laurentian and Baltican paleopoles for the time interval 1800 – 1270 Ma plotted in Laurentian coordinates. Baltica is rotated to Laurentia about a pole at 44.99°N, 7.45°E by +44.93°.

Fig. 3. Paleomagnetically supported reconstruction of Siberia and Laurentia at ca. 1000 Ma. Laurentia is rotated to the absolute framework about a pole at 24.21°N, 175.26°E by -150.19°. Siberia is rotated to Laurentia about a pole at 69.95°N, 133.23°E by +127.05°. Internal rotations in Siberia are also applied (see Section 3). Paleopoles' numbers are as in Table 1.

Fig. 4. Baltica – Amazonia SAMBA reconstruction, simplified from Johansson (2009).

Fig. 5. Paleomagnetic test of the SAMBA reconstruction: (a-c) at 1790 Ma; (d-f) at 1420 Ma. See text in Section 6.

Fig. 6. Geological matches in the paleomagnetically permissive Baltica-India reconstruction (after Pisarevsky et al., in press). India is rotated to Baltica about a pole at 30.7°N, 54.3°E by -184.9°.

Fig. 7. Global paleogeographic reconstruction at 1770 Ma. Filled polygons represent Archean crust. Paleopoles' numbers are as in Table 1 on the polar projection. La=Laurentia, Fennosc=Fennoscandia, VU=Volgo-Uralia, Sar=Sarmatia, NAC=North Australian craton, WAC=West Australian Craton, SAC=South Australian Craton, Maw=Mawson Craton, Si=Siberia, SF= São Francisco, Kal=Kalahari, Am=Amazonia, WA=West Africa, NC=North China.

Fig. 8. Global paleogeographic reconstruction at 1720 Ma. See notes to Fig. 7.

Fig. 9. Global paleogeographic reconstruction at 1650 Ma. Ba=Baltica. See notes to Fig. 7.

Fig. 10. Global paleogeographic reconstruction at 1580 Ma. The star denotes the position of the mantle plume head. See notes to Fig. 7.

Fig. 11. Global paleogeographic reconstruction at 1500 Ma. See notes to Fig. 7.

Fig. 12. Global paleogeographic reconstruction at 1470 Ma. See notes to Fig. 7.

Fig. 13. Global paleogeographic reconstruction at 1540 Ma. See notes to Fig. 7.

Fig. 14. Global paleogeographic reconstruction at 1380 Ma. See notes to Fig. 7.

Fig. 15. Global paleogeographic reconstruction at 1270 Ma. See notes to Fig. 7.

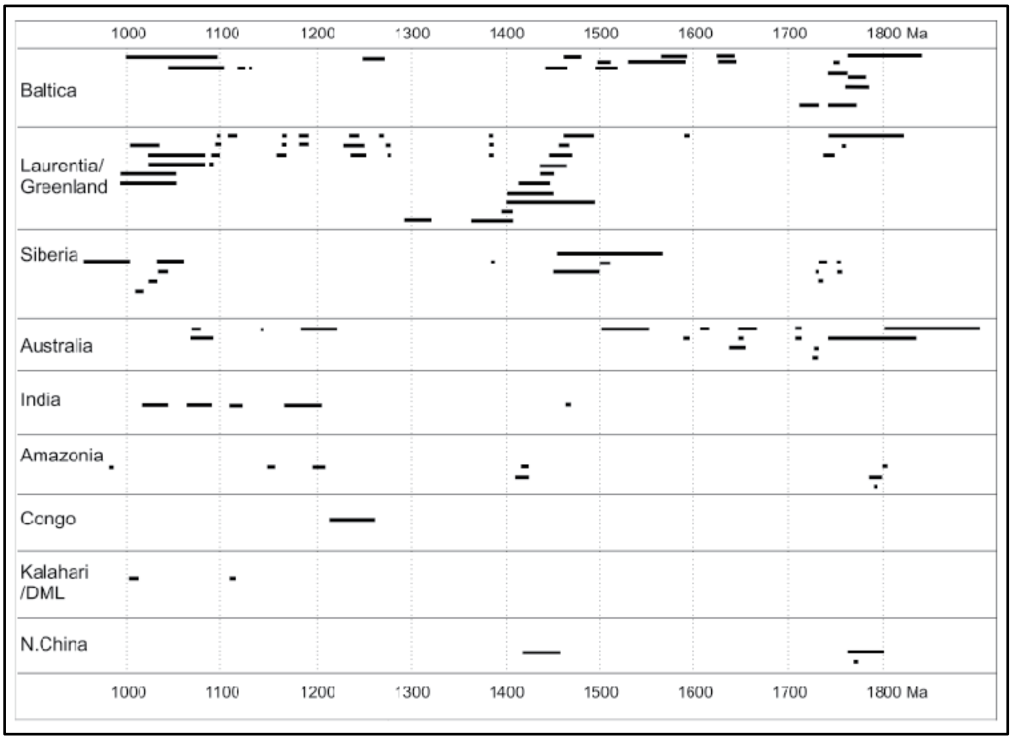


Figure 1

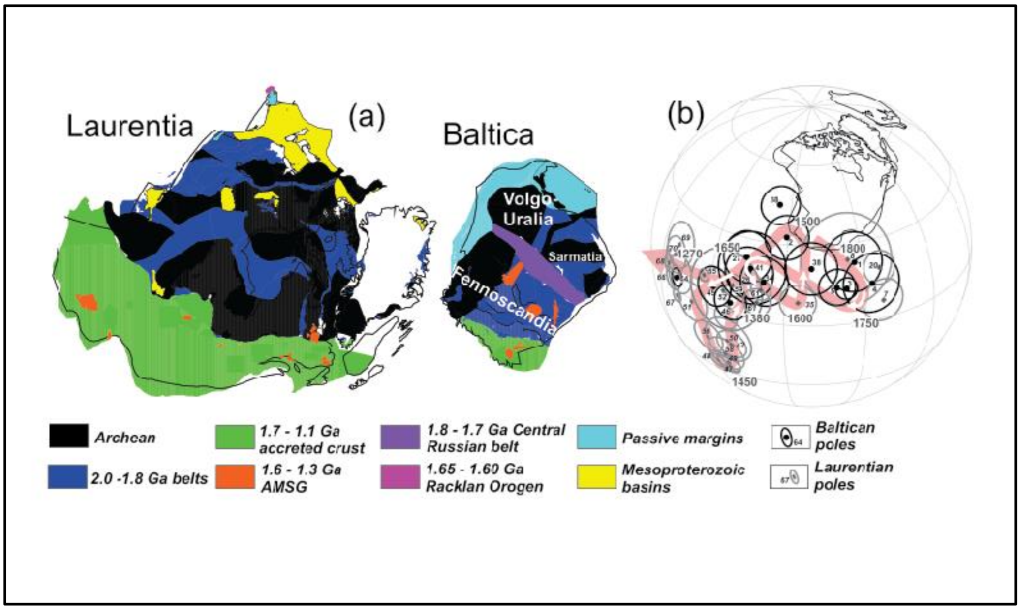
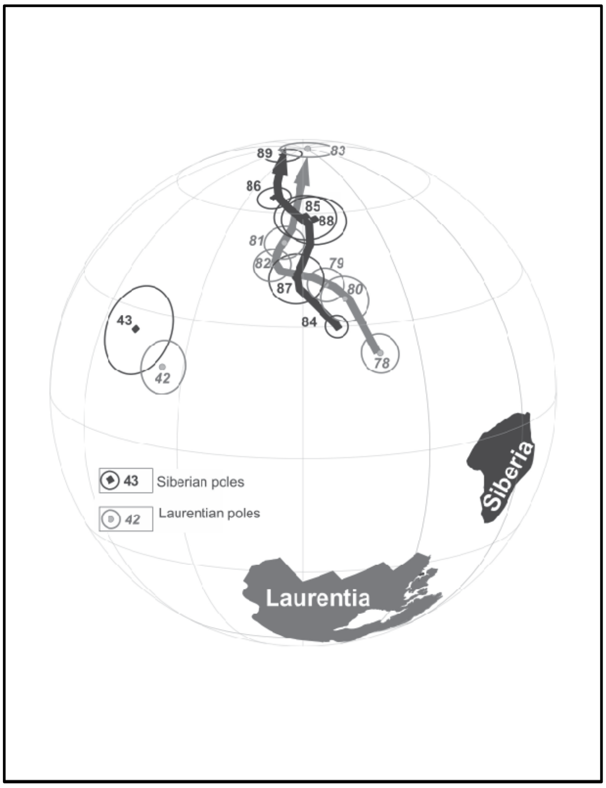


Figure 2



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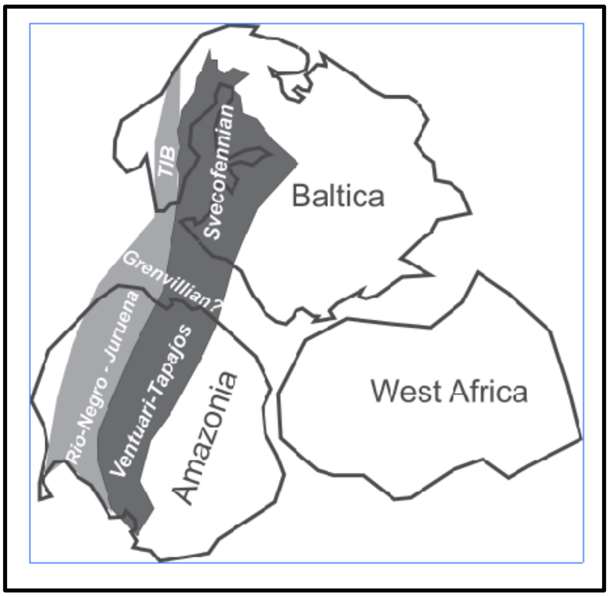

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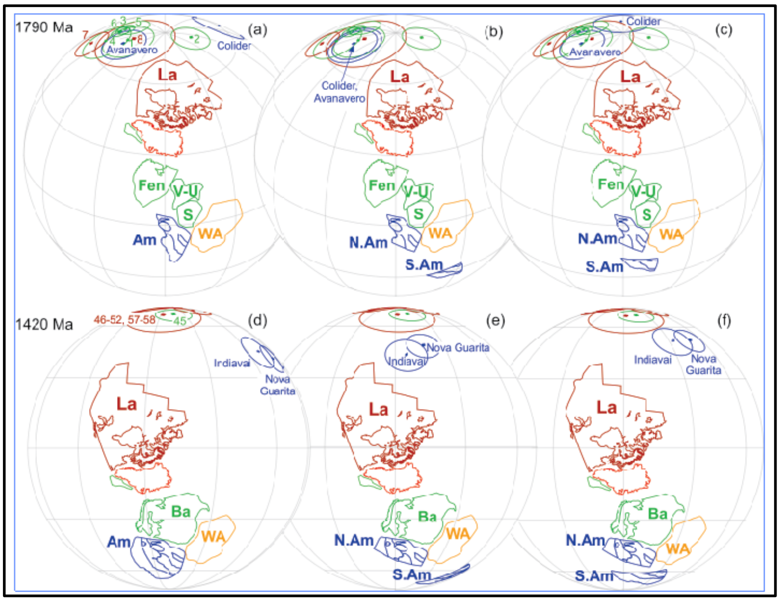

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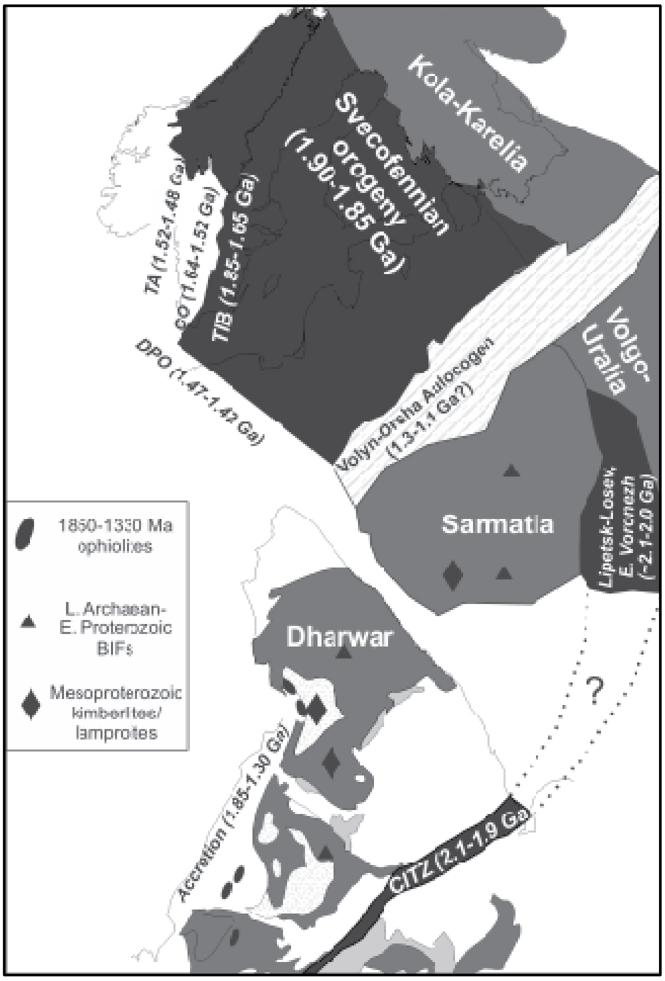

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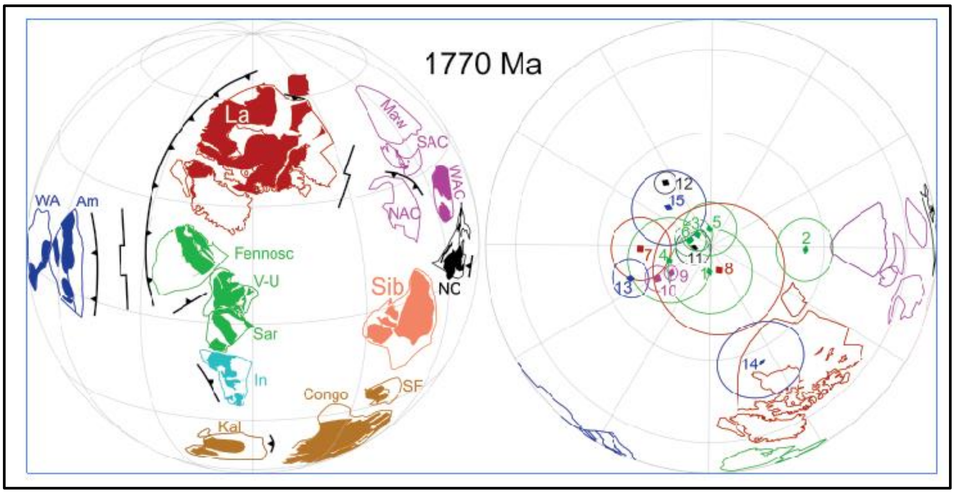

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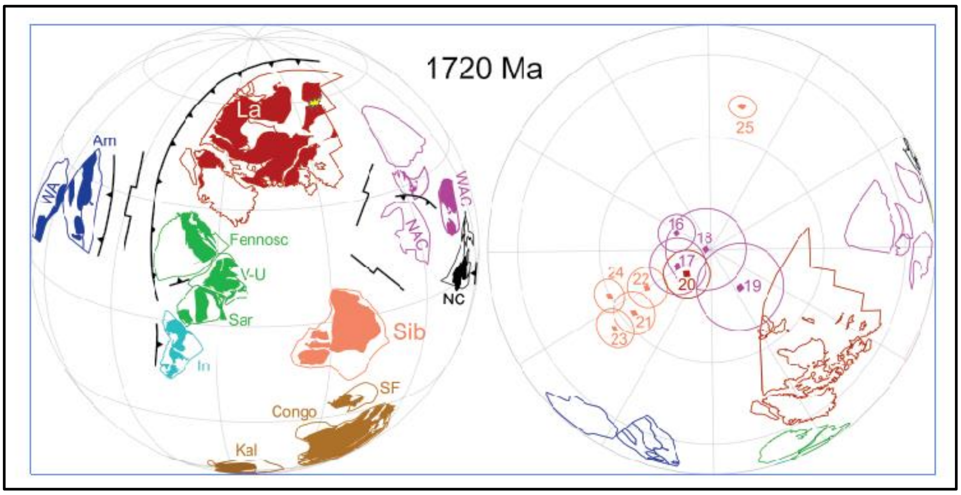

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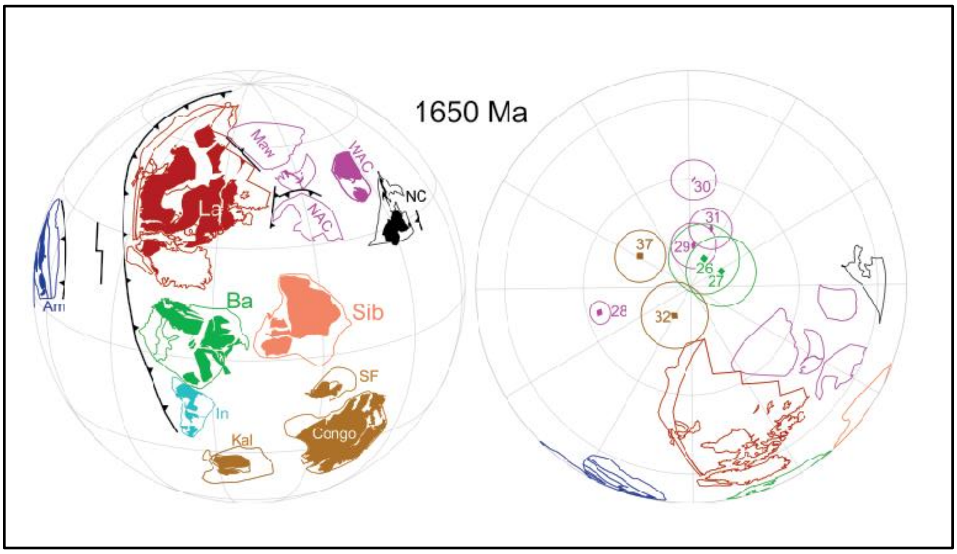

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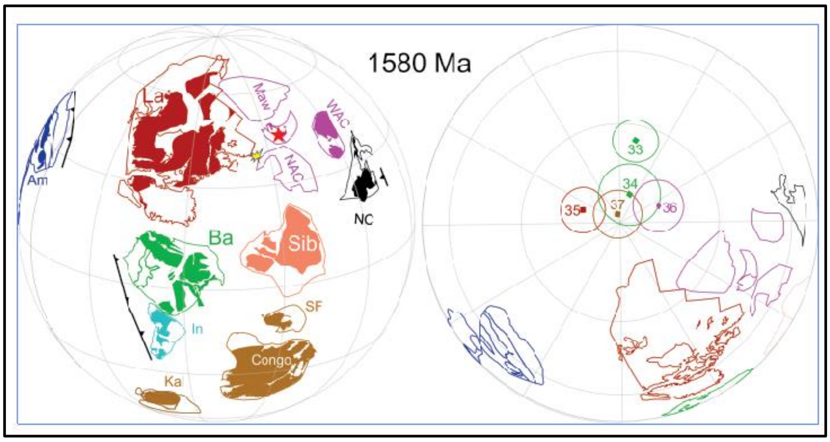

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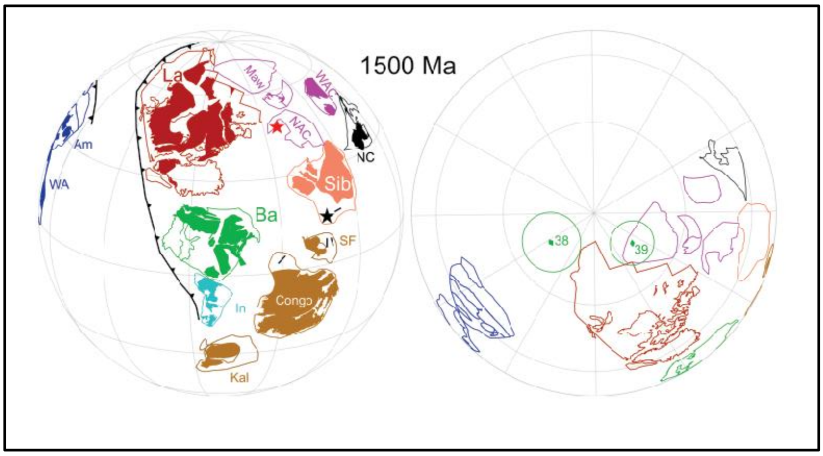

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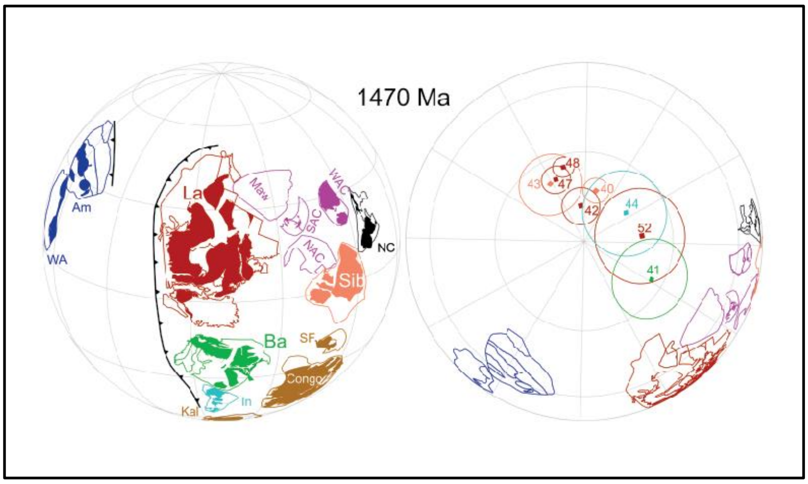

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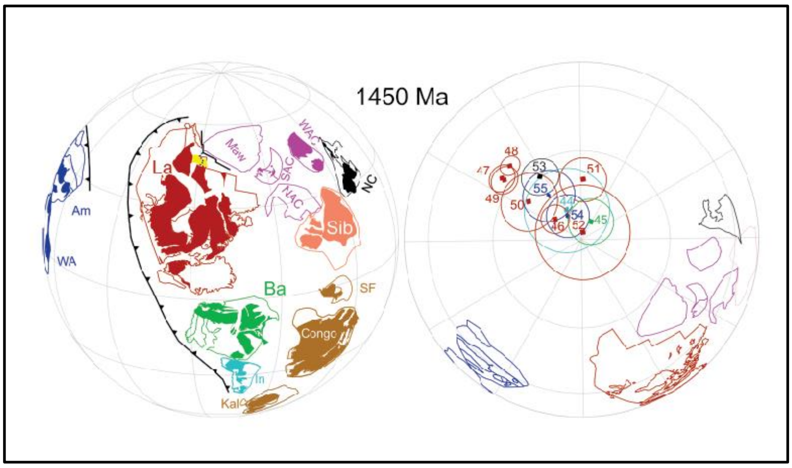

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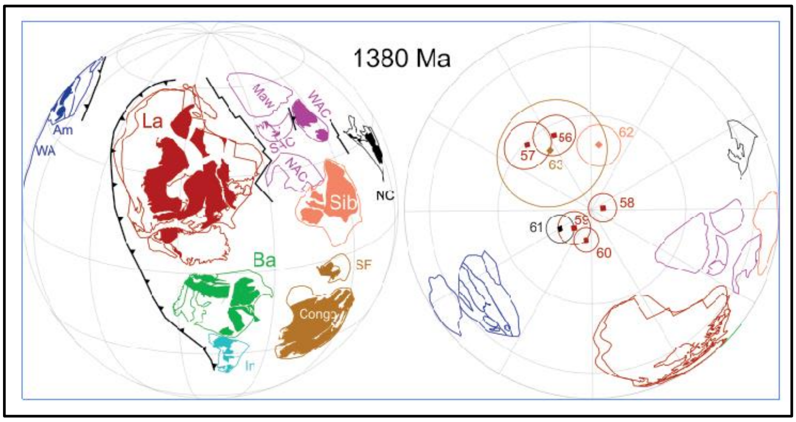

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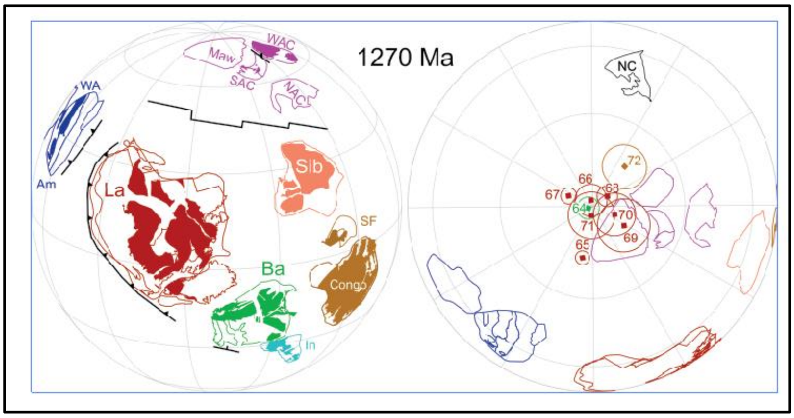

Figure 15

Table 1. Selected 1800-1000 Ma paleomagnetic poles (modified from the Luleå Workshop 2009 compilation).

#	Rockname	Continent	Age (Ma)	Plat (°N)	Plong (°E)	A_{95} (°)	Reference
				1770 Ma			
1	Late. Svecofennian Rocks, Mean	Fenn	~1800	49.6	221.0	10.8	In: Elming and Pesonen, 2010.
2	Småland Intrusions	Fenn	1784-1769	45.7	182.7	8.0	Pisarevsky and Bylund, 2010
3	Shoksha Formation	Fenn	1780-1760	39.7	221.1	4.0	Pisarevsky and Sokolov, 2001
4	Hoting Gabbro	Fenn	1760-1740	43.0	233.3	10.9	Elming et al., 2009b
5	Ropruchey Sill	Fenn	1754-1748	39.1	216.6	6.7	Fedotova et al., 1999; Lubnina et al., 2012
6	Korosten Pluton	Sarm	1770-1740	25.1	171.0	4.0	Elming et al., 2001
7	Dubawnt Group	Lau	1820-1750	7.0	277.0	8.0	Park et al., 1973
8	Jan Lake Granite	Lau	1759-1757	24.3	264.3	16.9	Gala et al., 1995
9	*Frere Formation*	*WAC*	*1900-1800*	*45.2*	*40.0*	*1.8*	*Williams et al., 2004*
10	*Elgee-Pentecost Formations*	*NAC*	*1834-1740*	*5.4*	*31.8*	*3.2*	*Schmidt and Williams, 2008; Wingate et al., 2011*
11	Xiong'er Group	N.Chi	~1780	50.2	263.0	4.5	Zhang et al., 2012
12	Taihang Dykes	N.Chi	1772-1766	36.0	247.0	2.8	Halls et al., 2000
13	Basic Dykes Group II	Am	1802-1798	42.0	180.0	5.0	Onstott et al., 1984
14	Colider Volcanics	Am	1796-1782	63.3	118.8	11.4	Bispo-Santos et al., 2008
15	Avanavero Intrusions	Am	1791-1786	48.4	207.9	9.6	Reis et al., in press
				1720 Ma			
16	Peters Creek Volc., upper part	NAC	1729-1725	26.0	41.0	4.8	Idnurm, 2000
17	Wollogorang Formation	NAC	1730-1723	17.9	38.2	7.2	Idnurm et al., 1995
18	Fiery Creek Formation	NAC	1712-1706	23.9	31.8	10.4	Idnurm, 2000
19	West Branch Volcanics	NAC	1712-1705	15.9	20.50	11.3	Idnurm, 2000
20	Cleaver Dykes	Lau	1745-1736	19.4	276.7	6.1	Irving et al., 2004
21	*Chaya Dyke 1 VGP*	*Sib*	*1755-1749*	*40.0*	*280.0*	*5.7*	*Vodovozov et al., 2007; Gladkochub et al., 2010*
22	*Chaya Dyke 2 VGP*	*Sib*	*1755-1749*	*39.0*	*270.0*	*5.3*	*Vodovozov et al., 2007; Gladkochub et al., 2010*
23	*Angara-Kan Granite VGP*	*Sib*	*1739-1729*	*42.9*	*289.6*	*5.3*	*Didenko et al., 2009*

24	Ulkan Granite*	Sib	1730-1725	48.0	278.8	4.4	Didenko et al., 2013
25	Elgetei Formation*	Sib	1736-1728	18.1	210.6	3.6	Didenko et al., 2013
				1650 Ma			
26	Sipoo Quartz Porphyry Dykes	Ba	1643-1623	26.4	180.4	9.4	Mertanen and Pesonen, 1995
27	Finnish Quartz Porphyry Dykes	Ba	1641-1621	30.2	175.4	9.4	Neuvonen, 1986
28	Mallpunyah Formation	NAC	1665-1645	35.0	34.3	3.1	Idnurm et al., 1995
29	Tooganinie Formation	NAC	1651-1645	61.0	6.7	6.1	Idnurm et al., 1995
30	Emmerugga Dolomite	NAC	1653-1635	79.1	22.6	6.1	Idnurm et al., 1995
31	Balbirini Dolomite, lower part	NAC	1617-1606	66.1	357.5	5.7	Idnurm, 2000
32	*Bathlaros Kimberlite*	*Kal*	*1700-1600*	*30.0*	*8.2*	*8.9*	*Hargraves et al., 1989*
				1580 Ma			
33	Kumlinge-Brändö Dykes	Ba	1590-1562	12.2	182.0	6.7	Pesonen and Neuvonen, 1981
34	Föglö-Sottunga Dykes	Ba	1589-1528	27.8	187.5	9.0	Pesonen and Neuvonen, 1981
35	Western Channel Diabase	Lau	1593-1587	9.0	245.0	6.6	Irving et al., 1972; Hamilton and Buchan, 2010
36	Balbirini Dolomite, upper part	NAC	1592-1586	52.0	356.1	7.5	Idnurm, 2000
37	*Van Dyk Mine Dyke.*	*Kal*	*1650-1550*	*12.4*	*13.9*	*7.0*	*Jones and McElhinny, 1966*
				1500 Ma			
38	Rødø basic dykes	Ba	1513-1497	41.6	201.7	9.5	Moakhar and Elming, 2000
39	Ragunda Formation	Ba	1519-1493	51.6	166.6	7.1	Piper, 1979
				1470 Ma			
40	*Fomich Mafic Intrusions*	*Sib*	*1564-1452*	*19.2*	*257.2*	*4.2*	*Veselovsky et al., 2006*
41	Bunkris/Glysjon/Oje Rocks	Ba	1478-1460	28.3	179.8	13.2	Bylund, 1985; Söderlund et al., 2005
42	St.Francois Mountains	Lau	1492-1460	-13.2	219.0	6.1	Meert and Stuckey, 2002
43	Kyutingde, Sololi intrusions, Siberia	Sib	1497-1449	33.6	253.1	10.4	Wingate et al., 2009
44	Lakhna Dykes, India	Ind	1468-1462	36.6	132.8	14.0	Pisarevsky et al., in press
				1450-1420 Ma			
45	Ladoga-Valaam Intrusions	Ba	1464-1440	11.8	173.3	7.4	Salminen and Pesonen, 2007; Shcherbakova et al., 2008

46	Michikamau Intrusion	Lau	1465-1455	-1.5	217.5	4.7	Emslie et al., 1976
47	Spokane Formation	Lau	1470-1445	-24.8	215.5	4.7	Elston et al., 2002
48	Snowslip Formation	Lau	1463-1436	-24.9	210.2	3.5	Elston et al., 2002
49	Purcell Lava	Lau	1450-1436	-23.6	215.6	4.8	Elston et al., 2002
50	Rocky Mountain Intrusions, Mean	Lau	1445-1415	-11.9	217.4	9.7	In: Elming and Pesonen, 2010.
51	Mistastin Pluton	Lau	1450-1400	-1.0	201.5	7.6	Fahrig and Jones, 1976
52	Tobacco Root Dykes A	Lau	1497-1399	8.7	216.1	15.5	Harlan et al., 2008
53	Tieling Formation	N.Chi	1458-1416	11.6	187.1	6.3	Wu et al., 2005
54	Nova Guarita Intrusives	Am	1423-1415	47.9	65.9	7.0	Bispo-Santos et al., 2012
55	Indiavai Intrusion	Am	1423-1409	57.0	69.7	8.6	D'Agrella-Filho et al., 2012
				1380 Ma			
56	McNamara Formation	Lau	1407-1395	-13.5	208.3	6.7	Elston et al., 2002
57	Pilcher, Garnet Range, Libby Formations	Lau	1407-1362	-19.2	215.3	7.7	Elston et al., 2002
58	Victoria Fjord Dolerite Dykes	Gre	1384-1380	10.3	231.7	4.3	Abrahamsen and Van der Voo, 1987
59	Midsommersoe Dolerite	Gre	1384-1380	6.9	242.0	5.1	Marcussen and Abrahamsen,1983
60	Zig-Zag Dal Basalts	Gre	1384-1380	12.0	242.8	3.8	Marcussen and Abrahamsen,1983
61	N.China Sills	N.Chi	1367-1333	5.9	359.6	4.3	Chen et al., 2013
62	*Chieress Dyke VGP*	*Sib*	*1386-1382*	*5.0*	*258.0*	*6.7*	*Ernst et al., 2000*
63	*Kunene Complex*	*Con*	*1385-1375*	*-3.0*	*255.0*	*17.4*	*Piper, 1974; Mayer et al., 2004; Drüppel et al., 2000; McCourt et al., 2004*
				1270 Ma			
64	Post-Jotnian Intrusions	Ba	1270-1246	-1.8	159.1	3.4	In: Elming and Pesonen, 2010.
65	Nain Anorthosite	Lau	1320-1290	11.7	206.7	2.2	Murthy, 1978
66	Mackenzie Dykes	Lau	1269-1265	4.0	190.0	5.0	Buchan and Halls (1990), LeCheminant and Heaman (1989)
67	Sudbury Dykes	Lau	1242-1232	-2.5	192.8	2.5	Palmer et al., 1977
68	Kungnat Ring Dyke	Gre	1277-1273	3.4	198.7	3.2	Piper and Stearn, 1977
69	North Qoroq Intrusions	Gre	1276-1274	13.2	202.6	8.3	Piper, 1992
70	West Gardar Dolerite Dykes	Gre	1251-1236	8.7	201.7	6.6	Piper and Stearn, 1977

71	West Gardar Lamprophyre Dykes	Gre	1249-1227	3.2	206.4	7.2	Piper and Stearn, 1977
72	Late Kibaran Intrusions	Con	1260-1212	-17.0	112.7	7.0	Meert et al., 1994
				Younger poles			
73	*Salla Dyke VGP*	*Ba*	*1129-1115*	*71.0*	*113.0*	*8.0*	*Salminen et al., 2009*
74	*Bamble Intrusions*	*Ba*	*1100-1040*	*-15.1*	*222.5*	*19.3*	*Lulea, 2009 workshop*
75	*Laanila Dolerite*	*Ba*	*1095-995*	*-2.1*	*212.2*	*13.8*	*Mertanen et al., 1996*
76	Abitibi Dykes	Lau	1143-1139	44.4	211.4	13.7	Ernst and Buchan, 1993
77	Nipigon Sills and Lavas, Mean	Lau	1115-1107	47.2	217.8	4.0	In: Elming and Pesonen, 2010.
78	Lake Shore Traps	Lau	1089-1085	22.2	180.8	4.5	Diehl and Haig, 1994; Davis and Paces, 1990
79	Freda Sandstone	Lau	1080-1020	2.2	179.0	4.2	Henry et al., 1977; Wingate et al., 2002
80	Nonesuch Shale	Lau	1080-1020	7.6	178.1	5.5	Henry et al., 1977; Wingate et al., 2002
81	Chequamegon Sandstone	Lau	1050-990	-12.3	177.7	4.6	McCabe and Van der Voo , 1983
82	Jacobsville Sandstone	Lau	1050-990	-10.0	184.0	4.2	Roy and Robertson, 1978
83	Haliburton Intrusion	Lau	1030-1000	-32.6	141.9	6.3	Warnock et al., 2000
84	Malgina Formation*	Sib	1043±14	-15.4	248.8	2.6	Gallet et al., 2000; Ovchinnikova et al., 2001
85	Kumakha Formation*	Sib	1040-1030	-3.2	221.4	7.0	Pavlov et al., 2000
86	Milkon Formation*	Sib	~1025	5.1	216.3	3.8	Pavlov et al., 2000
87	Nelkan Formation*	Sib	1025-1015	-4.4	238.8	6.3	Pavlov et al., 2000
88	Ignikan Formation*	Sib	1015-1005	-5.3	221.8	7.4	Pavlov et al., 2000
89	Kandyk Formation*	Sib	1000-950	7.0	196.7	4.3	Pavlov et al., 2002
90	W. Australian Rocks, Mean	WAC	1220-1180	59.9	331.8	27.0	Pisarevsky et al., 2003a
93	Harohalli Alkaline Dykes	Ind	1202-1182	24.9	78.0	15.0	Pradhan et al., 2008
94	Mahoba Dykes	Ind	1120-1106	38.7	229.5	12.4	Pradhan et al., 2012
95	*Majhgawan Kimberlite VGP*	*Ind*	*1088-1060*	*36.8*	*212.5*	*12.2*	*Gregory et al., 2006*
96	Anantapur Dykes	Ind	1040-1014	10.0	211.4	11.0	Pradhan et al., 2010

* Rotated to Anabar at 62°N, 117°E, 23°

Non-key poles are shown in italics

Table 2. Euler rotation parameters (to the absolute framework).

Craton/block/terrane	Pole		Angle
	(°N)	(°E)	(°)
	1770 Ma		
Laurentia	-52.03	60.09	215.25
Greenland	-51.30	63.17	228.72
Fennoscandia	-66.33	26.88	199.92
Sarmatia/Volgo-Uralia	-57.98	-10.80	172.80
India	-24.88	132.46	208.11
Wyoming	-53.02	60.69	215.51
NAC	-33.26	-0.68	206.88
WAC	-17.03	9.34	190.76
SAC	-1.92	18.32	177.99
Mawson	3.21	17.57	206.50
North China	-71.97	73.84	191.52
Siberia	-6.45	-0.31	121.40
Congo	-19.10	121.62	122.91
São Francisco	-15.26	97.91	86.64
Kalahari	17.65	116.44	114.65
Dronning Maud Land	-1.68	99.43	71.54
Rockall	-52.19	73.21	233.39
Amazonia	12.24	47.02	-166.35
West Africa	28.68	66.70	179.99
	1720 Ma		
Laurentia	-53.49	67.66	212.01
Greenland	-53.24	70.77	225.55
Fennoscandia	-68.38	35.70	194.11
Sarmatia/Volgo-Uralia	-66.51	16.45	183.12
India	-9.21	136.35	202.59
NAC	-31.05	8.72	203.04
WAC	-13.59	17.19	190.00
SAC	2.42	25.32	179.87
Mawson	5.74	25.61	209.45
North China	-68.59	73.42	176.38
Siberia	1.70	-13.68	115.28
Congo	-34.13	118.34	114.92
São Francisco	-33.41	95.14	71.86
Kalahari	-10.81	-59.61	-103.20
Dronning Maud Land	-10.65	103.77	58.09
Rockall	-53.85	81.22	230.04
Amazonia	5.04	49.98	-151.23
West Africa	24.68	67.25	-160.07
	1650 Ma		
Laurentia	-55.43	47.53	189.94
Greenland	-54.61	50.11	203.53
Baltica	-61.66	7.18	177.17
India	-16.14	135.69	199.83
NAC	-19.89	-1.91	184.72
WAC	-6.28	8.67	163.66
SAC	6.75	20.09	148.13
Mawson	10.74	22.67	176.97

North China	-71.38	22.13	177.25
Siberia	1.26	-19.76	98.53
Congo	-42.12	122.86	126.97
São Francisco	-45.07	106.43	79.56
Kalahari	-7.68	-58.91	240.38
Dronning Maud Land	-11.98	112.33	72.73
Rockall	-57.30	58.51	209.80
Amazonia	-5.74	41.42	-170.83
West Africa	10.81	60.89	-174.71

1580 Ma

Laurentia	-54.53	52.84	191.84
Greenland	-53.92	55.53	205.45
Baltica	-62.58	13.84	178.40
India	-13.21	136.86	197.48
NAC	-21.56	-0.07	189.25
WAC	-7.17	10.05	169.41
SAC	6.44	20.74	154.59
Mawson	10.43	22.98	183.51
North China	-71.37	32.48	177.56
Siberia	-10.49	-7.62	106.70
Congo	-27.82	121.43	135.59
São Francisco	-28.22	101.60	93.67
Kalahari	7.82	113.30	106.14
Dronning Maud Land	-17.65	97.61	66.07
Rockall	-56.31	64.35	211.21
Amazonia	-13.40	42.34	-155.37
West Africa	6.43	59.46	-155.01

1500 Ma

Laurentia	-59.30	53.77	179.10
Greenland	-58.93	55.76	192.93
Baltica	-64.38	9.28	163.41
India	-17.55	143.27	203.21
NAC	-22.31	3.46	174.80
WAC	-8.17	15.34	157.48
SAC	5.35	27.71	146.23
Mawson	7.54	29.47	176.03
North China	-74.68	23.99	163.92
Siberia	-16.13	6.76	94.22
Congo	-21.76	132.35	149.98
São Francisco	-20.55	114.54	108.58
Kalahari	5.78	123.79	120.09
Dronning Maud Land	-13.01	117.09	71.71
Rockall	-61.80	64.66	199.42
Amazonia	-28.31	44.66	-156.73
West Africa	-7.85	61.06	-144.89

1470 Ma

Laurentia	-41.88	52.75	173.88
Greenland	-41.56	56.85	186.46
Baltica	-48.36	22.06	169.89
India	-18.55	139.45	168.79
NAC	-9.30	9.38	195.76
WAC	6.95	15.65	175.94
SAC	21.73	24.01	159.63

Mawson	24.22	30.19	187.30
North China	-57.24	33.09	164.56
Siberia	-1.87	2.57	113.73
Congo	-20.83	128.53	120.35
São Francisco	-14.79	106.36	81.70
Kalahari	12.10	126.65	90.71
Dronning Maud Land	-7.24	105.23	42.78
Rockall	-44.65	63.62	190.33
Amazonia	-15.03	50.40	-155.16
West Africa	5.29	66.97	-149.67

1450 Ma

Laurentia	-49.45	47.34	166.33
Greenland	-49.01	50.83	179.54
Baltica	-52.17	11.71	159.27
India	-24.17	142.17	182.54
NAC	-10.69	7.32	177.96
WAC	4.30	16.48	158.32
SAC	16.42	26.24	145.57
Mawson	18.08	31.02	174.34
North China	-62.78	19.96	157.09
Siberia	-3.00	2.25	95.36
Congo	-26.50	134.70	132.06
São Francisco	-22.40	117.04	88.66
Kalahari	-3.26	-47.66	254.99
Dronning Maud Land	14.52	-52.59	306.61
Rockall	-52.53	57.44	185.10
Amazonia	-24.15	46.31	-164.17
West Africa	-5.12	63.80	-153.62

1380 Ma

Laurentia	-49.30	49.97	168.03
Greenland	-48.95	53.43	181.26
Baltica	-53.02	14.45	160.32
India	-22.33	142.65	182.02
NAC	-11.93	8.07	180.47
WAC	3.35	17.02	161.48
SAC	3.35	17.02	161.48
Mawson	8.52	18.37	189.86
North China	-38.51	28.95	127.44
Siberia	-3.86	4.00	97.84
Congo	-24.44	134.35	131.97
São Francisco	-19.98	115.95	89.69
Kalahari	-22.80	-19.79	257.70
Dronning Maud Land	-41.43	-23.88	309.43
Rockall	-52.33	60.31	186.59
Amazonia	-19.63	42.62	-146.16
West Africa	2.30	58.21	-142.29

1270 Ma

Laurentia	-45.58	33.22	147.89
Greenland	-45.06	37.64	160.47
Baltica	-41.66	1.14	147.80
India	-37.45	141.73	176.32
NAC	-10.76	16.93	149.35
WAC	4.24	30.23	136.50

SAC	4.24	30.23	136.50
Mawson	5.78	31.67	166.53
North China	-30.43	48.99	90.41
Siberia	11.06	-8.90	85.16
Congo	-40.05	141.07	124.22
São Francisco	-36.71	129.99	75.14
Kalahari	-26.92	13.49	204.38
Dronning Maud Land	-49.93	12.66	241.22
Rockall	-49.41	42.11	166.77
Amazonia	13.74	37.53	-145.13
West Africa	32.71	53.30	-166.16

1790 Ma in Fig. 5(a-c)

Laurentia	-56.21	45.56	221.94
Greenland	-54.83	47.70	235.53
Fennoscandia	-67.76	3.72	206.77
Sarmatia/Volgo-Uralia	-57.35	-28.40	176.11
Amazonia	-75.57	46.84	120.87
West Africa	-62.41	77.36	161.15
Rockall	-56.32	58.03	241.86

1420 Ma in Fig. 5(d-f)

Laurentia	-39.89	41.09	165.36
Greenland	-39.30	45.53	177.53
Baltica	-42.22	11.08	166.41
Amazonia	-51.59	6.39	91.42
West Africa	-51.89	52.92	116.82
Rockall	-43.03	51.20	182.20