Chapter 2
Paleo-Mesoproterozoic Assemblages of Continents: Paleomagnetic Evidence for Near Equatorial Supercontinents

S. Mertanen and L.J. Pesonen

2.1 Introduction

According to plate tectonic theory, the continents move across the Earth's surface through time. The hypothesis of plate tectonics and formation of supercontinents was basically developed already at 1912 by Alfred Wegener who proposed that all the continents formed previously one large supercontinent which then broke apart, and the pieces of this supercontinent drifted through the ocean floor to their present locations. According to the current plate tectonic model, the surface of the Earth consists of rigid plates where the uppermost layer is composed of oceanic crust, continental crust or a combination of both. The lower part consists of the rigid upper layer of the Earth's mantle. The crust and upper mantle together constitute the lithosphere, which is typically 50–170 km thick. This rigid lithosphere is broken into the plates, and because of their lower density than the underlying asthenosphere, they are in constant motion. The driving force for the plate motion are **convection currents** which move the lithospheric plates above the hot astenosphere. Convection currents rise and spread below divergent plate boundaries and converge and descend along the convergent plate boundaries. At converging plate boundaries the rigid plates either pass gradually downwards into the astenosphere or when two rigid plates collide, they form mountain belts, so called orogens.

S. Mertanen (✉)
Geological Survey of Finland, South Finland Unit, FI-02151 Espoo, Finland
e-mail: satu.mertanen@gtk.fi

L.J. Pesonen
Division of Geophysics and Astronomy, Department of Physics, University of Helsinki, FI-00014 Helsinki, Finland
e-mail: lauri.pesonen@helsinki.fi

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Supercontinent is a large landmass formed by the convergence of multiple continents so that all or nearly all of the Earth's continental blocks are assembled together. Their role is essential in our understanding of the geological evolution of the Earth. Rogers and Santosh (2003) presented that continental cratons began to assemble already by 3 Ga or possibly earlier. They proposed that during Archean time there existed two supercontinents, *Ur* (ca. 3 Ga, comprising Antarctica, Australia, India, Madagascar, Zimbabve and Kaapvaal cratons) and *Arctica* (ca. 2.5 Ga including the cratons of the Canadian shield and the Aldan and Anabar cratons of the Siberian shield) which were followed by a slightly younger supercontinent, *Atlantica* (including Amazonia, Congo-São Francisco, Rio de la Plata and West Africa cratons), that was formed during the early Paleoproterozoic at ca. 2.0 Ga. According to Rogers and Santosh (2003) these three ancient continental assemblies may have remained as coherent units during most of the Earth's history until their breakup of the youngest supercontinent Pangea at about 180 Ma ago. The existence of these supercontinents will be explored in this paper. Based on present geological knowledge, during the Paleo-Mesoproterozoic era there have been at least *two* times when all of the continental cratons were fused into one large supercontinent, and several other times when more than one craton were accreted to form smaller blocks (Rogers and Santosh 2003, 2004; Bleeker 2003). A larger continental assembly, *Nena* (including cratons of North America, Greenland, Baltica, Siberia and North China) existed at ca. 2–1.8 Ga and it formed part of the first real supercontinent *Nuna* (Hoffman 1997) which is also called as *Columbia* or *Hudsonland* (e.g. Meert 2002; Rogers and Santosh 2003; Zhao et al. 2004; Pesonen et al. 2003, 2011), where nearly all of the Earth's continental blocks were assembled into one large landmass at ca. 1.9–1.8 Ga (see Reddy and Evans 2009). The Nuna supercontinent started to fragment between 1.6 and 1.2 Ga and finally broke up at about 1.2 Ga. The next large supercontinent was *Rodinia* which existed from ca. 1.1 Ga to 800–700 Ma and comprised most of the Earth's continents (McMenamin and McMenamin 1990; Hoffman 1991). The breakup of Rodinia was followed by formation of the enormous Gondwana supercontinent at around 550 Ma including the present southern hemispheric continents Africa, most of South America and Australia, East Antarctica, India, Arabia, and some smaller cratonic blocks (Fig. 2.1). The present northern continents; Laurentia and Baltica collided at about 420–430 Ma, and formed the Laurussia continent (Fig. 2.1). The youngest and last world-wide supercontinent was *Pangea* that started to form at about 320 Ma when Gondwana, Laurussia, and other intervening terranes were merged together. Figure 2.1 shows the reconstruction at ca. 250 Ma when Pangea started to break apart. This process still continues today, seen for instance as spreading of the Atlantic ocean due to separation of Laurussia continents in the north (separation of North America and Europe) and the Gondwana continents in the south (separation of South America from Africa).

The oldest Precambrian continental assemblies presented above are in many cases based solely on geological evidences. However, geologically based reconstructions can be tested by the paleomagnetic method. In this paper, we will

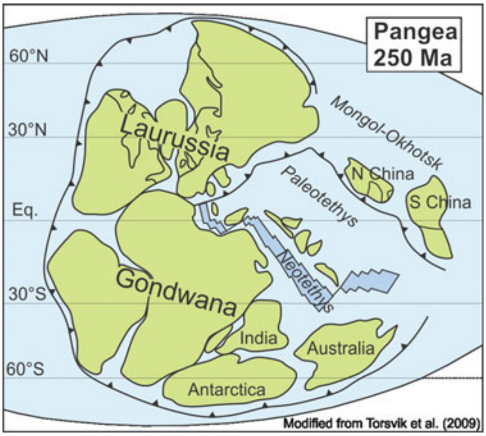

Fig. 2.1 Pangea supercontinent at ca. 250 Ma (modified from Torsvik et al. 2009, 2010b)

use the paleomagnetic method to reconstruct the Precambrian supercontinents during the time period 2.45–1.05 Ga. In the following, the basic principles of the method are shortly outlined.

2.2 Paleomagnetic Method

Paleomagnetism provides a method to constrain the configurations of cratons that have changed their relative positions through time. The method is based on the assumption that the Earth's magnetic field has always been dipolar and that the magnetic poles coincide as a long term approximation with the rotation axis of the Earth. Consequently, the magnetic field direction shows systematic variation between latitudes so that e.g. vertical geomagnetic field directions occur at the poles and horizontal directions at the equator. Deviations from these existing Earth's magnetic field directions shows that the continents have moved. By measuring the rock's remanent magnetization direction acquired when a magmatic rock cooled below the blocking temperatures of its magnetic minerals, or when magnetic particles were aligned according to the geomagnetic field direction of a sedimentary rock, it is possible to restore the craton back to its original latitude and orientation. The method has two limitations. First, because of the longitudinal symmetry of the Earth's magnetic field, only the ancient paleolatitude and paleo-orientation, but not the paleolongitude, can be defined. This gives the freedom to move the craton along latitude (Fig. 2.2). Second, due to the rapid (in geological time scheme) reversals of the Earth's magnetic field from normal to reversed polarity or vice versa, either polarity of the same magnetization direction can be used. This results to the possibility to place the continent to an antipodal hemisphere with inverted orientation (Fig. 2.2). In all cases, information about the continuations of geological structures between continents is vital in locating the cratons relative to each other.

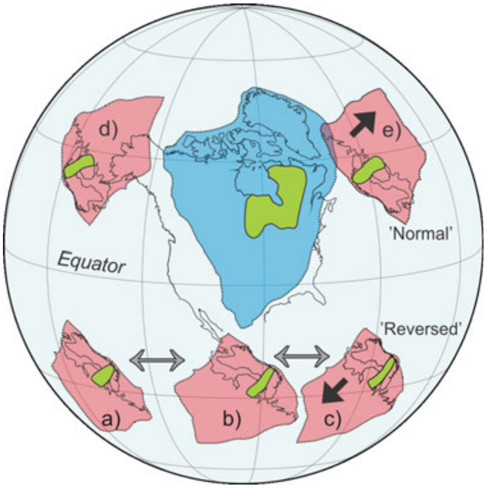

Fig. 2.2 Palaeomagnetic method for making reconstructions used in this paper. Laurentia (*blue*) and Baltica (*red*) are plotted at correct latitude and orientation, based on palaeomagnetic poles. The actual data come from the Superior (Laurentia) and Karelia (Baltica) cratons, marked in green, but for clarity, the whole continents are outlined. Here, Laurentia is kept stationary and Baltica can be moved around it as follows: positions (a), (b) and (c) show that the continent can be moved freely along latitude, but so that the continent retains its orientation. Positions (c) and (e) as well as (a) and (d) demonstrate that the polarity can be chosen between "Normal" and "Reversed" when the continent can be placed upside down on the antipodal hemisphere, depending on the polarity choice. The black arrow shows the antipodal remanence directions. Note that due to spherical projection, the form of the continent varies

2.3 Sources of Data and Cratonic Outlines

In the previous paleomagnetic compilation (Pesonen et al. 2003), the continents were assembled into their Proterozoic positions using the high quality paleomagnetic poles, calculated from the remanent magnetization directions, which were available at that time. Since then, not only have new data been published but also novel, challenging geological models of the continental assemblies during the Proterozoic have been proposed (e.g. Cordani et al. 2009; Johansson 2009; Evans 2009). In this paper, we use the updated (to 2011) paleomagnetic database (Pesonen and Evans 2012), combined with new geological information, to define the positions of the continents during the Paleoproterozoic (2.5–1.5 Ga) and Mesoproterozoic (1.5–0.8 Ga) eras. The data presented here come mainly from the largest continents (Fig. 2.3) which are Laurentia (North America and Greenland), Baltica, Amazonia, Kalahari, Congo, São Francisco, India, Australia, North China and Siberia. The smaller "microcontinents", such as Rio de la Plata, Madagascar or South China are not included due to lack of reliable data from the investigated period 2.45–1.04 Ga (see Li et al. 2008 and references therein). In the following, we use terms such as Laurentia and Baltica for the continents and within

Fig. 2.3 Map showing the continents in their present day geographical positions. Precambrian continental cratons (partly overlain by younger rock sequences) are outlined by yellow shading. The exposed Archean rocks are roughly outlined by orange color. The following continents are used in the reconstructions or discussed in text: Laurentia, Baltica, Siberia, North China, India, Australia, Kalahari, Congo, West Africa, Amazonia and São Francisco. In addition, the Precambrian continents not used in present reconstructions, Ukraine, South China, East Antarctica, Dronning Maud Land and Coats Land are shown. The Archean cratons are marked as follows: for Laurentia Superior (S), Wyoming (W), Slave (Sl), Rae (R), and Hearne (H); for Baltica Karelia (K); for Australia North Australia (NA) (Kimberley and Mc Arthur basins), West Australia (WA) (Yilgarn and Pilbara cratons), and South Australia (SA) (Gawler craton); and for Amazonia Guyana Shield (G) and Central Amazonia (C). Galls projection

each continent those *cratons* (the nuclei of the ancient continents) where the source paleomagnetic data come from are outlined. The Archean to Proterozoic continents consist of individual cratons which may have been drifting, colliding and rifting apart again. Therefore, the consolidation time of the Precambrian continents should be taken into account. For example, most of the poles from Laurentia are derived from rocks within the Superior Province and only a few are derived from other provinces like Slave or Hearne (Fig. 2.3). According to paleomagnetic studies of Symons and Harris (2005), it is possible that the presently assembled Archean terranes of Laurentia did not drift as a coherent continent until at ca. 1,815 Ma to ca.1,775 Ma. Therefore, the data from e.g. Superior craton before 1.77 Ga concerns only that craton. The same is true for Baltica, where Kola and Karelia cratons may have had their own drift histories during Archean-Paleoproterozoic even though they are close to each other within present-day Baltica.

Some cratons, which are now attached with another continent than their inferred original source continent, have been rotated back into their original positions before paleomagnetic reconstruction. For example, the Congo craton is treated together with the São Francisco craton (Fig. 2.3), since geological and paleomagnetic data are consistent that they were united already at least since 2.1 Ga.

2.4 Data Selection

The used paleomagnetic poles come from the updated Precambrian paleomagnetic data compilation that includes the paleopoles from all continents (Pesonen and Evans 2011). The data are graded with the so called Van der Voo (1990) grading scheme (Q-values) that takes into account e.g. statistics of the data, used paleomagnetic methods, isotopic age determinations and tectonism of the studied unit. The highest grade has Q-value 6; we have used data with a minimum value four. In some exceptional cases, however, lower values were accepted. Seven age periods were chosen for reconstructions: 2.45, 1.88, 1.78, 1.63, 1.53, 1.26 and 1.04 Ga. These ages were chosen because paleomagnetic data are available for them from several cratons. In some cases, there are many coeval well-defined paleomagnetic poles from the same craton, and in those cases a mean pole (Fisher 1953) was calculated to be used in the reconstruction. The poles, either individual or mean poles, their ages and other relevant data are listed in Table 2.1.

All original poles are given in Pesonen et al. (2011). The reconstructions are shown in Figs. 2.4, 2.5, 2.6, 2.7, 2.8, 2.9 and 2.10. The main errors with the relative positions of cratons arise from the uncertainty in the pole positions as expressed by the 95% confidence circles of the poles, and from the age difference of poles between different cratons. In some extreme cases when exactly matching data were not available, an age difference of even as high as about 100 Ma was accepted (like e.g. the 2.45 Ga reconstruction where the age of the pole from the Superior craton is ca. 2,470 Ma and that from the Dharwar craton ca. 2,370 Ma, see Pesonen et al. 2012).

2.5 Continental Reconstructions During the Paleo-Mesoproterozoic

2.5.1 Reconstruction at 2.45 Ga

Paleomagnetic data for 2.45 Ga reconstruction (Fig. 2.4) are available from two Nena continental fragments (from Superior craton of Laurentia and Karelia of Baltica) and from two Ur continental fragments (Yilgarn craton of Australia and Dharwar craton of India). At about 2.45 Ga the Nena cratons of Laurentia and Baltica lie near the equator whereas the Ur cratons of Australia and especially India are clearly at high, almost polar (south) latitudes. Although the relative positions of

Table 2.1 Mean values of paleopoles used for reconstructions

Continent (Craton)	Age (Ma)	N	Dr (°)	Ir (°)	Plat (°N)	Plon (°E)	A95 (°)	$\bar{S}$ (°)	$Q_{1–6}$	E-Plat (°N)	E-Plon (°E)	E-Angle (°)
2.45 Ga reconstruction												
Laurentia (Superior)	2,473	1	23.7	43.9	−52.0	239.0	3.3	3.5	6.0	64.0	14.0	96.1
Baltica (Karelia)	2,440	1	312.1	−15.6	9.6	256.2	4.9	7.9	2.0	29.5	317.7	−95.7
Australia (Yilgarn)	2,415	1	248.5	−67.4	−8.0	157.0	8.2	14.9	4.0	0	247.0	82.0
India (Dharwar)	2,367	1	91.4	−83	−17.8	243.4	16.8	24.3	6.0	14.0	313.4	−112.8
1.88 Ga reconstruction												
Laurentia (Superior)	1,880	1	258.6	59.1	28.7	216.0	8.2	14.6	5.0	0	126	61.3
Baltica (Karelia)	1,880	8	341.7	35.1	43.7	232.2	3.5	10.1	2.5	11.5	317.2	−47.3
Amazonia	1,880	3	158.5	−5.4	−68.3	32.4	10.9	14.1	2.3	65.6	147.4	54.2
Australia (WA)	1,850	1	34.7	23.6	45.2	40.0	1.8	11.2	5.0	13.3	275	−143.6
Siberia (Akitkan)	1,878	1	185.4	−1.9	−30.8	98.7	3.5	6.1	5.0	28.6	82.7	164.3
Kalahari	1,875	8	237.9	66.4	−13.6	190.2	10.3	15.4	5.1	34.3	312.7	97.0
1.78 Ga reconstruction												
Laurentia (Churchill)	1,781	1	177.5	56.4	7.0	277.0	8.0	16.4	5.0	16.3	352	−87.3
Baltica (Karelia)	1,788	3	349.1	33.8	43.9	222.4	11.2	10.9	4.0	0	132.4	46.1
Amazonia	1,789	1	358.1	−45.1	−63.3	298.8	11.4	19.4	5.0	69.4	69.8	85.7
Australia (NA)	1,770	3	91.5	38.3	8.5	25.1	18.3	15.3	5.0	12.5	280.1	−101.8
Kalahari	1,770	1	299.4	54.5	−7.0	159.0	7.1	14.8	5.0	41.9	302.5	125.8
India (Bundelkhand)	1,798	1	253.8	0.1	15.4	173.2	7.9	13.7	5.0	21.5	100.7	81.3
North China	1,769	1	37.0	−4.2	−36.0	67.0	3.0	8.1	5.0	53.0	294.5	−97.9
1.63 Ga reconstruction												
Laurentia (Greenland)	1,622	1	201.7	52.0	4.3	256.8	3.0	3.2	–	8.0	174.3	86.8

(continued)

Table 2.1 (continued)

Continent (Craton)	Age (Ma)	N	Dr (°)	Ir (°)	Plat (°N)	Plon (°E)	A95 (°)	$\bar{S}$ (°)	Q_{1-6}	E-Plat (°N)	E-Plon (°E)	E-Angle (°)
Baltica (Karelia)	1,637	3	23.1	5.1	26.3	182.1	12.0	14.3	3.7	34.2	117.1	79.3
Amazonia	1,640	2	323.8	10.1	53.5	213.6	15.9	10.1	3.0	65	168.6	95.6
Australia (NA)	1,641	5	166.4	49.1	−74.1	183.2	8.0	17.7	4.6	4.6	128.2	167
Kalahari	1,649	1	154.7	−71.5	−8.7	202.0	19.3	20.3	4.0	45.3	352.0	135.4
1.53 Ga reconstruction												
Laurentia (Slave)	1,525	3	191.3	24.8	−16.4	263.5	20.7	14.3	4.3	41.1	230.0	138.4
Baltica (Karelia)	1,538	3	15.9	8.8	29.3	189.7	9.4	15.8	3.3	58.8	174.7	154.2
Amazonia	1,535	3	318.7	−32.1	45.8	179.6	15.9	15.6	3.3	65.9	204.6	−133.9
Australia (NA)	1,525	1	185.2	49	−79.0	110.6	8.4	12.0	4.0	1.4	185.6	−169.4
Siberia (Anabar)	1,513	1	205.8	15.3	−19.2	77.8	4.2	18.3	5.0	2.5	164.3	−109.4
North China	1,503	2	84.0	16.8	10.1	202.2	8.8	21.9	5.0	36.0	149.7	105.1
1.26 Ga reconstruction												
Laurentia (incl. Greenland)	1,256	6	267.8	17.6	6.7	191.4	6.2	13.5	4.5	0	101.4	83.3
Baltica (Karelia)	1,257	13	53.1	−31.7	−0.8	158.2	3.2	10.1	4.0	2.5	70.7	90.9
Amazonia	1,200	1	301.0	−55.6	24.6	164.6	5.5	4.0	4.0	41.8	109.6	92.9
Kalahari	1,240	1	358.1	32.6	47.2	22.3	2.9	8.8	5.0	65.7	52.3	−124.5
West Africa	1,250	1	338.3	−36.6	48.7	206.6	1.9	8.7	4.0	48.3	271.6	−64
Congo-São Fr. (Congo)	1,236	1	107.0	3.0	−17.0	112.7	8.0	10.9	3.0	15.6	123.0	−150
1.04 reconstruction (Rodinia)												
Laurentia	1,050	3	274.0	−4.7	−0.1	180.4	14.6	11.3	4.3	22.9	115.4	100.4
Baltica (Karelia)	1,018	1	355.2	−46.8	−2.1	212.2	13.8	11.3	4.0	4.8	127.2	92.5
Amazonia	1,065	1	20.3	−55.3	49.5	89.3	13.2	16.0	4.0	9.7	206.8	144.2
Australia (WA)	1,073	2	321.2	53.9	18.4	87.03	82.0	15.2	5.0	47.7	112	−141.9
Siberia (Aldan)	1,053	4	156.1	45.2	−16.4	220.3	33.7	12.4	4.0	51.5	60.3	−148.2

Kalahari	1,085	1	348.2	11.7	57.0	3.0	7.0	7.9	2.0	55	67	−59.3
India (Dharwar)	1,026	1	24.4	55.6	10.0	211.4	12.4	18.5	5.0	39.6	21.4	167.2
Congo-São Fr. (São Fr.)	1,011	7	93.6	−77.1	−10.3	290.0	13.5	20.3	4.1	40.3	155	−114.2

Continent (Craton) refers to text and Fig. 2.3. Original poles and references are given in Pesonen et al. (2012). N number of entries used for mean calculation. Dr, Ir refer to mean Declination, Inclination of the characteristic remanent magnetization of a central reference location for each craton/continent. Reference locations: Laurentia: 60°N, 275°E, Baltica: 64°N, 28°E, Australia: North Australia NA: 20°S, 135°E, West Australia WA: 27°S 120°E, South Australia SA: 30°S, 135°E, India: 18ºN, 78ºE, Siberia: 60ºN, 105ºE, Kalahari: 25ºS, 25ºE, West Africa: 15ºN, 35ºE, Amazonia: 0°, 295°E, Congo: 5°S, 23°E, São Francisco (São Fr.): 13°S, 315°E, North China: 40°N, 115°E. Plat, Plon are latitude and longitude of the paleomagnetic pole. A95 is the 95% confidence circle of the pole. Greenland poles have been rotated relative to Laurentia using Euler pole of 66.6°N, 240.5°E, rotation angle −12.2° (Roest and Srivistava 1989). S is the mean Angular Standard Deviation as explained in text. Q_{1-6} is the mean Q of N entries in Appendix 1. E-Plat, E-Plon are the co-ordinates of the single Euler rotation pole, Angle: Euler rotation angle

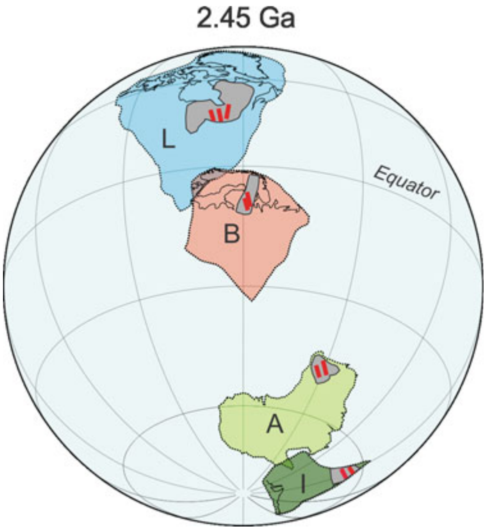

Fig. 2.4 Reconstruction of Archean cratons at 2.45 Ga. Data available from Laurentia (L), Baltica (B), Australia (A) and India (I) (Table 2.1). The Archean cratons Superior (Laurentia), Karelia (Baltica), Yilgarn (West Australia) and Dharwar (India) are shown in grey. Dyke swarms are shown as red sticks and they are: Matachewan dykes (Laurentia), Russian-Karelian dykes (Baltica), Widgiemooltha dykes (Yilgarn) and Dharwar E-W dykes (India). Orthogonal projection

Yilgarn and Dharwar are different to Ur configuration of Rogers and Santosh (2002), the existence of Ur may hold true during the early Paleoproterozoic.

Bleeker (2003) and Bleeker and Ernst (2006) have presented a model of "Superia supercraton" that implies a Superior-Karelia (together with Kola-Hearne-Wyoming blocks) unity at 2. 45 Ga, where Karelia is located on the southern margin of the Superior craton. When using a paleomagnetic pole that is not so well-defined from the 2.45 Ga dolerite dykes in Karelia (Mertanen et al. 1999) and the well-defined pole from the 2.45 Ga Matchewan dykes in Superior (Evans and Halls 2010), we end up to a reconstruction shown in Fig. 2.4. This reconstruction is in close accordance with the "Superia" model, when taking into account the error limits of the poles, which allows the cratons to be put closer to each other. It is possible that the previously used pole for Karelia (Mertanen et al. 1999) which clearly separates the two cratons, is actually slightly younger, ca. 2.40 Ga, obtained during cooling of Karelia after heating by the 2.45 Ga magmatism. In the present configuration (Fig. 2.4), the Matachewan and the Karelia dyke swarms become parallel, pointing to a mantle plume centre in the Superia supercraton, as suggested by Bleeker and Ernst (2006).

Dykes of 2.45–2.37 Ga ages exist also in Australia and India as shown in the reconstruction of (Fig. 2.4). The Widgiemooltha swarm (~2.42 Ga; Evans 1968) of the Yilgarn craton (Australia) has a similar trend as the Matachewan-Karelia swarms in this assembly, but its distance to these swarms is more than 90° in latitude (>10,000 km), which does not support a genetic relationship between Australia and Laurentia-Baltica at 2.45 Ga. On the other hand, the E-W trending dykes in the Dharwar craton of India, with an age of 2.37 Ga (Halls et al. 2007; French and Heaman 2010), form a continuation with the Widgiemooltha dyke swarm (Fig. 2.4).

Between 2.40 and 2.22 Ga the Superior, Karelia and Kalahari cratons experienced one to three successive glaciations (Marmo and Ojakangas 1984; Bekker et al. 2001). It is noteworthy that the sequences also contain paleoweathering layers, lying generally on top of the glaciogenic sequences (Marmo et al. 1988). These early Paleoproterozoic supracrustal strata are similar to Neoproterozoic strata that also contain glaciogenic sequences and paleoweathering zones (e.g. Evans 2000). Moreover, in both cases the paleomagnetic data point to low latitudes ($\leq 45°$) during glaciations. Taking Laurentia as an example, it maintained a low latitude position from 2.45 to 2.00 Ga during the time when the glaciations took place (e.g. Schmidt and Williams 1995). If the Superia model of Bleeker and Ernst (2006) is valid, according to which the Karelia and Superior cratons formed a unity during the whole time period from 2.45 to 2.1 Ga, then also Karelia was located at subtropical paleolatitudes of 15–45° at that time (see also Bindeman et al. 2010).

Various models have been presented to explain the fascinating possibility of glaciations near the equator (see Maruyama and Santosh 2008 and references therein). These include the hypothesis of “Snowball Earth” which proposes that the whole Earth was frozen at ca. 2.4–2.2 Ga, possibly resulting from high Earth’s orbital obliquity (e.g. Maruyama and Santosh 2008). Eyles (2008) presented that glaciations near the equator could be due to high elevations by tectonic processes. In paleomagnetic point of view one explanation could be remagnetization, or the enhanced non-dipole nature of the geomagnetic field (see Pesonen et al. 2003 and references therein).

In addition to the development of nearly coeval glaciogenic sequences and paleoweathering zones during the Paleoproterozoic, Laurentia, Baltica, Australia and India experienced another rifting episode at ca. 2.20–2.10 Ga as evidenced by widespread mafic dyke activity (e.g. Vuollo and Huhma 2005, Ernst and Bleeker 2010, French and Heaman 2010) and passive margin sedimentations (Bekker et al. 2001). It is possible that this rifting finally led to breakup of Laurentia-Baltica and possibly also Australia-India. Based on geological evidence, Lahtinen et al. (2005) proposed that the breakup of Laurentia-Baltica took place as late as 2.05 Ga ago.

2.5.2 Reconstruction at 1.88 Ga

The period 1.90–1.80 Ga is well known in global geology as widespread orogenic activity. Large amounts of juvenile crust were added to the continental margins, and black shales, banded iron formations (BIFs), evaporites as well as shallow marine phosphates were deposited in warm climatic conditions (Condie et al. 2001).

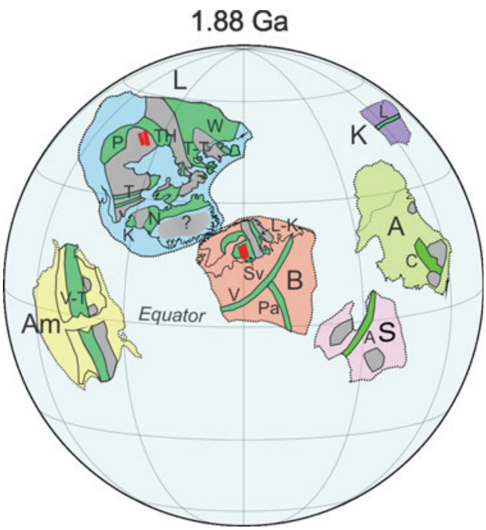

Fig. 2.5 Reconstruction of cratons and orogenic belts (*green*) at 1.88 Ga. The Archean cratons are shown in gray. Data available from Laurentia (L), Baltica (B), Amazonia (Am), Siberia (S), Australia (A) and Kalahari (K). The ca. 1.90–1.80 Ga orogenic belts are shown in dark green and they are: in Laurentia Nagssugtoqidian (N), Ketilidian (K), Torngat (T), Trans-Hudson (TH), Penokean (P), Woopmay (W), and Taltson-Thelon (T-T); in Baltica Lapland-Kola (L-K) and Svecofennian (Sv); in Amazonia Ventuari-Tapajos (V-T); in Siberia Akitkan (A); in Australia Capricorn (C); and in Kalahari Limpopo (L)

These deposits support the existence of a supercontinent at low to moderate latitudes at ca. 1.88 Ga (see Pesonen et al. 2003 and references therein).

Reliable poles of the age of about 1.88 Ga are available from three Nena cratons (Baltica, Laurentia and Siberia), from two Ur cratons (Australia and Kalahari), and from one Atlantica craton (Amazonia). The reconstruction is shown in Fig. 2.5. All continents have moderate to low latitudinal positions with the exception of Kalahari which seems not to belong to this “Early Nuna” landmass. The proposed Ur continent is thus not supported due to significant separation between Australia and Kalahari. Likewise, based on dissimilarity of paleomagnetic data on ca. 2.0 Ga units from Amazonia and Congo-São Francisco, D’Agrella-Filho et al. (2011) argue that neither Atlantica supercontinent ever existed.

The assembly of Laurentia and Baltica cratons at 1.88 Ga, together with Australia and Siberia, marks the onset of development of the supercontinent Nuna although the final amalgamation may have occurred as late as ~1.53 Ga (see later). The position of Baltica against Laurentia is rather well established as the paleomagnetic data from Baltica are available from several Svecofennian 1.88–1.87 Ga gabbros. However, the age of magnetization is somewhat uncertain because the paleomagnetic data from Baltica come from slowly cooled plutons, in which the magnetization may block a few years later compared to the crystallization age. The uncertainty of the position of Laurentia is due to complexity related to the paleomagnetic pole of the 1.88 Ga Molson dykes (Halls and Heaman 2000). In the 1.88 Ga reconstruction (Fig. 2.5) the relative position of Laurentia (Superior craton) and Baltica (Karelia craton) departs significantly from that at 2.45 Ga (Fig. 2.4), consistent with separation of Laurentia from Baltica at about 2.15 Ga. The data further suggest that a considerable latitudinal drift and rotation from 2.45 to 1.88 Ga took place for Laurentia but much less for Baltica.

The model in Fig. 2.5 provides the following scenario to explain the ca. 1.90–1.80 Ga orogenic belts in Laurentia and Baltica. After rifting at 2.1 Ga the cratons of both continents drifted independently until ~1.93 Ga. Subsequently, the Laurentia cratons collided with Baltica cratons causing the Nagssugtoqidian and Torngat orogens in Laurentia and the Lapland–Kola orogen in Baltica. It is likely that collision between Laurentia and Baltica caused intra-cratonic orogenic belts (e.g. between Superior and Slave in Laurentia and between Kola and Karelia in Baltica). Simultaneously, in Baltica, accretion and collision of several microcontinents to the Karelia continental margin may also have taken place (Lahtinen et al. 2005). The complexity of these collisions is manifested by the anastomosing network of 1.93–1.88 Ga orogenic belts separating the Archean cratons in Baltica and Laurentia (Fig. 2.5). The same seems to have happened also in other continents, like in Australia, Kalahari, and Amazonia.

In addition to the above mentioned collisions within Baltica and Laurentia, a collision of Laurentia-Baltica with a "third continent" may be responsible for at least some of the 1.93–1.88 Ga orogenic belts (Pesonen et al. 2003). Candidates for this "third continent" include Amazonia, North China, Australia, Siberia and Kalahari. Each of these have 1.93–1.88 Ga orogenic belts: the Trans China orogen in China, the Capricorn orogen in Australia, the Ventuari-Tapajos orogen in Amazonia, the Akitkan orogen in Siberia and the Limpopo belt in Kalahari (Geraldes et al. 2001; Wilde et al. 2002). Although the data from Amazonia are not of the best quality (quality factor Q only 2–3), Amazonia was probably not yet part of the 1.88 Ga Laurentia-Baltica assembly (Fig. 2.5).

2.5.3 Reconstruction at 1.78 Ga

Reliable paleomagnetic data (Table 2.1) at 1.78 Ga come from Laurentia, Baltica, North China, Amazonia, Australia, India and Kalahari (Fig. 2.6). These continents remained at low to intermediate latitudes during 1.88–1.77 Ga. The 1.78 Ga configuration of Baltica and Laurentia differs from that at 1.88 Ga. This difference is mostly due to rotation of Laurentia relative to more stationary Baltica. The considerable rotation of Laurentia may reflect poor paleomagnetic data, but it is also possible that there was a long-lasting accretion to the western margin of the closely situated Laurentia-Baltica cratons. This may have included relative rotations along transform faults between the accreting blocks (Nironen 1997) until their final amalgamation at ca. 1.83 Ga. Support for the continuation of Laurentia-Baltica from 1.83 to 1.78 Ga comes from the observations that the

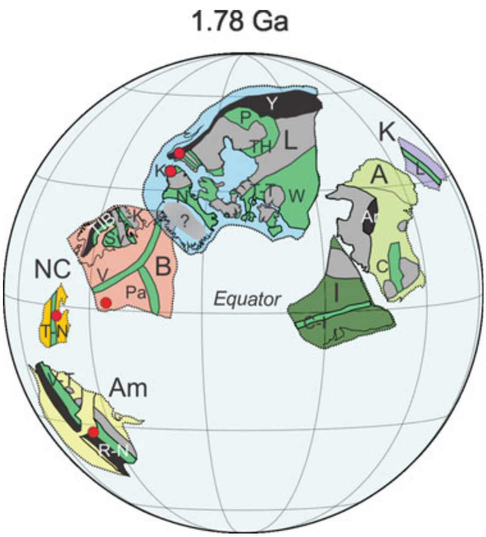

Fig. 2.6 The reconstruction of continents at 1.78 Ga. Data available from Laurentia (L), Baltica (B), North China (NC), Amazonia (Am), India (I), Australia (A) and Kalahari (K). The Archean cratons are shown as grey shading (see Figs. 2.3 and 2.4). The 1.90–1.80 Ga orogenic belts (*green*) in Laurentia, Baltica, Australia, Amazonia and Kalahari are the same as in Fig. 2.5. In North China: Trans-North China orogen (T-N); in India: Central Indian tectonic zone (C-I). The ca. 1.8–1.5 Ga orogenic belts (*black*) are in Laurentia Yavapai (Y); in Baltica Transscandinavian Igneous Belt (TIB); in Amazonia Rio Negro-Juruena (R-N); in Australia Arunta (Ar). The 1.78–1.70 Ga rapakivi granites are shown as *red circles*

geologically similar Trans Scandinavian Igneous (TIB) belt in Baltica and the Yavapai/Ketilidian belts of Laurentia (e.g. Karlström et al. 2001; Åhäll and Larson 2000) become laterally contiguous when reconstructed according to paleomagnetic data of the age of 1.83, 1.78 Ga and 1.25 Ga (see Buchan et al. 2000; Pesonen et al. 2003; Pisarevsky and Bylund 2010).

The configuration of Laurentia, Baltica, North China and Amazonia in the "Early Nuna" configuration at 1.78 Ga is similar with that of Bispo-Santos et al. (2008) where the North China craton is placed between Amazonia and Baltica. This location of North China probably lasted only for a short time period. If the Trans-North China orogen was formed at 1,850 Ma, possibly representing the same orogenic event as the orogens in Baltica and Amazonia, it probably drifted apart from Amazonia-Baltica after 1.78 Ga, as already suggested by Bispo-Santos et al. (2008).

The paleomagnetic data from Amazonia at 1.78 Ga shows that it was located in the southern hemisphere (Fig. 2.6). The 2.0–1.8 Ga Ventuari-Tapajos and 1.8–1.45 Ga Rio Negro-Juruena orogenic belts of Amazonia are coeval with the 1.9–1.8 Ga Svecofennian orogenic belt and ca. 1.8–1.7 Ga TIB and 1.7–1.6 Ga Kongsbergian-Gothian belts of Baltica, and with the corresponding 1.8–1.7 Ga Yavapai and 1.7–1.6 Ga Mazatzal and Labradorian belts in Laurentia (Zhao et al. 2004). Accordingly, Amazonia, North China, Baltica and Laurentia may have formed a united

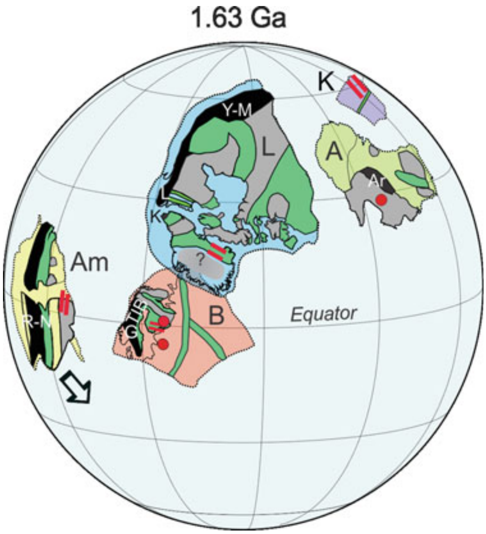

Fig. 2.7 The reconstruction of continents at 1.63 Ga. Data available from Laurentia (L), Baltica (B), Amazonia (Am), Australia (A) and Kalahari (K). The 1.8–1.5 Ga orogenic belts (*black*) are in Laurentia Yavapai-Mazatzal (Y-M), Labradorian (L), and Ketilidian (K); in Baltica Gothian (G) and Transscandinavian Igneous Belt (TIB); in Amazonia Rio Negro-Juruena (R-N); in Australia Arunta (Ar). For other belts, see Figs. 2.5 and 2.6. The SE pointing arrow shows the possible direction of placing Amazonia below Baltica. The 1.63 Ga rapakivi intrusions and related dykes are shown as *red circles* and sticks, respectively

continent with a joint western active margin. This is supported by geological reasoning about the continuity of Amazonia-Baltica-Laurentia (e.g. Åhäll and Larson 2000; Geraldes et al. 2001 and references therein) which favours the idea that all these coeval belts are accretional and were formed during Cordilleran type subduction and arc-accretion from west onto a convergent margin. However, taking into account the possible existence of North China between Baltica and Amazonia at 1.78 Ga, and the reconstruction at 1.63 Ga (Fig. 2.7) where Amazonia is clearly apart from Baltica, it is possible that Amazonia may have been separated from Laurentia-Baltica until 1.53 Ga (Figs. 2.7 and 2.8). This is discussed in the following chapters.

At 1.78 Ga (Fig. 2.6) Australia is located slightly apart from Laurentia to let it be together with its possible Ur counterparts India and Kalahari. Karlström et al. (2001) stressed that geological data of the 1.80–1.40 Ga belts from Laurentia-Baltica landmass (such as Yavapai – Ketilidian and TIB belts) continue into the 1.8–1.5 Ga Arunta belt of eastern Australia. This is paleomagnetically possible: if we take into account the error of pole of 18.3° (Table 2.1), we can shift Australia upwards (Fig. 2.6), which would bring the assembly of Baltica-Laurentia-Australia close to the one suggested by Karlström et al. (2001).

Several episodes of rapakivi magmatism are known during the Paleo-Mesoproterozoic (e.g. Rämö and Haapala 1995, Vigneresse 2005). The

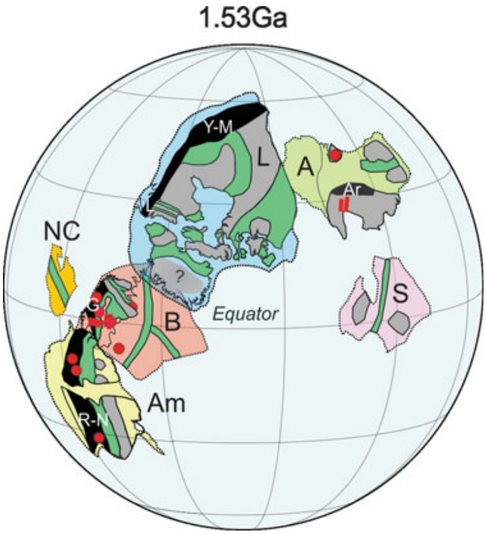

Fig. 2.8 Paleomagnetic reconstruction at 1.53 Ga. Data available from Laurentia (L), Baltica (B), Amazonia (Am), North China (NC), Siberia (S) and Australia (A). The ca. 1.55–1.50 Ga rapakivi intrusions and related dykes are shown as red circles and sticks, respectively. For other explanations, see Figs. 2.5, 2.6 and 2.7

1.77–1.70 Ga and the slightly younger 1.75–1.70 Ga rapakivi-anorthosites are known in Laurentia, Ukraine (part of Baltica), North China and Amazonia (Fig. 2.6). Due to their sparse occurrence at 1.78 Ga they cannot be used to test the paleomagnetic reconstruction, but as will be shown in 1.53 Ga reconstruction (Fig. 2.8), the occurrence of younger rapakivi granites can give some hints for the continuity of the cratons.

2.5.4 Reconstruction at 1.63 Ga

As previously described, the current geological models for Laurentia, Baltica and Amazonia favour the scheme that the post-1.83 Ga orogenic belts were formed along the joint western margin by prolonged subduction and arc-accretions. For the 1.63 Ga reconstruction, paleomagnetic data are available from Laurentia, Baltica, Amazonia, Australia and Kalahari (Fig. 2.7, Table 2.1).

The exact paleomagnetic data places Amazonia onto the same latitude as Baltica and into a situation where the successively younging orogenic belts in Baltica have a westerly trend, in the same sense as in Amazonia. Therefore, in Pesonen et al. (2003) Amazonia was shifted some 25° southeast which was within maximum error of data from both continents. This configuration formed the previously proposed elongated continuation to the 1.78–1.63 Ga Laurentia-Baltica assembly. In that configuration, the successive orogenic belts show a westward younging trend in all three continents (e.g. Åhäll and Larson 2000; Geraldes et al. 2001). However, here the Amazonia craton at 1.63 Ga has been kept in the position defined by the paleomagnetic pole as such (Fig. 2.7), because, as discussed below, there is still the possibility that the final docking of Amazonia took place later than 1.63 Ga.

2.5.5 Reconstruction at 1.53 Ga

Reliable paleomagnetic data at 1.53 Ga come from Laurentia, Baltica, Amazonia, Australia, North China and Siberia (Fig. 2.8). The Laurentia-Baltica assembly at 1.53 Ga differs only slightly from the 1.78 and 1.63 Ga configurations. Therefore, taking into account the uncertainties in the poles, we believe that the previously proposed Laurentia-Baltica unity (where the Kola peninsula is adjacent to present southwestern Greenland) still holds at 1.53 Ga (see also Salminen and Pesonen 2007; Lubnina et al. 2010).

In this reconstruction the successively younging 1.88 Ga to ~1.3 Ga orogenic belts in Laurentia, Baltica and Amazonia are now continued as described in the context of 1.78 Ga and 1.63 Ga reconstructions. However, because in the 1.63 Ga reconstruction (Fig. 2.7) Baltica and Amazonia were still separated at 1.63 Ga, when using the most strict paleomagnetic data, it is possible that the final amalgamation between Baltica and Amazonia took place as late as between 1.63 Ga and 1.53 Ga. Likewise, comparison of reconstructions at 1.78 Ga, 1.63 Ga and 1.53 Ga (Figs. 2.6, 2.7, and 2.8) reveals that North China was still moving with respect to Baltica and Amazonia during 1.78–1.53 Ga. Consequently, by using paleomagnetic data alone, we suggest that the formation of Nuna supercontinent was still going on at ca. 1.53 Ga.

One of the major peaks of rapakivi-anorthosite pulses took place during 1.58–1.53 Ga (Rämö and Haapala 1995; Vigneresse 2005). The coeval occurrences of bimodal rapakivi granites and anorthosites associated with mafic dyke swarms in Baltica and Amazonia during 1.58–1.53 Ga further supports the close connection between these continents in the Nuna configuration.

The position of Australia in (Fig. 2.8), on the present western coast of Laurentia is consistent with the previous reconstructions, thus suggesting that Australia was also part of the Nuna supercontinent. The occurrence of ca. 1.60–1.50 Ga rapakivi intrusions in Australia further supports the idea that Australia was in close connection with Laurentia-Baltica and Amazonia at 1.53 Ga.

Paleomagnetic data could allow Siberia to be in contact with northern Laurentia at 1.53 Ga (Fig. 2.8). However, Pisarevsky and Natapov (2003) noted that almost all the Meso-Neoproterozoic margins in Siberia are oceanic margins and therefore a close connection between Siberia and Laurentia is not supported by their relative tectonic settings. Also in recent Laurentia-Siberia reconstructions (Wingate et al. 2009; Lubnina et al. 2010) the two continents have been left separate although they would become parts of the Nuna supercontinent at ~1.47 Ga. Possibly there was a third continent between Laurentia and Siberia at ~1.53 Ga (see Wingate et al. 2009; Lubnina et al. 2010).

Laurentia and Baltica probably remained at shallow latitudes from 1.50 to 1.25 Ga (Buchan et al. 2000). Preliminary comparisons of paleomagnetic poles from the ca. 1.7–1.4 Ga red beds of the Sibley Peninsula (Laurentia) and Satakunta and Ulvö sandstones (Baltica) (e.g. Pesonen and Neuvonen 1981; Klein et al. 2010), support the 1.53 Ga reconstructions within the uncertainties involved. Buchan et al. (2000) implied that the paleomagnetic data from the ca. 1.3 Ga Nairn anorthosite of Laurentia suggest that it remained at low latitudes during ca. 1.40–1.30 Ga, also consistent with a low latitude position of Laurentia at that time.

In some studies (e.g. Rogers and Santosh 2002, 2004; Zhao et al. 2004), the breakup of Nuna supercontinent is regarded to have started by continental rifting already at ca. 1.6 Ga, the timing corresponding with the widespread anorogenic magmatism in most of its constituent continents. This rifting is considered to have continued until the final breakup at about 1.3–1.2 Ga, marked by the emplacement of ca. 1.26 Ga dyke swarms and associated basaltic extrusions in Laurentia, Baltica, Australia and Amazonia (e.g. Zhao et al. 2004). However, we suggest that the separation of Laurentia and Baltica probably occurred much later (even as late as ~1.12 Ga) when a number of rift basins, graben formation and dyke intrusions occurred globally (see below).

2.5.6 Reconstruction at 1.26 Ga

Figure 2.9 shows the assembly of Laurentia, Amazonia, Baltica, West Africa, Kalahari and Congo/São Francisco at ca. 1.26 Ga. These continents are all located at low to intermediate latitudes. The configuration of Laurentia-Baltica is similar to the previous reconstructions during 1.78–1.53 Ga. The Kalahari, Congo-São Francisco and West Africa cratons form a unity slightly west from Amazonia-Baltica-Laurentia. Although the relative position of Baltica-Laurentia at this time is roughly the same as during 1.78–1.53 Ga, the whole assembly has been rotated 80° anticlockwise and drifted southwards.

The 1.26 Ga assembly of Baltica-Laurentia is supported by geological data. For example, as shown previously, the 1.71–1.55 Ga Labradorian-Gothian belts will be aligned in this configuration. As suggested by Söderlund et al. (2006), the ages of the 1.28–1.23 Ga dolerite sill complexes and dike swarms in Labrador, in SW Greenland and in central Scandinavia (Central Scandinavian Dolerite Group, CSDG) are best explained by long-lived subduction along a continuous Laurentia-Baltica margin (see Fig. 2.9). Consequently, the rifting model with separation of Laurentia and Baltica at ca. 1.26 Ga, as presented previously in Pesonen et al. (2003) is not valid any more. It is worthwhile to note that the 1.26 Ga dyke activity is a global one and is well documented in several other continents (see Ernst et al. 1996). Unfortunately, reliable paleomagnetic data from 1.26 Ga dykes are only available from Laurentia and Baltica.

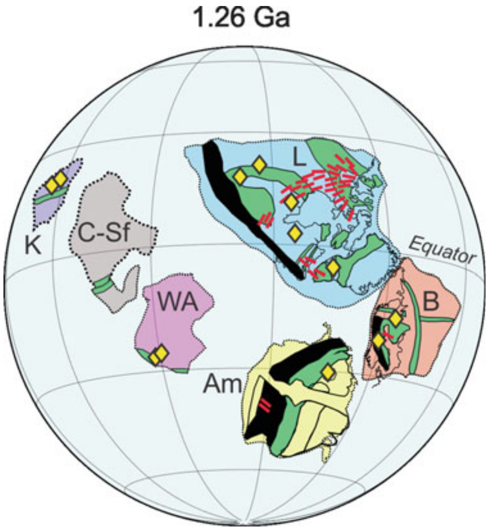

Fig. 2.9 Reconstruction of continents at 1.26 Ga. Data available from Laurentia (L), Baltica (B), Amazonia (Am), West Africa (WA), Congo-São Francisco (C-Sf) and Kalahari (K). The ca. 1.26 Ga dyke swarms in Laurentia and Baltica are shown as red sticks. Kimberlite occurrences of about this age are shown as yellow diamonds. For explanation, see Figs. 2.5, 2.6, 2.7 and 2.8

In (Fig. 2.9), the ca. 1.25–1.20 Ga kimberlite pipes are plotted on the 1.26 Ga reconstruction. The kimberlite pipes seem to show a continuous belt crossing the whole Laurentia up to Baltica, making then a ~90° swing and continuing from Baltica to Amazonia. However, the coeval kimberlites in Kalahari and West Africa seem to form clusters rather than a belt. We interpret the kimberlite belt to support the proximity of Laurentia, Baltica and Amazonia although the underlying geological explanation for it remains to be solved (Pesonen et al. 2005; Torsvik et al. 2010a and references therein).

2.5.7 Reconstructions 1.04 Ga: Amalgamation of Rodinia

Baltica and Laurentia probably still formed a unity at 1.25 Ga, but after that, possibly as late as after 1.1 Ga, Baltica was separated from Laurentia and started its journey further south (Fig. 2.10). The southerly drift of Baltica between 1.25 and 1.05 Ga is associated with a ca. 80° clockwise rotation and ca. 15° southward movement. This rotation, suggested already by Poorter (1975), is supported by coeval paleomagnetic data from dolerite dykes in northern Baltica and from the Sveconorwegian orogen of southwestern Baltica (Table 2.1). In this Rodinia model (Fig. 2.10), the Sveconorwegian belt appears continuous with the Grenvillian belt of Laurentia.

After the course of drift and rotations of the detached continents during about 1.10–1.04 Ga, almost all of the continents were amalgamated at ~1.04 Ga to form the Rodinia supercontinent (Fig. 2.10). Unlike most Rodinia models (e.g. Hoffman 1991; Li et al. 2008; Johansson 2009), the new paleomagnetic data of Amazonia

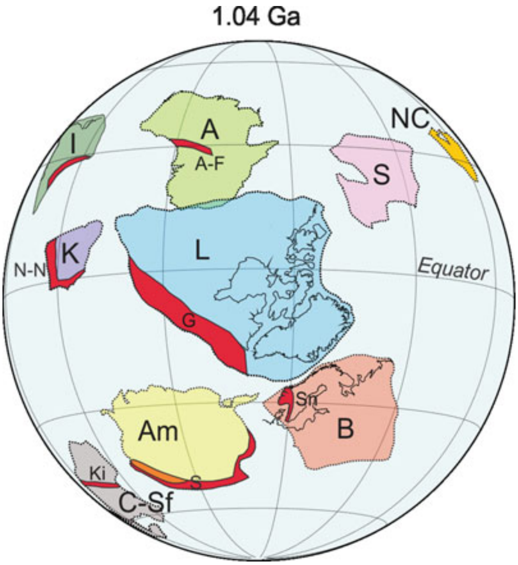

Fig. 2.10 Reconstruction of continents at 1.04 Ga showing the Rodinia configuration. Data available from Laurentia (L), Baltica (B), Amazonia (Am), Congo/SãoFrancisco (C-Sf), Kalahari (K), India (I), Australia (A), Siberia (S) and North China (NC). The Grenvillian age orogenic belts are shown in red and they are: in Laurentia Grenvillian (G), in Baltica Sveconorwegian (Sn), in Amazonia Sunsas (S), in Congo-São Francisco Kibaran (Ki), and in Kalahari Natal-Namagua (N-N). The orange belt in Amazonia marks the possible first collisional location after which the continent was rotated, the red belt was formed in a subsequent collision. For explanation, see text

places the Grenvillian Sunsas-Aguapei belt to be oceanward and not inward (see also Evans 2009). One possible scenario to explain this position is that the Grenvillian collisions occurred episodically, including rotations and strike slip movements (e.g. Fitzsimons 2000; Tohver et al. 2002; Pesonen et al. 2003; Elming et al. 2009). We suggest that during the first collisional episode between 1.26 and 1.1 Ga Amazonia collided with Laurentia on its southwestern border. This collision produced a piece of the inward (against Laurentia's SW coast) pointing Sunsas orogenic belt. Subsequently, Amazonia must have been rotated ~140° anticlockwise swinging the older part of the Sunsas belt to an oceanward position (Fig. 2.10). The second collision by Amazonia, now with Baltica took place at ~1.05 Ga (Fig. 2.10) producing the younger part of the Sunsas-Aguapei belt. The two-phase collisional scenario of Amazonia could explain the oceanward position relative to Laurentia, provided that the Sunsas-Aguapei belt has two segments of variable ages. The same observation may also concern the Namagua-Natal belt in Kalahari, which is also oceanward (Fig. 2.10).

Australia and India are located to the southwest of the present western coast of Laurentia (Fig. 2.10), the space between them occupied by East Antarctica, which formed part of the Gondwana continent. The position and orientation of Siberia

(Fig. 2.10) is somewhat different from that at 1.53 Ga (Fig. 2.8) indicating that Siberia may have been separated from Laurentia during ca. 1.50–1.10 Ga.

The 1.04 Ga time marks the final assembly of Rodinia with possible minor adjustments taking place during 1.04–1.0 Ga. This scenario predicts that late Grenvillian events should have occurred in NW Baltica, in Barentia (Svalbard) and in eastern coast of Greenland due to the collision of Baltica with NE Laurentia (Fig. 2.10). Different scenarios to describe the continent-continent collisions and the formation of Rodinia are presented by Li et al. (2008), Pisarevsky et al. (2003) and Evans (2009).

2.6 Conclusions

1. In this paper we present reconstructions of continents during the Paleo-Mesoproterozoic eras as based on updated global paleomagnetic data. The new data suggest that continents were located at low to intermediate latitudes for much of the period from 2.45 to 1.04 Ga. Sedimentological latitudinal indicators are generally consistent with the proposed latitudinal positions of continents with the exception of the Early Proterozoic period where low-latitude continental glaciations have been noted.
2. The data indicate that two large supercontinents (Nuna and Rodinia) existed during the Paleo-Mesoproterozoic. The configurations of Nuna and Rodinia depart from each other and also from the Pangea assembly. The tectonic styles of their amalgamations are also different reflecting changes in size and thickness of the cratonic blocks, and in the thermal conditions of the mantle with time.
3. The present paleomagnetic data implies that Nuna supercontinent was possibly assembled as late as ~1.53 Ga ago. The configuration of Nuna is only tentatively known but comprises Laurentia, Baltica, Amazonia, Australia, Siberia, India and North China. We suggest that the core of the Nuna was formed by elongated huge Laurentia-Baltica-Amazonia landmass. Australia was probably part of Nuna and in juxtaposition with the present western margin of Laurentia. A characteristic feature of Nuna is a long-lasting accretion tectonism with new juvenile material added to its margin during 1.88–1.4 Ga. These accretions resulted in progressively younging, oceanward stepping orogenic belts in Laurentia, Baltica and Amazonia. The central parts of Nuna, such as Amazonia and Baltica, experienced extensional rapakivi-anorthosite magmatism at ca. 1.65–1.3 Ga. The corresponding activity in Laurentia occurred slightly later. Global rifting at 1.25 Ga, manifested by mafic dyke swarms, kimberlite belts, sedimentary basins, and graben formations took place in most continents of Nuna.
4. The Rodinia supercontinent was fully amalgamated at ca. 1.04 Ga. Rodinia comprises most of the continents and is characterized by episodical Grenvillian continent-continent collisions in a relatively short time span.

Acknowledgement The new Precambrian paleomagnetic database used in this work would not be possible without the years lasting co-operation with David Evans (Yale University).

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