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Palaeomagnetic configuration of continents during the Proterozoic

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Abstract

Palaeomagnetic data are used to study the configurations of continents during the Proterozoic. Applying stringent reliability criteria, the positions of the continents at 12 times in the 2.45- to 1.00-Ga period have been constructed. The continents lie predominantly in low to intermediate latitudes. The sedimentological indicators of palaeoclimate are generally consistent with the palaeomagnetic latitudes, with the exception of the Early Proterozoic, when low latitude glaciations took place on several continents.

The Proterozoic continental configurations are generally in agreement with current geological models of the evolution of the continents. The data suggest that three large continental landmasses existed during the Proterozoic. The oldest one is the Neoarchaean Kenorland, which comprised at least Laurentia, Baltica, Australia and the Kalahari craton. The protracted breakup of Kenorland during the 2.45- to 2.10-Ga interval is manifested by mafic dykes and sedimentary rift-basins on many continents. The second 'supercontinental' landmass is Hudsonland (also known as Columbia). On the basis of purely palaeomagnetic data, this supercontinent consisted of Laurentia, Baltica, Ukraine, Amazonia and Australia and perhaps also Siberia, North China and Kalahari. Hudsonland existed from 1.83 to ca. 1.50–1.25 Ga. The youngest assembly is the Neoproterozoic supercontinent of Rodinia, which was formed by continent–continent collisions during ~1.10–1.00 Ga and which involved most of the continents. A new model for its assembly and configuration is presented, which suggests that multiple Grenvillian age collisions

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took place during 1.10–1.00 Ga. The configurations of Kenorland, Hudsonland and Rodinia depart from each other and also from the Pangaea assembly. The tectonic styles of their amalgamation are also different reflecting probable changes in sizes and thicknesses of the cratonic blocks as well as changes in the thermal conditions of the mantle through time.

Keywords: Palaeomagnetism; Proterozoic; Supercontinent; Mantle plume; Kenorland; Hudsonland; Columbia; Rodinia; Palaeolatitude; Palaeogeography; Accretion; Mafic dykes

1. Introduction

The importance of supercontinents in our understanding of the geological evolution of the Earth has been discussed in some depth (e.g., Dalziel, 1995; Rogers, 1996; Aspler and Chiarenzelli, 1998; Piper, 2000; Rogers and Santosh, 2002, and references therein). Geological processes linked to the supercontinent formation include mantle superplume events (e.g.,Condie et al., 2001), low latitude glaciations and either the "Snowball Earth" or 'high-obliquity' concepts (e.g., Kirschvink, 1992; Williams and Schmidt, 1997; Hoffman and Schrag, 2002), carbon isotope excursions (e.g., Bekker et al., 2001), fragmentation of continental dyke swarms (Ernst and Buchan, 2001), truncations of tectonic belts and major rifts (e.g., Brookfield, 1993; Dalziel, 1999), matching of orogenic belts (e.g., Hoffman, 1991), true polar wander (e.g., Kirschvink et al., 1997; Evans, 1998; Meert, 1999; Evans, 2003) and peaked age distributions of geological events (Condie, 1998; Meert, 2003).

Three supercontinent assemblies (Pangaea 350–165 Ma, Gondwanaland 550–400 Ma, Rodinia ~1050–750 Ma) have existed during or since the Neoproterozoic (e.g., Bond et al., 1984; McMenamin and McMenamin, 1990; Dalziel, 1995, and references therein). The two younger assemblies have been constructed by sea floor magnetic data (Pangaea), and by palaeomagnetic and biostratigraphic results, supported by geology (Gondwanaland). A current debate concerns the relative positions of the continents in Rodinia, and the timing of its assembly and breakup (e.g., Piper, 2000; Buchan et al., 2001; Pisarevsky and Natapov, 2003; Meert and Torsvik, 2003).

The consequences of supercontinents on geological evolution of the Earth have led some people to look for pre-Rodinian supercontinents (e.g., Piper, 1976; Williams et al., 1991; Rogers, 1996; Zegers et al., 1998). Archaean landmasses, such as Ur, Vaalbara, Zimvaalbara, Kenorland, and Palaeo-Mesoproterozoic assemblies like Arctica, Atlantica, Nena and Columbia have been proposed mainly on geological grounds (e.g., Cheney, 1996; Aspler and Chiarenzelli, 1998; Rogers and Santosh, 2002, and references therein). Palaeomagnetism, coupled with precise isotope age data, is the only method which provides direct knowledge of ancient latitudes of continents. Nevertheless, its role in many previous reconstructions (e.g., Rogers and Santosh, 2002) has been limited perhaps because of poor age control or large scatter of poles, or because the dated poles are not coeval (e.g., Buchan et al., 2000; Meert, 2002).

In this paper, we use good quality palaeomagnetic data, combined with isotope ages and geological information, to define the positions of the continents during 2.45–1.00 Ga. Palaeomagnetically defined latitudes are tested with sedimentological indicators of palaeoclimate. Some of the continental configurations and the tectonic styles of their amalgamations presented here are in contrast with our previous interpretations — mainly due to the addition of newer, more reliable, data (Pesonen et al., 2000, 2001a,b,c; Elming et al., 2001a,b; Mertanen and Pesonen, 2000, 2003; Mertanen et al., 2001).

2. Sources of data

Fig. 1 shows 16 cratons from which reliable palaeomagnetic data are available. Other cratons, provinces or microcontinents, such as Rio de La Plata, Seychelles, Madagascar, Rockall Bank, Barentia, Sahara, Oaxaquia, etc., which contain Protero-

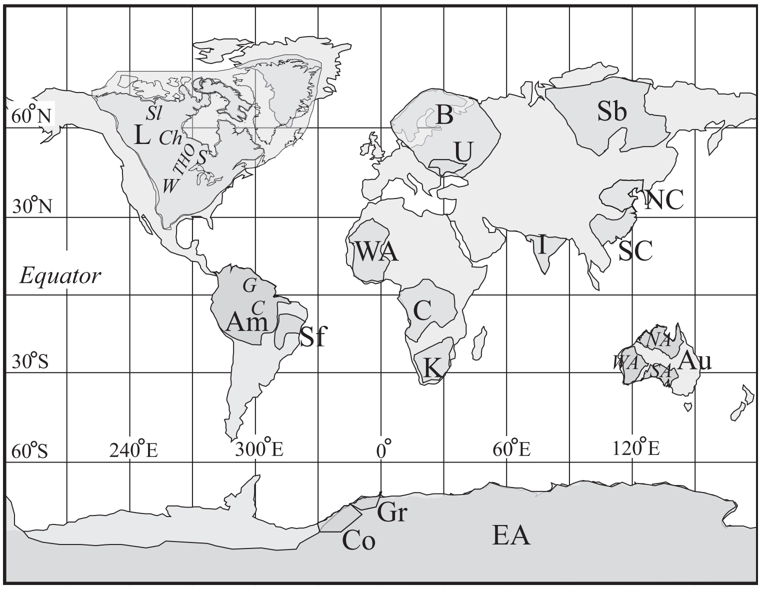


Fig. 1. Map showing the continents (light shading) in their present-day geographical positions. Dark shadings show the outlines of the Precambrian cratons and their shapes approximately as they existed in pre-1.00 Ga times (i.e., younger orogenic belts have been generally removed). The following continents (and corresponding abbreviations) are used in the reconstructions or discussed in text: Laurentia (L), Baltica (B), Ukraine (U), Siberia (Sb), North China (NC), South China (SC), India (I), Australia (Au), Amazonia (Am), Congo (C), São Francisco (Sf), West Africa (WA), Kalahari (K), East Antarctica (EA), Grunehogna (Gr), Coats Land (Co). The within-continent cratons are shown as follows; for Laurentia: S, Superior; W, Wyoming; Sl, Slave; THO, Trans-Hudson Orogen; Ch, Churchill; for Australia: NA, North Australia (Kimberley and Mc Arthur basins); WA, West Australia (comprising Yilgarn and Pilbara cratons); SA, South Australia (e.g., Gawler craton; Musgrave block in central Australia is not shown); for Amazonia: G (Guyana Shield); C (Central Amazonian Shield). Galls projection.

zoic rocks, are not shown in Fig. 1 since they (so far) lack reliable palaeomagnetic data. Not included in this analysis also are several South American (e.g., Pampia, Paraná, Arequipa-Antofalla; see Almeida et al., 2000; Geraldes et al., 2001), Indian (Eastern Ghats, Dharwar), East Antarctican (e.g., Mawson, Rayner, Wilkes, Prydz Bay), East European (Volgo-Uralia) microcontinents and the large Saharan craton (Abdelsalam et al., 2002) since no palaeomagnetic data are so far available from them (see also Fitzsimons, 2000a,b; Bogdanova, 2001). Some cratons, which today are attached with another continent than their original "mothercontinent", are first rotated back into their original position before palaeomagnetic reconstruction are made for Proterozoic times (e.g., Aspler and Chiarenzelli, 1998; Powell et al., 2001). An example of this is the Grunehogna block of East Antarctica, which will be treated together with its ancient mothercontinent Kalahari (e.g., Gose et al., 1997; Powell et al., 2001). Similarly, the Congo craton will be treated together with the São Francisco craton since geological and palaeomagnetic data are consistent with the idea that they were united since at least 2.1 Ga (e.g., D'Agrella-Filho et al., 1996). The rotations are done assuming that their fragmentation took place in the breakup of Gondwanaland and therefore they (e.g., Grunehogna and Kalahari, Congo and São Francisco) are treated in their traditional Gondwana configuration. In a similar way, Greenland is treated in its pre-Mesozoic fit with North America using the Roest and Srivistava (1989) model of their separation.

The geographic markers of the continents in text refer to their present orientations unless otherwise stated. The continents or cratons and their shapes are approximately as they existed in pre-1.00 Ga times (i.e., younger orogenic belts have generally been removed). However, this palinspastic technique is not always possible. Most data (ca. 70%) were taken from the Global Palaeomagnetic Data Base (GPDB; McElhinny and Lock, 1996; http://www.dragon.ngu), and the rest were compiled from the literature (see Abrahamsen et al., 2001).

3. Procedure for reconstructions

In making continental reconstructions we used the following procedure:

(1) All palaeopoles for the 2.45- to 1.00-Ga period were compiled with respect to their source cratons (Table 1, Fig. 1).

(2) Applying stringent reliability criteria as a filter, we selected the most reliable poles for further analysis. Fourteen key poles (Buchan et al., 2000), eighteen class A poles (Pesonen et al., 1989) and sixty-eight class B and C poles (Pesonen et al., 1989) were deemed most useful. The drawback of accepting a few less reliable C poles for the analysis is that the reconstructions with such poles (e.g., 1.70, 1.50 Ga) are considered less reliable than those which are based on key or A and B poles only (e.g., 1.25, 1.10 Ga).

(3) The continents were plotted in their ancient latitudes and azimuthal orientations as defined by the poles using the GMAP program (Torsvik and Smethurst, 1999).

(4) Geological features, such as orogenic belts, rifts, major lineaments, mafic dyke swarms, large igneous provinces, ophiolite occurrences, and lithostratigraphic data were plotted on the continents to see if meaningful geological correlations or matchings at certain times can be identified. If geologically sound configurations of the continents were found, we kept them together to indicate that they were part of a large landmass, (e.g., Hudsonland; Fig. 6), or part of a supercontinent (Rodinia; Fig. 14). If we did not find an acceptable geological correlation, we kept the continents separated. Our approach differs from some previous palaeomagnetic approaches (e.g., Weil et al., 1998; Idnurm and Giddings, 1995; Meert and Torsvik, 2003) in that we did not draw the APW paths for continents. Instead, we used the individual poles for making the reconstructions, following the method of Buchan et al. (2000). This is because the time-successive poles of the cratons have large age gaps resulting in poor APWP definition. The only exception is the Laurentian APWP during Keweenawan times (1.14–1.00 Ga) that is sufficiently well defined to allow the APWP to be used (Weil et al., 1998; Buchan et al., 2001; Powell et al., 2001; Meert and Torsvik, 2003; see dalso Chapter 7.10). Due to large age gaps in the time-successive poles, the polarity ambiguity becomes important and therefore both polarity options must be studied (see Fig. 3; Buchan et al., 2000).

Continents have grown by amalgamation of cratons or tectonic blocks (e.g., Cavanaugh and Seyfert, 1977; Pesonen et al., 1989). Laurentia provides a good example of continental growth via accretion. Most of its palaeomagnetic poles are derived from rocks within the Superior Province and only a few are derived from other provinces like Churchill, Slave, Coronation Geosyncline or the Trans-Hudson Orogen (THO) (Fig. 1, Table 1). For post-1.77 Ga, Laurentia is probably consolidated (Symons et al., 2000; Buchan et al., 2000) since there is an overall agreement of poles from several provinces at this time. However, prior to 1.77 Ga, the situation is more complex. For example, the 1.83 Ga data from Laurentia show two distinct groups of directions (Table 1). Group A (case A) has moderate shallow, and Group C (case C) very steep inclinations, respectively (case B is a modification of A, see Table 1). Since moderate inclinations are observed in coeval data from three provinces of Laurentia (Churchill, Coronation and THO), we interpret this case to represent the consolidated Laurentia at moderate latitudes (a). Case C, with steep inclinations, is derived from THO data only and forces Laurentia to high latitudes (Fig. 7b; Meert, 2002). The second possibility is that there was a large (Manikewan) ocean between THO and the remaining Laurentia at 1.83 Ga (Symons and MacKay, 1999). A third possibility, which we favour, is that the steep inclinations from THO are not primary (see also Buchan et al., 2000).

For other continents, the data are too scarce to examine their tectonic coherence during the Proterozoic (see e.g., Onstott and Hargraves, 1981; D'Agrella-Filho et al., 1996; Nomade et al., 2001;

Table 1
Paleomagnetic poles used for reconstructions

Craton	Formation	D_R, I_R (°)	Plat (°N)	Plong (°E)	A95 (°)	Age (Ma)	References
Reconstruction at 2.45 Ga							
B	Russian Karelian dykes, D' comp.	312, −15	10.0	256.0	–	2446 ± 5/4	Mertanen et al., 1999
L	Matachewan dykes	208, −31	−42.0	238.0	3.0	2446–2473	Bates and Halls, 1990
Au (WA)	Widgiemooltha dykes	69, 68	−9.0	157.0	8.0	2418–2420	Evans, 1968; Nemchin and Pidgeon, 1998
K	Ongeluk lavas	264, −25	1.0	281.0	5.0	2442	Evans et al., 1997; Bekker et al., 2001
Reconstruction at 2.00 Ga							
L	Minto dykes	300, 46	38.0	174.0	10.0	1998 ± 2[1]	Buchan et al., 1998
U	Gabbro monzonite	33, 34	51.0	156.0	8.0	1999[1]–2001[1]	Elming et al., 2001a; Skobelev et al., 1991
U	Gabbro diabase	45, 52	53.0	127.0	13.0	2000[7]	Elming et al., 2001a
U	Mean Ukraine	38, 44	53.0	142.0	–	2000	this work
Am	Oyapok tonalites	304, −53	28.0	166.0	14.0	2036 ± 14[2]	Nomade et al., 2001
Am	Encrucijada pluton	323, −4	53.0	202.0	4.0	2064 ± 87[4], 1958 ± 45[5]	Onstott et al., 1984b; Nomade et al., 2001
Am	Mean Amazonia	315, −33	42.0	181.0	–	2019	this work
C-SF	Uauá dykes	24, 67	24.0	331.0	4.0	1983 ± 31[4], 2200 ± 23[4]	D'Agrella-Filho and Pacca, 1998; Bastos Leal et al., 1994
WA	Liberia M	106, −16	−18.0	89.0	13.0	2050 ± 6[2]	Onstott and Dorbor, 1987
K	Vredefort Ring	3, 62	22.0	27.0	16.0	2023[1,2]	Hargraves, 1970
K	Vredefort dykes	7, 57	27.0	31.0	7.0	2023[1,2]	Pesonen et al., 2002
K	Bushveld middle complex	11, 63	20.0	33.0	5.0	2060 ± 2[1,4]	Hattingh, 1989
K	Bushveld upper complex	10, 66	16.0	32.0	11.0	2061 ± 27[1,4]	Hattingh, 1989, 1999
K	Mean Kalahari	7, 62	21.0	31.0	6.0	2042	this work
Reconstruction at 1.88 Ga							
B	Vittangi gabbro	345, 33	43.0	228.0	5.0	1886 ± 14[1]	Elming, 1985
B	Kiuruvesi gabbro–diorites	341, 31	41.0	231.0	4.0	1886 ± 5[1]	Neuvonen et al., 1981
B	Pohjanmaa gabbro–diorites	335, 28	38.0	239.0	11.0	1879 ± 5[1]	Pesonen and Stigzelius, 1972
B	Jalokoski gabbro	340, 35	43.0	234.0	7.0	1871 ± 4[1]	Mertanen and Pesonen, 1992
B	Mean Baltica	341, 31	41.0	233.0	5.0	1881	this work
L	Molson dykes, B comp.	254, 59	27.0	219.0	4.0	1877 + 7/ − 4[1]	Halls and Heaman, 2000
Reconstruction at 1.83 Ga							
B	Haukivesi dykes	348, 40	48.0	225.0	3.0	1840[1]	Neuvonen et al., 1981
L (Case A, Churchill)	Sparrow dykes	159, 60	12.0	291.0	8.0	1827 ± 4[1]	McGlynn et al., 1974; Bostock and van Breemen, 1992

(continued on next page)

Table 1 (*continued*)

Craton	Formation	D_R, I_R (°)	Plat (°N)	Plong (°E)	A95 (°)	Age (Ma)	References
Reconstruction at 1.83 Ga							
L (Coron.)	Seton formation	189, 51	2.0	267.0	6.0	1830 ± 10[4]	Irving and McGlynn, 1979
L (Coron.)	Akaitcho River formation	188, 44	−4.0	268.0	6.0	1820–1840[7]	Evans et al., 1980
L (THO)	Wathaman batholith	158, 57	9.0	293.0	4.0	1854 ± 11[1]	Symons, 1991
L (Case B)	Mean Churchill + Coron. + THO	175, 54	5.0	279.0	19.0	1838	this work
L (THO)	Boot-Phantom pluton	42, 89	62.0	279.0	8.0	1838 ± 1[1]	Symons and MacKay, 1999
L (THO)	Hanson Lake pluton	198, 77	36.0	266.0	10.0	1844 ± 2[1]	Gala et al., 1994
L (THO)	Macoun Lake pluton	148, 81	44.0	288.0	15.0	1854 ± 10[1]	Symons et al., 1994
L (THO)	Davin Lake granodiorite	219, 86	54.0	267.0	9.0	1801[4]–1867[1]	Symons et al., 1996
L (Case C)	Mean high lat. data (THO)	181, 85	49.0	275.0	16.0	1843	this work
Am	Rio Guaniamo dykes (Gr.2)	128, 38	−35.0	359.0	15.0	1820[2]	Onstott et al., 1984a
Am	Rio Aro dykes (Gr.2)	143, 29	−50.0	0.0	12.0	1869 ± 65[5]	Onstott et al., 1984a
Am	Mean Amazonia	135, 34	−42.0	0.0	6.0	1845	this work
Reconstruction at 1.77 Ga							
B	Ropruchey-Shosksha form.	350, 30	42.0	221.0	7.0	ca. 1770[7]	Pisarevsky and Sokolov, 2001
L (Superior)	Molson dykes, A comp.	178, 27	−16.0	277.0	4.0	ca. 1750[7]	Halls and Heaman, 2000
L (Coron.)	Peninsular sill	191, 15	−22.0	263.0	7.0	1760[4]	Irving and McGlynn, 1979
L (Churchill)	Dubawnt Group	178, 56	7.0	277.0	8.0	1785 ± 4[4]	Park et al., 1973
L (Case A)	Mean Superior + Coron. + Churchill	183, 35	−11.0	272.0	27.0	1765	this work
L (THO)	Deschambault formation	344, 68	77.0	258.0	6.0	1796 ± 15	Symons et al., 2000
L (THO)	Jan Lake granite	196, 84	48.0	270.0	15.0	1767–1773[1]	Gala et al., 1995
L (Case B)	Mean high lat. data (THO)	303, 88	62.0	267.0	–	1783	this work
U	NW anorthosites	31, −14	29.0	175.0	4.0	1760–1770	calculated from Elming et al., 2001a
Au	Elgee formation	261, −24	−4.0	30.0	5.0	1704 ± 14[1], 1786 ± 14	Li, 2000
Au	Peters Creek volcanics	294, −23	26.0	41.0	5.0	1725 ± 25[1]	Idnurm, 2000
Au (NA)	Mean Australia	277, −24	11.0	35.0	–	1738	this work
K	Mashonland dolerite	300, 53	8.0	338.0	5.0	1770 ± 20[5]	Bates and Jones, 1996
NC	North China dykes	37, −4	36.0	247.0	3.0	1769 ± 2.5[1]	Halls et al., 2000
Reconstruction at 1.65 Ga							
B	SE quartz pophyry dykes	28, 15	30.0	175.0	9.0	1638–1617[1]	Neuvonen, 1986
B	Sipoo quartz porphyry dykes	25, 5	26.0	180.0	7.0	1630[1]	Mertanen and Pesonen, 1995
B	Mean Baltica	27, 12	29.0	177.0	6.0	1628	this work
L	Proterozoic quartzites	216, 65	21.0	250.0	18.0	1700–1650[7]	calculated from Chandler and Morey, 1992
Au	Tatoola sandstone	152, 55	−61.0	187.0	6.0	1634	Idnurm et al., 1995
Au	Emmerrugga dolomite	169, 41	−79.0	203.0	2.0	1640 ± 7	Idnurm et al., 1995
Au (NA)	Mean Australia	161, 49	−70.0	191.0	–	1637	this work

Table 1 (*continued*)

Craton	Formation	D_R, I_R (°)	Plat (°N)	Plong (°E)	A95 (°)	Age (Ma)	References
Reconstruction at 1.65 Ga							
Am	Rio Aro basic dolerites (Gr.1)	320, −3	50.0	203.0	9.0	1640[3,5]	Onstott et al., 1984a
Am	Roraima dolerites (Gr.1)	335, 22	63.0	231.0	9.0	1640[3,5]	Hargraves, 1968
Am	La Escalera basic dykes (Gr.1)	328, 22	56.0	226.0	12.0	1640[3,5]	Onstott et al., 1984a
Am	Mean Amazonia	330, 17	59.0	222.0	8.0	1640	this work
Reconstruction at 1.50 Ga							
B	Rödö dykes	5, 30	42.0	202.0	10.0	1513[7]	Moakhar and Elming, 1998; Andersson, 1997
B	Mårdsjö gabbro	42, 28	33.0	157.0	7.0	1524[1]	Moakhar and Elming, 1998; Andersson, 1997
B	Mean Ragunda formation	28, 50	52.0	167.0	7.0	1505[1]	Piper, 1979; Andersson, 1997
B	Gävle granite	35, 28	35.0	165.0	10.0	1500[1]	Piper, 1980; Andersson, 1997
B	Hälleforsnäs dyke	36, 13	27.0	167.0	7.0	1518 ± 38[4]	Piper, 1980
B	Mean Baltica	30, 31	39.0	171.0	16.0	1512	this work
L	St. Francois Mtn	234, 9	−13.0	219.0	7.0	1476 ± 16[1]	Meert and Stuckey, 2002
Au (NA)	Mt Isa block intrusions IM	185, 49	−79.0	111.0	8.0	1550–1500	Tanaka and Idnurm, 1994
Sb	Kuonamka dykes	52, −25	6.0	234.0	20.0	1503 ± 5[1]	Ernst et al., 2000
Reconstruction at 1.25 Ga							
B	Vaasa dolerites	45, −23	7.0	164.0	4.0	1268 ± 13[1]	Neuvonen, 1966
B	Satakunta dolerites	52, −27	2.0	158.0	4.0	1264 ± 12[1]	Neuvonen, 1965
B	Märket dolerites	67, −32	−6.0	146.0	9.0	1265 ± 6[1]	Neuvonen and Grundström, 1969
B	Mean Baltica	52, −24	4.0	158.0	4.0	1265	this work
L	Sudbury dykes	262, 2	−3.0	192.0	3.0	1235 + 7/−3[1]	Schwarz and Buchan, 1982; Dudas et al., 1994
L	Mackenzie dykes	268, 12	4.0	190.0	5.0	1267 + 7/−3[1]	Buchan and Halls, 1990; LeCheminant and Heaman, 1989
L	Mean Laurentia	265, 8	1.0	191.0	–	1251	this work
Am	Nova Floreste	303, −56	26.0	163.0	6.0	1200	Tohver et al., 2002
C-SF	Late Kibaran intrusives	107, 3	−17.0	113.0	8.0	1236 ± 24[2]	Meert et al., 1994
C-SF	Late Kibaran intrusives (rot.)	139, 37	−47.0	78.0	8.0	1236	this work
Reconstruction at 1.15 Ga							
L	Abitibi dykes	278, 65	43.0	208.0	–	1141 ± 1	Ernst and Buchan, 1993; Krogh et al., 1987
L (Greenl.)	Giant gabbro dykes	261, 71	42.0	226.0	9.0	1163 ± 2	Piper, 1977; Buchan et al., 2001
L (Greenl.)	Giant gabbro dykes (rot.)	270, 70	44.0	219.0	9.0	1163 ± 2	this work
L	Mean Laurentia	274, 68	44.0	214.0	–	1156	this work

(continued on next page)

Table 1 (*continued*)

Craton	Formation	D_R, I_R (°)	Plat (°N)	Plong (°E)	A95 (°)	Age (Ma)	References
Reconstruction at 1.15 Ga							
Au (NA)	Lake view dolerite	340, 84	−10.0	131.0	17.0	1140	Duff and Embleton, 1976
K	Premier kimberlite	203, −34	−41.0	235.0	7.0	1165 ± 10	Powell et al., 2001
Grunehogna	Ahlmanryggen	244, 1	−9.0	240.0	6.0	1183 ± 33[3]	Peters, 1990
Grunehogna	Ahlmanryggen (rot.)	210, 66	−64.0	225.0	6.0	1183 ± 33[3]	this work
Grunehogna	Ritscherflya Supergroup	236, −6	−8.0	232.0	4.0	1130 ± 10	Powell et al., 2001
Grunehogna	Ritscherflya Supergroup (rot.)	202, 62	−61.0	209.0	4.0	1130 ± 10	Powell and Li, 1994
K	Mean Kalahari-Grunehogna	197, 34	−56.0	225.0	23.0	1159	this work
Reconstruction at 1.10 Ga							
B	Bamble intrusions	7, −34	7.0	201.0	8.0	975–1120[3]	Stearn and Piper, 1984
B	Bamble-Kongsberg amphibolites	0, −54	−8.0	208.0	6.0	975–1120[3]	Poorter, 1975
B	Nenset-Gumöy hyperite	352, −40	3.0	215.0	8.0	1040[7]	Stearn, 1979
B	Mean Baltica	0, −44	1.0	208.0	16.0	1093	this work
L	Portage Lake volcanics	288, 38	27.0	181.0	2.0	1095 ± 3[1]	Halls and Pesonen, 1982; Books, 1972
L	Keweenawan dykes, R + N	287, 61	44.0	197.0	11.0	1102	Green et al., 1987; Powell et al., 2001
L	Mean Laurentia	287, 51	36.0	188.0	–	1099	this work
Au (NA)	IA dykes	306, 83	−12.0	124.0	11.0	1116 ± 10	Duff and Embleton, 1976
C-SF	Olivenca basic dykes R	301, 66	10.0	280.0	6.0	1078 ± 18[2], 1180–770[3]	D'Agrella-Filho et al., 1990
K	Timbavati gabbros	190, −1	−63.0	227.0	3.0	1098 ± 30	Hargraves et al., 1994
K	Umkondo combined	185, 3	−66.0	217.0	7.0	1100 ± 5	Jones and Powell, 2001
K	Post Waterberg diabases	191, 4	−65.0	231.0	5.0	1090 ± 15	Jones and McElhinny, 1966
K	Mean Kalahari	188, 2	−65.0	225.0	5.0	1096	this work
Co	Coats Land Nunatak	94, −43	23.0	80.0	7.0	1112 ± 4[1]	Gose et al., 1997
Reconstruction at 1.05 Ga							
B	Laanila-Ristijärvi dykes	356, −47	−2.0	212.0	14.0	1037[6]	Mertanen et al., 1996
L	Nonesuch shale + Freda sst.	278, 5	6.0	179.0	3.0	1050[7]	Henry et al., 1977
Au (WA)	Bangemall sills	337, 42	34.0	95.0	–	1070 ± 6[1]	Wingate et al., 2002
SF	Itaju do Colonia dykes	280, 77	−8.0	291.0	9.0	1010–1080[3]	D'Agrella-Filho et al., 1990
SF	Salvador basic dykes R	304, 71	7.0	287.0	13.0	1070	D'Agrella-Filho, 1992
C-SF	Mean Congo-São Francisco	294, 75	−0.5	289.0	–	1058	this work
K	Ntimbankulu intrusion	129, −26	−27.0	147.0	13.0	1030–1060[7]	Mare and Thomas, 1997
K	Kalkpunt formation	168, −12	−57.0	183.0	–	1065	Briden et al., 1979; Onstott et al., 1986

Table 1 (*continued*)

Craton	Formation	D_R, I_R (°)	Plat (°N)	Plong (°E)	A95 (°)	Age (Ma)	References
Reconstruction at 1.05 Ga							
K	Mean Kalahari	149, − 20	− 43.0	160.0	–	1055	this work
Sb	Malgina formation	72, − 59	− 25.0	231.0	3.0	1043 ± 14[8]	Gallet et al., 2000; Ovchinnikova et al., 2001
Reconstruction at 1.00 Ga							
B	Protogine zone dolerites	356, − 57	− 12.0	211.0	7.0	980–1041	Pisarevsky and Bylund, 1998
L	Jacobsville sandstone	267, − 17	− 9.0	183.0	4.0	ca. 1000	Roy and Robertson, 1978
L	Grenville A comp.	286, − 62	− 29.0	149.0	15.0	ca. 1000	Berger et al., 1979
L	Mean Laurentia	275, − 44	− 20.0	167.0	–	1000	this work
SF	Ilheus basic dykes	237, 70	− 30.0	280.0	4.0	1011–1012[2]	D'Agrella-Filho et al., 1990
SF	Olivenca basic dykes N	260, 76	− 16.0	287.0	8.0	1010–1080	D'Agrella-Filho et al., 1990
SF	Salvador basic dykes N	281, 83	− 10.0	301.0	15.0	1003–1021[2]	D'Agrella-Filho, 1992; D'Agrella-Filho et al., 1998
C-SF	Mean Congo-São Francisco	253, 77	− 19.0	290.0	22.0	1020	this work
K	W O'Kiep intrusion	121, − 53	− 9.0	159.0	8.0	1020 ± 30[4]	Muller et al., 1978
K	O'Kiep intrusions	124, − 46	− 15.0	155.0	16.0	1020 ± 30[4]	Piper, 1975
K	Central Namaqua metamorphics	114, − 46	− 8.0	150.0	10.0	1050 ± 50[1,5], 1000 ± 20[2]	Onstott et al., 1986; Renne et al., 1990
K	Mean Kalahari	12, − 49	− 11.0	155.0	9.0	1023	this work
Sb	Sette-Daban Sills	108, 11	− 4.0	177.0	2.0	1005 ± 4	Pavlov et al., 1992; Rainbird et al., 1998

For cratons, see Figs. 1 and 2. B = Baltica, L = Laurentia (Coron. = Coronation Geosyncline, THO = Trans Hudson Orogen), Au = Australia (WA, NA, SA = West, North and South Australia, respectively), K = Kalahari, U = Ukraine, Am = Amazonia, C-SF = Congo-São Francisco, WA = West Africa, NC = North China, Sb = Siberia, Co = Coats Land. D_R, I_R refer to declination, inclination of a central reference location for each craton/continent. Reference locations: Baltica: 64°N, 28°E, Laurentia: 60°N, 275°E, Ukraine: 47°N, 30°E, Australia: NA: 20°S, 135°E, WA: 27°S, 120°E, SA: 30°S, 135°E, Amazonia: 0°, 295°E, São Francisco: 13°S, 315°E, Congo: 5°S, 23°E, Kalahari: 25°S, 25°E, Kalahari + Grunehogna: 50°S, 15°E, West Africa: 15°S, 355°E, Coats Land: 75°S, 340°E, Siberia: 60°N, 105°E, North China: 40°N, 115°E. Plat, Plon are the latitude and longitude of the paleomagnetic pole. A95 is the 95% confidence circle of the pole (Irving, 1964). Rot means that the pole has been rotated. In 1.15 Ga, reconstruction Grunehogna is rotated to Kalahari by an anticlockwise rotation of 56.28° about a pole at 9.67° S, 328.77°E (Powell and Li, 1994). Ages (Ma), dating method = 1: U–Pb, 2: Ar–Ar, 3: K–Ar, 4: Rb–Sr (whole rock), 5: Rb–Sr (mineral), 6: Sm–Nd, 7: geological age, 8: Pb–Pb.

Idnurm, 2000; Mertanen and Pesonen, submitted for publication).

4. Age bins

Fig. 2 shows the age distribution of the accepted poles. The following terminology is used. The age bin is a median value of a narrow age band for which poles are available from two or more continents. This band is generally less than 60 Ma in width (i.e., binning age ±30 Ma). The reconstructions are named according to these bins (e.g., 2.45, 2.00 Ga, etc). Our survey of the dated poles revealed that at certain bins there are poles from two or more continents making reconstructions feasible at these times. Twelve bins were chosen and they are 2.45, 2.00, 1.88, 1.83, 1.77, 1.65, 1.50, 1.25, 1.15, 1.10, 1.05 and 1.00 Ga, respectively (Fig. 2). These poles and their ages are listed in Table 1 and the corresponding continental reconstructions are shown in Figs. 4–16. In some cases, the age estimates for the poles fall outside the designated age bin and provide an additional degree of freedom in our reconstructions. It arises from the

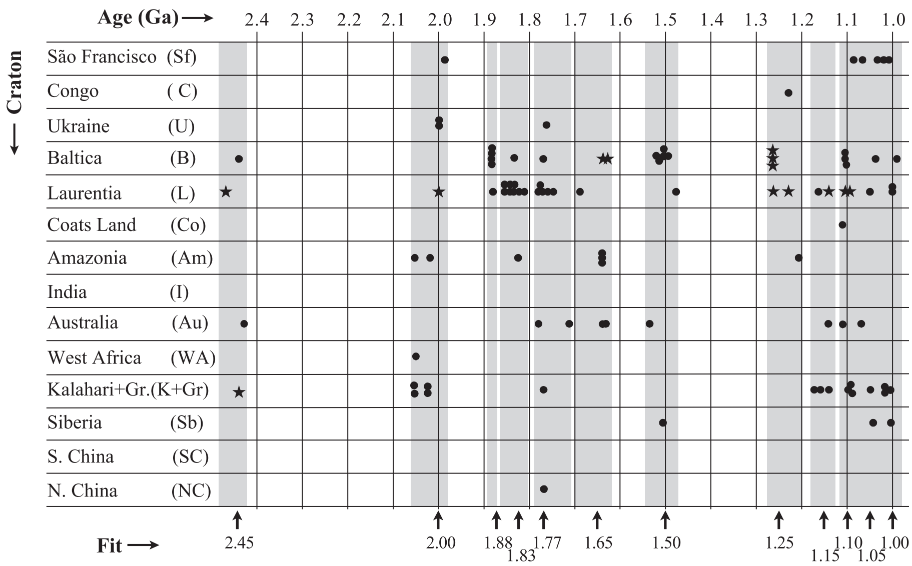


Fig. 2. The distribution of the ages of poles from each continent/craton. Star indicates a key-pole and closed circle denotes other reliable pole as explained in text.

drift of the continents during the age band and amounts roughly to $\pm 5°$ (at maximum) depending on the drift rate (Buchan et al., 2000). The main error arises from the uncertainty in the pole and is expressed by the 95% confidence circles of the mean poles in Table 1.

5. Reconstruction techniques

The principle of our palaeomagnetic technique for making reconstructions is outlined in Fig. 3 (see also Buchan et al., 2000). To simplify, only two hypothetical continents, A and B, are shown. A palaeomagnetic pole at time *t* places A and B in correct latitudes (defined by the inclinations) and orientations (defined by the declinations), respectively. Both hemispheres are possible and only the "northern" one for continent A is shown. Continent B (or A) can be moved into any position along this latitude circle since the palaeolongitude is undetermined due to axial symmetry of the dipole field. This is analogous to the 'closest approach' technique of Meert (2002). Four such locations are drawn for B (positions a–d). One of them (c) is in juxtaposition with A. The geological features are then drawn on both continents to seek

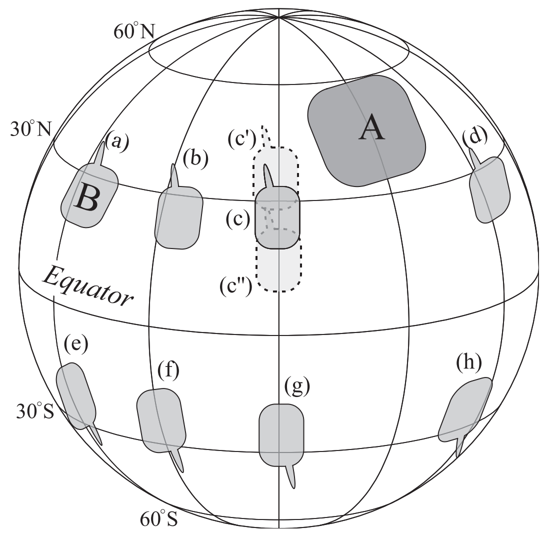


Fig. 3. The principle of the palaeomagnetic technique for making reconstructions (see also Buchan et al., 2000). A and B are hypothetical continents plotted in correct latitudes and orientations as based on palaeomagnetic poles. Only northern hemisphere option for continent A is shown. Positions a–d show continent B in four possible positions along a latitude circle defined by palaeomagnetic data. c′ and c are positions for B allowed by the errors in palaeolatitudes. Positions e–h in the opposite hemisphere (with B upside down) can also be used in seeking better geological matchings between A and B. See text for details.

possible continuations from A to B. If we found acceptable geological matchings we kept A and B together (position c). If not, we kept A and B separated. Occasionally, in order to find the best possible match, continent B is plotted in opposite hemisphere (with inverted orientation) as shown by positions e–h in Fig. 3. This is also allowed since we do not know the true polarities for A and B.

Each pole has a palaeomagnetic uncertainty as expressed by the values of the 95% confidence circles in Table 1. These values range from 3° to 27° with an average of 9.2°. A further error up to ±5° (maximum) is to be added due to the age uncertainty of the poles as described previously (Chapter 2). These errors together can lead roughly to ca. ±5–15° uncertainty in palaeolatitudes of the continents (up to 1500 km). This is demonstrated schematically in Fig. 3, where continent B is plotted at 15° higher (c′), or 15° lower (c) latitude positions from its mean position (c).

The palaeomagnetic and geologic data show further that at certain times (e.g., 2.00 Ga) the continents have been separated. At some other times, there is strong palaeomagnetic and geologic evidence that large landmasses (not necessarily supercontinents) existed, e.g., Kenorland 2.45–2.10 Ga and Hudsonland 1.83–1.25 Ga, respectively. In one case, the Neoproterozoic Rodinia, a supercontinent is strongly supported by palaeomagnetic and geological data.

6. Piercing points

Dalziel (1999 and references therein) has proposed a set of piercing points in making continental reconstructions. These include matching of conjugate rifts or orogenic belts, correlating major lineaments, dyke swarms, isotope age provinces, magmatic provinces and lithostratigraphic data, etc. Other useful geological piercings include the identification of source provinces of detrital zircons, the study of the Sm–Nd or Rb–Sr isotope systematics, and analysis of thermal subsidence curves (Burrett and Berry, 2000; Karlström et al., 2001; Sircombe, 2001).

In addition to these geological piercing points, we used the following palaeomagnetic criteria in validating the reconstructions:

(i) The magnetic polarity had to be the same from one continent to another during the lifetime of the assembly. Since we do not know the "absolute" polarity during Proterozoic, we sought distinct polarity patterns (e.g., long single polarity intervals) from one continent to another (e.g., Pesonen and Neuvonen, 1981; Pesonen, 1983; Buchan et al., 2000).

(ii) The drift rates, and the sense of drifts of the cratons had to be comparable during the lifetime of the assembly. The rates should not have exceed markedly the Cenozoic rates (e.g., Meert et al., 1993).

(iii) The palaeomagnetic latitudes were compared with those provided by sedimentological latitude indicators (e.g., Pesonen et al., 1989; Pesonen, 1992; Elming et al., 1993).

7. Continental reconstructions during the Proterozoic

7.1. Reconstruction at 2.45 Ga

Fig. 4 shows the positions of Laurentia, Baltica, Australia and Kalahari at ~2.45 Ga (Table 1). Laurentia, Baltica and Kalahari lie near the equator

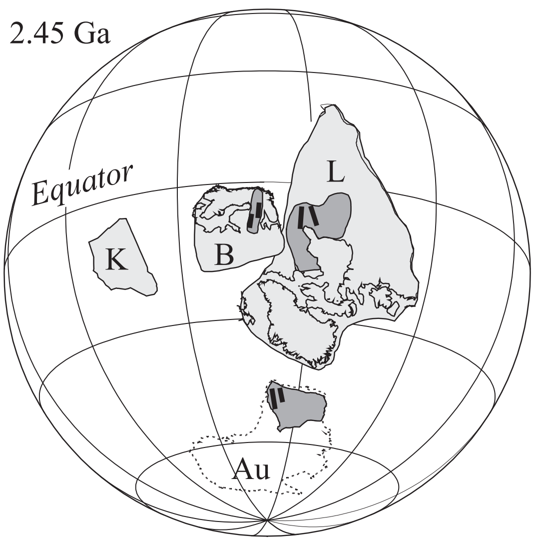


Fig. 4. The reconstruction of continents at 2.45 Ga. Data available from Laurentia, Australia, Baltica and Kalahari (Table 1). Karelia (Baltica), Superior (Laurentia) and West Australian (Australia) are shown in dark shading. Dyke swarms are shown as sticks and they are: Matachewan (Laurentia), Russian Karelian (Baltica) and Widgiemooltha (West Australia), respectively. Orthogonal projection with 20° tilt.

whereas Australia (Yilgarn) is clearly at higher (southern) latitudes. The Matachewan (Bates and Halls, 1990) and Karelian (Mertanen et al., 1999) dyke swarms become parallel in this configuration suggesting that Laurentia (Superior) and Baltica (Karelia) were united at 2.45 Ga. The Widgiemooltha dyke (~2.42 Ga) of the Yilgarn craton has a similar trend as the Matachewan-Karelia swarms in this assembly, but its distance to the latter swarms is more than 40° in latitude, an observation which does not support a close relationship between Australia and Laurentia–Baltica at 2.45 Ga. So far there is no information on 2.45-Ga-old dykes in Greenland, which lies between the Superior-Karelia unity and Yilgarn craton (Fig. 4).

The position of Kalahari is based on palaeomagnetic data of the Ongeluk lavas of South Africa (age 2.49–2.39 Ga; Evans et al., 1997; Bekker et al., 2001). Kalahari may have been attached with Baltica in the west or with Laurentia in the east, respectively (Fig. 4). Similar lithostratigraphic sequences are documented in Kalahari, Baltica and Laurentia during 2.45–2.20 Ga (Bekker et al., 2001), which support their proximity. We place the Kalahari craton slightly away from Baltica–Laurentia at 2.45 Ga since there are no 2.45-Ga-old dykes or other geological features in Kalahari to adjust its position more accurately.

Heaman (1997) has proposed that the 2.45-Ga mafic formations reflect a mantle plume (see also Ernst and Buchan, 2001), which could explain the parallel trends of the Matachewan-Karelian swarms and the associated intrusive activity in Wyoming and Karelia, respectively. A mantle plume has also been proposed for the origin of Ongeluk magmatism in Kalahari (Eriksson and Reczko, 1998). Heaman (1997) interprets the 2.45-Ga dyke activity as a global event marking the onset of rifting of the Kenorland supercontinent (as defined by Williams et al., 1991) of which the Superior and Wyoming cratons were members. Our data support this and suggest further that other cratons (e.g., the Kaapvaal craton of Kalahari) were also members of Kenorland. The palaeomagnetic data are too scarce to say whether Kenorland was a true supercontinent, or merely an agglomeration of few continents. Aspler and Chiarenzelli (1998) have included also Siberia in Kenorland. They also discuss Zimvaalbara, a second large landmass at 2.45 Ga as the presumed southern companion of Kenorland. Their Zimvaalbara is composed of the Zimbabwe, Kaapvaal and Pilbara cratons. However, our palaeomagnetic data show that the Kaapvaal craton was likely a part of Kenorland at 2.45 Ga. We do note further that it is possible that the Yilgarn craton of Australia, located in high southerly latitudes (Fig. 4), was a member of Zimvaalbara in Early Proterozoic.

Between 2.40 and 2.22 Ga, the Superior, Karelia and Kalahari cratons experienced one to three successive glaciations (Marmo and Ojakangas, 1984; Sturt et al., 1994; Williams and Schmidt, 1997; Bekker et al., 2001). It is noteworthy that the glaciogenic sequences also contain paleoweathering zones (regoliths or palaeosols), lying generally on top of the glaciated layers. These Early Proterozoic supracrustal strata with glaciogenic and palaeoweathering layers are lithostratigraphically similar to Neoproterozoic strata that also contain glaciogenic layers and palaeoweathering zones (e.g., Evans, 2000). Moreover, in both cases (Early Proterozoic and Neoproterozoic), the palaeomagnetic data point to low, and even equatorial, latitudes (≤45°) during glaciations (e.g., Williams and Schmidt, 1997; Evans, 2000; Evans et al., 1997). Taking Laurentia as an example, it maintained a low latitude position from 2.45 to 2.00 Ga (Figs. 4 and 5) during the time when the glaciations took place (e.g., Williams and Schmidt, 1997; Buchan et al., 1998). For the other continents we do not have reliable palaeomagnetic data to show their latitudinal positions during the Early Proterozoic glaciations. Tentatively, Baltica appears to be at low to intermediate latitudes during 2.45–2.15 Ga (Neuvonen et al., 1997; Mertanen et al., submitted for publication).

Various models have been presented to explain the late Neoproterozoic low-latitude glaciations. These include (i) the "Snowball Earth" hypothesis (Kirschvink, 1992; Hoffman and Schrag, 2002), (ii) the concept of a large Earth's obliquity (Williams, 1993), (iii) the non-dipole model of the geomagnetic field (Kent and Smethurst, 1998; Van der Voo and Torsvik, 2001) and (iv) the remagnetisation explanation (Meert and Van der Voo, 1994). These explanations are also possible for the Early Proterozoic glaciations. If models (iii) and (iv) turn out to be valid, our palaeomagnetic reconstructions would be in error. The sedimentary indicators of palaeolatitudes during Early Proterozoic are controversial since the low latitudes are supported by palaeoweathering observations during 2.40–2.2 0 Ga. The occurrence of both glacial deposits and paleoweathering zones without an obvious hiatus suggests that rapid climatic changes took place during the 2.40–2.22 Ga interval (Sturt et al., 1994; Bekker et al., 2001). Further palaeomagnetic studies of the 2.40 -to 2.20-Ga old units, coupled with U–Pb isotope determinations, are required to explain the apparent development of low-latitude, low-elevation continental glaciations.

The timing of breakup of Kenorland is not known precisely. Evidence of rifting at ca. 2.45 Ga in Kenorland come from the igneous activity (e.g., dykes) and concomitant developments of sedimentary basins in Laurentia, Kalahari and Karelia (Heaman, 1997; Aspler and Chiarenzelli, 1998; Bekker et al., 2001). At ca. 2.20–2.10 Ga, Baltica and Laurentia experienced another rifting episode as evidenced by passive margin sediments and widespread mafic dyke activity (e.g., Vuollo et al., 1995). It is possible that the rifting at 2.20–2.10 Ga led to breakup of Kenorland and separation of Laurentia and Baltica. The rifting has been linked to the observed global peak in the ∂13C-curve at 2.15 Ga (e.g., Karhu and Holland, 1996; Bekker et al., 2001).

7.2. Reconstruction at 2.00 Ga

Palaeomagnetic data for 2.00 Ga come from Laurentia, Kalahari, West Africa, Congo/São Francisco, Amazonia and Ukraine (Fig. 5; Table 1). These continents occupy low (Laurentia, Amazonia, West Africa and Ukraine) to moderate (Congo/São Francisco, Kalahari) latitudes. The 2.00 Ga configuration of the continents resembles (but is not the same) the present plate tectonic framework where most of the continents are separated. From 2.45 to 2.00 Ga, Laurentia drifted into low northerly latitudes and rotated more than 100° anticlockwise. This rotation is not a consequence of the polarity ambiguity since the result is based on sequential and precisely (U–Pb) dated palaeopoles of mafic dykes from Laurentia ranging in age from 2.45 to 1.97 Ga (Buchan et al., 2000). Unfortunately, there are no reliable data from Baltica during this period to constrain its drift history (but see Pisarevsky and Sokolov, 1999). The position of Baltica at 1.93 Ga (Mertanen and Pesonen, 1994) is different from that at 2.45 Ga, suggesting that it also underwent a period of considerable drift and rotation during this interval.

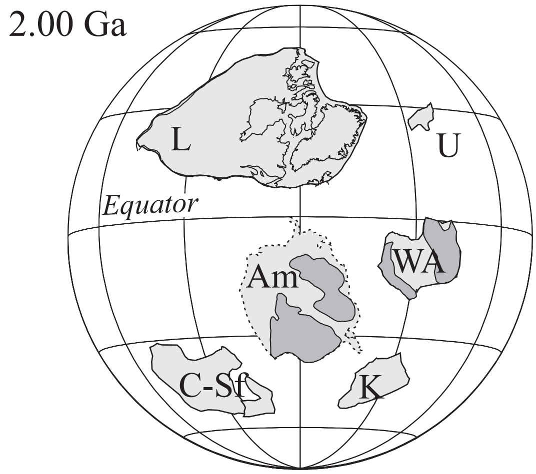


Fig. 5. The reconstruction of continents at 2.00 Ga. Data available from Laurentia, Congo/São Francisco, Amazonia, West Africa, Kalahari and Ukraine. The shaded areas in the West Africa craton represent mainly Eburnean cratonized areas (the Man block to the right and the Reguibat block to the left, Trompette, 1994) and in the Amazonia craton they represent the Guyana Shield (to the right) and the Guaporé Shield (to the left), respectively (see e.g. Bettencourt et al., 1999). Note the low to intermediate latitudinal locations of the continents. For explanation, see Fig. 4.

Tentative palaeomagnetic data from Baltica also support the low to intermediate latitudinal positions of Baltica during 2.20–1.97 Ga (Neuvonen et al., 1997; Pisarevsky and Sokolov, 1999). Sedimentological (palaeoclimatological) latitude indicators, such as stromatolites, black shales, shungites, phosphate deposits and evaporities in Baltica of the age of ca. 2.2–2.0 Ga are consistent with Baltica remaining at low latitudes during 2.45–2.0 Ga (Perttunen, 1970; Äikäs, 1989; Lager and Loberg, 1990; Loukola-Ruskeeniemi and Heino, 1996; Melezhik et al., 1999).

At 2.00 Ga, the Amazonian, Congo/São Franciscan, West African, Ukrainian and Kalahari cratons are plotted separately from each other because there are no obvious geologic reasons for putting them together. However, several cratons experienced tectonic acitivity also at that time. The Trans-Amazonian orogen in South America took place at 2.20–2.00 Ga (Hartmann, 2002). Coeval orogenic belts also exist in West Africa (Ledru et al., 1994). Nomade et al. (2001) argue that part of Amazonia (the Guyana Shield) and West Africa, which are geologically similar, may have been in juxtaposition at 2.00 Ga based on palaeomagnetic evidence from the two cratons. This is allowed by present palaeomagnetic data (Fig. 5) since both cratons lie at low southerly latitudes and can be assembled together.

7.3. Reconstruction at 1.88 Ga

The period of 1.90–1.80 Ga is well known geologically. Large amounts of juvenile crust were added to the continents, and black shales, banded iron formations (BIFs) and shallow marine phosphates were deposited indicating warm climatic conditions (Condie, 1998; Condie et al., 2001). These deposits may point to the existence of a supercontinent at low latitudes (Condie, 2002), or to an association of continents with a mantle superplume (Condie et al., 2001; Rogers and Santosh, 2002).

Unfortunately, at 1.88 Ga, reliable poles are available only from Baltica and Laurentia to test these ideas (Fig. 6). Laurentia appears to have been rotated ca. 45° clockwise from its 2.00 Ga position (Figs. 5 and 6). However, the 1.88-Ga position of Laurentia is based on a controversial Molson dykes B-pole of Halls and Heaman (2000; see also Zhang et al., 1994; Halls and Hanes, 1999). The corresponding pole from Baltica (mean of several ca. 1.88 Ga gabbros), and hence Baltica's position, is well established, but the age of the pole is uncertain since the magnetisation ages of the slowly cooling plutons may be 10–20 Ma younger than their crystallization age of 1.88 Ga (see Buchan et al., 2000; Mertanen and Pesonen, submitted for publication). However, we note that Laurentia and Baltica form a large landmass at low to intermediate latitudes consistent with occurrences of evaporites and phosphates in both continents indicating warm palaeoclimates during deposition (Äikäs, 1989; Elming et al., 1993; Condie et al., 2001 and references therein).

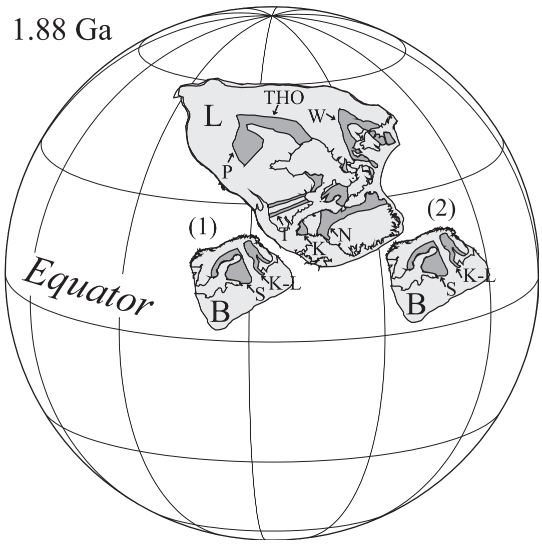


Fig. 6. The reconstruction of continents at 1.88 Ga. Data available from Laurentia and Baltica (see also Buchan et al., 2000). Baltica is shown in two possible positions. The ca. 1.90–1.80 Ga orogenic belts in Laurentia are shown with darker shading and they are: N, Nagssugtoqidian; T, Torngat; THO, Trans-Hudson Orogen; P, Penokean; W, Woopmay; K, Ketilidian. The corresponding belts in Baltica are: K-L, Kola-Lapland; S, Svecofennian. For explanation, see Fig. 4 and text.

Two models are offered to explain the Laurentia–Baltica unity and the tectonic belts that were formed when they collided during 1.90–1.80 Ga (Fig. 6). In model 1, Baltica is placed south of Greenland and in model 2 at the NE corner of Greenland. The first alternative is similar to models by Park (1991), Patchett and Arndt (1986), Gorbatschev and Bogdanova (1993) and Bridgwater et al. (1990) within the uncertainties involved. Others (e.g., Hoffman, 1989; Gower, 1990; Poorter, 1981) place Baltica along the eastern margin of Greenland, but in ca. 60° anticlockwise position relative to Laurentia.

The first model provides the following scenario to explain the ca. 1.90–1.80 Ga orogenic belts in Laurentia–Baltica. After rifting at ca. 2.15 Ga ago, both continents drifted independently until ~1.93 Ga. Subsequently, Laurentia collided with Baltica from the north causing the Nagssugtoqidian and Torngat orogens in Laurentia and the Kola-Lapland orogen in Baltica (Fig. 6; e.g., Park, 1994; Pesonen et al., 2001a,b). The plate tectonic processes causing these collisional belts are poorly known. It is likely that in addition to the collision between Laurentia and Baltica, there was additional assembly of the individual cratons within Laurentia (e.g., Slave and Rae/Hearne) and in Baltica (Kola and Karelia). The complexity of these collisions is manifested by the anastomosing network of 1.93–1.88 Ga orogenic belts separating the Archaean cratons (Fig. 6). Park (1991) and Buchan et al. (2000) discuss in more detail how the oblique pattern of these belts are formed during these collisions.

In addition to the above-mentioned belts, a collision with a third unknown continent may be responsible for at least some of the 1.93–1.88 Ga orogenic belts (see Park, 1994). Candidates for this 'third continent' include North China, Australia or Siberia. Each of these have 1.93–1.88 Ga orogenic belts; the Trans-North China Orogen in China, the Capricorn orogen in Australia and the Stanovoy block in Siberia (e.g.; Halls et al., 2000; Zhao et al., 2000; Wilde et al., 2002).

7.4. Reconstruction at 1.83 Ga—the assembly of Hudsonland

Palaeomagnetic data for 1.83 Ga reconstruction come from Laurentia, Baltica and Amazonia (Table 1, Fig. 7). The position of Baltica is based on a well-defined pole from the Haukivesi lamprophyres of Finland (Neuvonen et al., 1981). The choice of the corresponding pole for Laurentia is more difficult since Laurentia may not have been consolidated yet (see above). For this reason, two cases (A, Fig. 7a; C, Fig. 7b) for Laurentia are presented (case B in Table 1 is a modification of A). In case A (intermediate inclinations), Laurentia is consolidated and represented by the 1.83-Ga Sparrow dyke pole from Churchill Province (McGlynn et al., 1974). This pole places Laurentia at intermediate latitudes (Fig. 7a). Table 1 shows that this position is supported by data from two other provinces, the Coronation Geosyncline and the Trans-Hudson orogenic belt (THO). Case C places Laurentia at high polar latitudes (Fig. 7b). This position is defined by data from THO only (e.g., Symons and MacKay, 1999; see Table 1). Meert (2002) used this latter option to test possible models of Columbia supercontinent assembly. We favour case A for two reasons. First, rigorous field tests are lacking from the THO to show that the magnetisations are primary although the high inclination data are derived from numerous studies over a wide geographic area. Second, although Proterozoic glaciations are not necessarily indicative of high latitudes, there is no palaeoclimatological evidence for nearly polar latitudes of Laurentia at 1.83 Ga.

A comparison of Figs. 6 and 7a shows that from 1.88 to 1.83 Ga, Laurentia has remained nearly in the same latitude but it experienced a large and rapid ~80° clockwise rotation. Baltica has drifted slightly northwards without significant rotation before docking with Laurentia. If the collision of Laurentia and Baltica occurred nearer to 1.88 Ga, then the palaeomagnetic

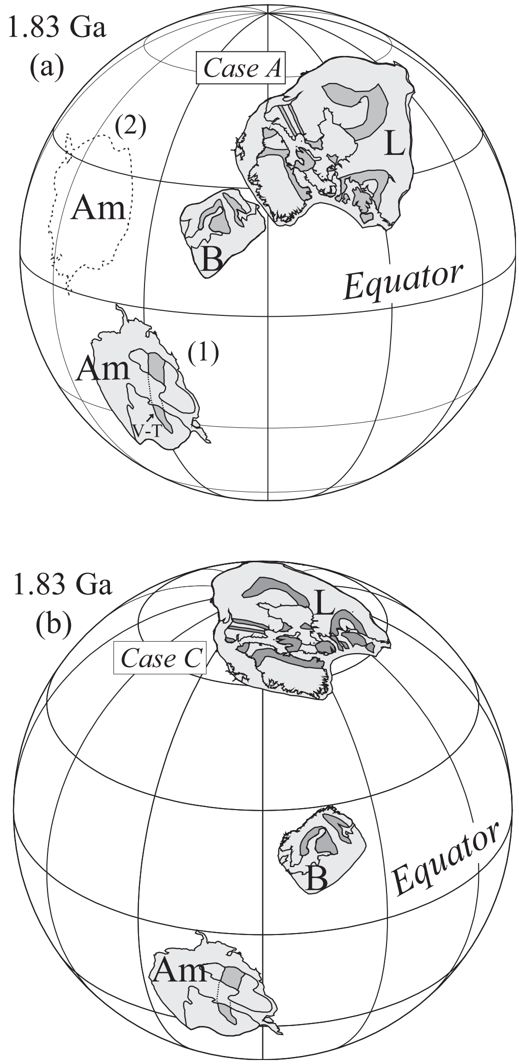


Fig. 7. The reconstruction of continents at 1.83 Ga. Data available from Laurentia, Baltica and Amazonia. The 1.90–1.80 Ga Svecofennian–Hudsonian orogenic belts in Laurentia and Baltica shown in dark are the same as in Fig. 6. The coeval Ventuari–Tapajós belt in Amazonia is added. (a) Laurentia is represented by the pole of Sparrow dykes from the Superior province (case A in Table 1). Amazonia is shown in two possible positions (1 and 2) depending of the polarity choice of the 1.83-Ga Amazonian pole. Previously (e.g., Pesonen et al., 2001a,b), the position (2) was used. Position (1) is consistent with current geological thinking (e.g., Geraldes et al., 2001). It allows Amazonia to be contiguous with Laurentia–Baltica in the Hudsonland assembly as discussed in text. (b) Laurentia is represented by a group of poles (case C) with steep inclinations from the Trans-Hudson Orogen (THO). For explanation, see Fig. 4.

data indicate relative rotations and latitudinal shifts during docking (e.g., Wilson, 1990; Nironen, 1997).

The position of Amazonia at 1.83 Ga is problematic. Two possibilities (positions 1 and 2 in Fig. 7a) are shown depending on the polarity choice for Amazonia. Previously (e.g., Pesonen et al., 2000; Pesonen et al., 2001a,b; Elming et al., 2001a; Pesonen and Mertanen, 2002), Amazonia has been placed in the same latitude as Baltica (position 2). This lead us to propose that the Svecofennian orogenic belt in Baltica (1.88–1.86 Ga) and the coeval Ventuari-Tapajos belt in Amazonia, and also the successively younger belts like the TIB I belt in Baltica and the Rio Negro-Juruena belt in Amazonia, were caused by a prolonged collision of Baltica with Amazonia during ca. 1.88–1.50 Ga. In spite of this earlier assertion, we note that the current geological data (e.g. Geraldes et al., 2001) from Amazonia cannot confirm the assumption and the sense of subduction is similar in both continents making the link more difficult to argue on geologic grounds. Therefore, we now suggest that the position 1, where Amazonia is in the southern hemisphere (and upside down from position 2) and, within error limits, in a laterally contiguous position with Laurentia–Baltica, is better than model 2. According to present (model 1) reconstruction, Amazonia is not facing Baltica in the same latitude but is contiguous with Baltica. Current geological thinking (e.g., Bettencourt et al., 1996; Tassinari et al., 2000; Åhäll and Larson, 2000; Geraldes et al., 2001) also favour the idea that the coeval belts in Laurentia, Baltica and Amazonia are accretional and formed during Cordilleran-type subduction and arc accretion from west onto a convergent margin because these belts become successively younger towards west in all three continents. Moreover, this model allows also the subsequently younger orogenic belts, such as the Gothian/Kongsbergian (in Baltica), Labradorian/Mazatzal (in Laurentia) and the Rondonia-San Ignacio (in Amazonia) belts, to be formed in accretions from west of this laterally contiguous landmass.

The assembly of Laurentia, Baltica and possibly Amazonia at 1.83 Ga (model 2) marks the onset of Hudsonland development (after Williams et al., 1991). This large continent probably involved other continents, too, such as Australia, Siberia and North China, although palaeomagnetic data are still lacking from them at 1.83 Ga. A similar large continental assembly (but not identical) called Columbia has also been proposed for this period (Rogers and Santosh, 2002; Meert, 2002) although our palaeomagnetic data show that these Columbia configurations differ from Hudsonland.

7.5. Reconstruction at 1.77 Ga

Reliable palaeomagnetic data at 1.77 Ga come from Laurentia, Baltica, North China, Australia, Ukraine and Kalahari (Fig. 8). These continents, belonging to Hudsonland, remain at low to intermediate latitudes during 1.83–1.77 Ga. The position of Baltica is based on the key pole from the Shoksha sediments and Ropruchey sill of Russian Karelia (Fedotova et al., 1999; Pisarevsky and Sokolov, 2001). Laurentia is represented by two data sets, but only the low inclination case (case A in Table 1; see previous discussion) is studied here.

The pre-1.77 Ga palaeomagnetic data from Ukraine differ from coeval data from Baltica suggesting that the two continents were separated before 1.77 Ga (e.g., Elming et al., 2001a,b; Bogdanova, 2001). Fig. 8 shows that at 1.77 Ga Ukraine is slightly

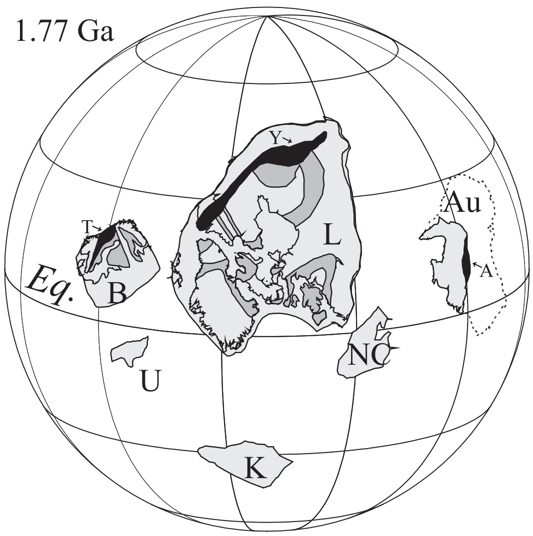


Fig. 8. The reconstruction of continents at 1.77 Ga. Data available from Laurentia, Baltica, Congo/São Francisco, North China, Ukraine and Kalahari. Laurentia is represented by poles from the Superior craton (case A in Table 1). The new orogenic belts (shown in black), which are formed after the Svecofennian–Hudsonian belts (shown in grey) in Figs. 6 and 7, are: Y, Yavapai (Laurentia); T, TIB (Trans Scandinavian Igneous Belt, Baltica); A, Arunta (Australia). See also Karlström et al. (2001). For explanation, see Fig. 4.

separated from Baltica and probably on its way to dock with Baltica from the south. The docking takes place sometime between 1.77-1.70 Ga (Elming et al., 2001a,b; Bogdanova, 2001).

The 1.77 Ga configuration of Baltica and Laurentia differs from that at 1.83 Ga, suggesting a ca. 25° latitudinal movement and minor anticlockwise rotation of Laurentia relative to Baltica during 1.83–1.77 Ga. Most likely, however, this difference reflects poor palaeomagnetic data of Laurentia rather than real movements (Table 1). It is possible that the long-lasting accretion to the western margin of the combined Laurentia–Baltica landmass was not a singular event but also included some relative movements along transform faults between the accreting blocks (Wilson, 1990; Nironen, 1997). It is also possible that the docking of Ukraine with Baltica triggered minor block rotations within Baltica (Bogdanova, 2001). If the data from Laurentia turn out to be valid, the difference of the Laurentia–Baltica configurations between 1.83 and 1.77 Ga implies that they were separated at 1.77 Ga. We consider this unlikely since the geologically similar TIB 1 (in Baltica) and Yavapai/Ketilidian (in Laurentia) belts (e.g., Karlström et al., 2001; Åhäll and Larson, 2000) become laterally contiguous when reconstructed according to palaeomagnetic data of the age of 1.83 and 1.25 Ga.

The configuration of Laurentia, Baltica and North China in the Hudsonland configuration at 1.77 Ga is similar with that of Halls et al. (2000). However, Meert (2002) places Laurentia at high southerly latitudes and the position of Baltica is antipodal to the reconstruction given here. We do note that this 'alternative position' was not necessarily advocated strongly in that paper as the author was merely trying to show a closest approach to Laurentia. It is worthwhile to note that Australia may also be part of Hudsonland at 1.77 Ga (Fig. 8). Idnurm and Giddings (1995) show a reconstruction between Australia and Laurentia during 1.70–1.60 Ga ago, which differs from our model. The model of Idnurm and Giddings (1995) places Australia close to the SWEAT configuration of Moores (1991), whereas our data suggest that Australia is not compatible with either the SWEAT or AUSWUS configuration. Karlström et al. (2001) stress that geological data of the 1.80- to 1.40-Ga belts from Laurentia–Baltica landmass continue into eastern Australia in their reconstruction, which is palaeomagnetically possible within the uncertainties involved. (Fig. 8). We shifted Australia slightly off from Laurentia–Baltica assembly (see also Brookfield, 1993; Blewett et al., 1998; Idnurm and Giddings, 1995; Li, 2000; Burrett and Berry, 2000; Karlström et al., 2001).

Unfortunately, no palaeomagnetic data from Amazonia are available at 1.77 Ga to test whether it remained in its 1.83 Ga position relative to other Hudsonland continents (e.g., Laurentia, Baltica) to this time.

Geological data, such as mafic dykes and rapakivi–anorthosite occurrences, can be used to test the 1.77-Ga configuration. There are several genetic models to explain the episodic rapakivi–anorthosite magmatic pulses. For example, the rapakivi magmatism has been explained in terms of their relationship to supercontinents (Rämö and Haapala, 1995; Hoffman, 1989; Bettencourt et al., 1999); as representing the distal expressions of the long lasting accretional margins of continents (Åhäll and Larson, 2000); or caused by collisional orogenies between cratons (e.g., collision of Ukraine with Baltica; Bogdanova, 2001). Whatever the correct explanation for rapakivi magmatism, the occurrence of coeval rapakivi magmatism during the Proterozoic suggests that the continents have been close to each other.

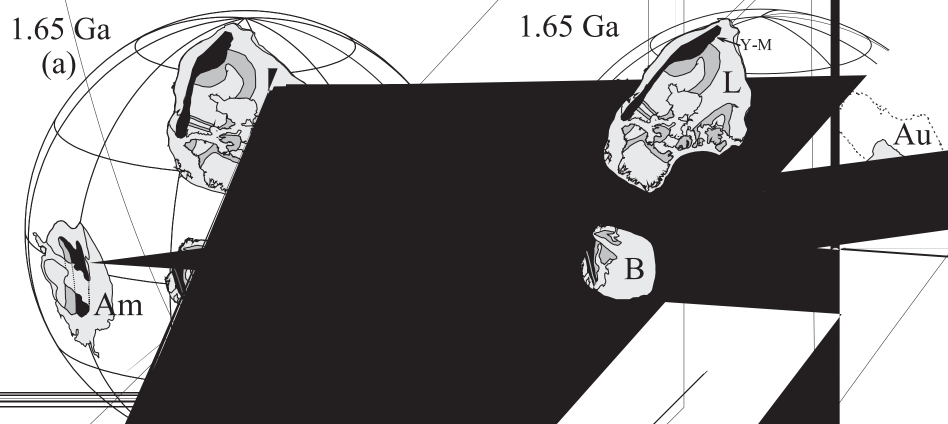
Four pulses of rapakivi magmatism are known during the Proterozoic and these are: 1.80–1.77, 1.69–1.65, 1.58–1.53, 1.43–1.39 and the early Neoproterozoic pulse, respectively (e.g., Rämö and Haapala, 1995; Bettencourt et al., 1999; Dall'Agnol et al., 1999). From the above pulses, the 1.80- to 1.77-Ga-old rapakivi–anorthosites are known in Ukraine, South Greenland, North China and North Australia (Rämö and Haapala, 1995) implying that these continents may have been close to each other at this time. This idea gains some support from palaeomagnetism (Fig. 8) since all these four cratons are at nearly same equatorial latitudes. We return to the role of rapakivi magmatism later in analysing the Hudsonland configuration of continents in more detail.

7.6. Reconstruction at 1.65 Ga

Current geological models for Laurentia, Amazonia and Baltica favour that the post-1.83 Ga orogenic belts, such as Yavapai/Mazatzal and Labradorian belts in Laurentia, the TIB II and Gothian/Kongsbergian belts in Baltica and the Rio Negro Juruena and Rondonia-San Ignacio belts in Amazonia are formed along the convergent continental margin by prolonged subduction and arc accretions onto this long contiguous landmass comprising Laurentia, Baltica and Amazonia. Palaeomagnetic data can be used to test these ideas at 1.65 Ga.

For the 1.65 Ga reconstruction, palaeomagnetic data are available from Laurentia, Baltica, Australia and Amazonia (Fig. 9, Table 1). The Baltica pole is derived from quartz porphyre dykes in southern Finland and is considered as key pole. The Laurentian pole is a mean pole derived from Proterozoic quartzite bodies from the Mid-Continent region with poorly defined ages between 1.70 and 1.60 Ga (Chandler and Morey, 1992; see also Kean and Mercer, 1986). The Amazonian pole is a mean of three dyke swarms and is also poorly dated at ca. 1.64 Ga. The Australian pole is an average of two sedimentary formations and is reasonably well dated at ca. 1.65 Ga (Idnurm, 2000). These data allow us to consider three possible models for the continents at 1.65 Ga (Fig. 9a–c).

The first model (Fig. 9a) is based strictly on the available palaoemagnetic data of Table 1 and follows



Geraldes

our previous interpretation regarding the position of Amazonia relative to Laurentia–Baltica (e.g., Pesonen et al., 2001a,b and references therein). In this model, Amazonia and Baltica are in the same low northerly latitudes close to each other. According to the previous model at 1.83 Ga (Fig. 7a), the Gothian/Kongsbergian and Rio Negro-Juruena belts were formed by collision of Amazonia with Baltica. This continent–continent collision model is now discounted for two reasons. First, these belts are accretional and not collisional, involving juvenile magma production in both continents. Second, these successive orogenic belts show a westward younging and are therefore less likely to have formed by a simple collisional model between Amazonia and Baltica.

In model 2 (Fig. 9b), Baltica and Amazonia are in the same equatorial latitude but now Amazonia has been inverted using the opposite polarity for the palaeomagnetic data. Thus, although both Baltica and Amazonia experience subduction and arc accretion, these processes represent the closure of two distinct oceans. The coeval Gothian-Labradorian and the Rio Negro-Juruena belts are thus formed by two separate events.

Fig. 9c shows model 3, which is based on geological reasoning (e.g., Sadowski and Bettencourt, 1996; Bettencourt et al., 1996; Åhäll and Larson, 2000; Geraldes et al., 2001; Sadowski, 2002). Amazonia is in a laterally contiguous position with the Laurentia–Baltica landmass following the 1.83-Ga model 1 in Fig. 7a. However, a strict interpretation of the palaeomagnetic data at 1.65 Ga does not support this model since it would require Baltica to be shifted 15° to north and Amazonia 15° to south, respectively, which exceeds the errors in Table 1. We do note that neither the poles, nor their ages, are particularly well constrained for this time period and therefore this model cannot be rejected a priori.

The proposed configuration of Hudsonland at 1.65 Ga (Fig. 9c) is different from Columbia supercontinent models by Rogers and Santosh (2002) and by Meert (2002). For example, our data places Amazonia in close connection with Baltica–Laurentia landmass at this time and not with West Africa and Kalahari as in Rogers and Santosh (2002).

One of the major peaks of rapakivi–anorthosite pulses took place during 1.58–1.53 Ga (Rämö and Haapala, 1995; Bettencourt et al., 1999; Dall'Agnol et al., 1999). The coeval occurrences of bimodal rapakivi granites and mafic dyke swarms in Baltica, Amazonia and also in South Australia during ca. 1.58–1.53 Ga further support the close connection between these continents in the Hudsonland configuration (Åhäll and Larson, 2000). This rapakivi activity is consistent with a hot spot underlying the Baltica–Amazonia–Australia landmass (Pesonen et al., 1989; Moakhar and Elming, 1998). Another possibility is that the coeval rapakivi–anorthosite magmatism is a distal response in the foreland for the prolonged accretions that took place in the continental margin of Baltica–Amazonia as described previously (Åhäll and Larson, 2000).

The position of Australia in the 1.65 Ga reconstruction is located in the northwestern side of Laurentia, fairly close to the SWEAT model of Moores (1991) (see also Ross et al., 1992; Blewett et al., 1998; Idnurm and Giddings, 1995; Thorkelson et al., 2001). Palaeomagnetic data allow Australia to be shifted on the other side of Laurentia as well, which then would bring the 1.7- to 1.6-Ga Arunta belt into close association with the Labradorian/Gothian and Rio Negro-Juruena belts (Figs. 8 and 9).

7.7. Reconstruction at 1.50 Ga

Palaeomagnetic data at 1.50 Ga come from Laurentia, Baltica, Australia and Siberia (Fig. 10). The

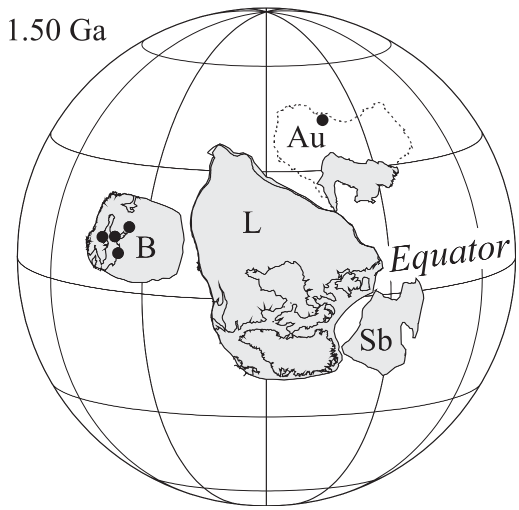


Fig. 10. The reconstruction of continents at 1.50 Ga. Data available from Laurentia, Baltica, Siberia and Australia. Rapakivi granites of the age of 1.60–1.50 Ga are marked as black dots. For explanation, see Fig. 4.

assembly of Laurentia–Baltica at 1.50 Ga differs from the 1.83 Ga configurations. This could indicate independent drift of Baltica and Laurentia from 1.83 to 1.50 Ga (e.g., Pesonen and Neuvonen, 1981). The poles of Baltica for the 1.50 Ga, however, show large scatter (Table 1; Moakhar and Elming, 1998). Moreover, the Baltica mean pole (age 1.52 Ga) for this reconstruction is 40 My older than the corresponding Laurentian pole (St. Francois Mountains pole, Table 1; Meert and Stuckey, 2002) which may explain part of the discrepancy. Taking into account the age difference and the large uncertainties in the poles, at present, we cannot verify if Laurentia and Baltica were indeed joined at 1.50 Ga (see also Åhäll and Connelly, 1998; Buchan et al., 2000).

The position of Australia in Fig. 10 on the western coast of Laurentia is consistent with the AUSWUS configuration of Karlström et al. (2001) for 1.6–1.3 Ga. The close connection of Australia and Laurentia at 1.50 Ga is therefore possible as discussed by Karlström et al. (2001) and is based on continuation of geological belts from Laurentia to Australia in this reconstruction. The palaeomagnetic data thus suggest that Australia was also part of Hudsonland. The occurrence of ca. 1.60–1.50 Ga rapakivi intrusions in Australia further support the idea that Australia was in close connection with Laurentia–Baltica and Amazonia at 1.50 Ga. However, it is important to note that the paleomagnetic data alone do not constrain the AUSWUS configuration as the only possibility (see Meert and Torsvik, 2003).

Palaeomagnetic data allow Siberia to be in contact with northern Laurentia at 1.50 Ga. This position is similar to that by Hoffman (1991) and is based on preliminary palaeomagnetic data of Ernst et al. (2000). They point out that the errors in pole positions and ages are so large that it is impossible to totally rule out other reconstructions, including that favoured by Sears and Price (2000; see also Meert and Stuckey, 2002) where Siberia is on the western coast of Laurentia. One of the major unanswered questions with regard to this proposed connection is the exact timing of the Siberia–Laurentia collision.

A recent criticism of the various Siberia–Laurentia connections was noted by Pisarevsky et al. (2003) and Pisarevsky and Natapov (2003). These papers note that almost all the Meso-Neoproterozoic margins in Siberia are oceanic margins (either active or passive) and therefore a close connection between Siberia and Laurentia is not strongly supported by their relative tectonic settings.

The exact timing of Hudsonland (or Columbia) breakup is often related to the emplacement of ca.1.52–1.38 Ga rapakivi–anorthosite magmas (Rogers and Santosh, 2002). This magmatism is well documented in Laurentia, SW Baltica and Amazonia (e.g., Dall'Agnol et al., 1999; Åhäll et al., 2000; Rogers and Santosh, 2002). Another possibility is that the breakup occurred much later (ca. 1.25 Ga) when a number of rift basins, graben formation and dyke intrusions occur globally (see below).

Laurentia and Baltica remained probably in low latitudes from 1.50 to 1.25 Ga (Buchan et al., 2000). Preliminary comparisons of palaeomagnetic poles from the ca. 1.4-Ga-old red beds of the Sibley Peninsula (Laurentia) and Satakunta-Ulvö (Baltica) (e.g., Pesonen and Neuvonen, 1981; Pesonen et al., 1991; Elming et al., 1993) support the 1.50- and 1.25-Ga reconstructions within the uncertainties involved. Buchan et al. (2000) mention that the palaeomagnetic data from the ca. 1.3-Ga-old Nairn anorthosite of Laurentia suggest that it remained at low latitudes during ca. 1.40–1.30 Ga, also consistent with low-latitude position of Laurentia at that time.

7.8. Reconstructions at 1.25 Ga

Fig. 11a shows the 1.25-Ga assembly of Laurentia, Amazonia, Baltica and Congo/São Francisco (Table 1). These continents are located at low to intermediate latitudes at 1.25 Ga. This configuration of Laurentia–Baltica is similar to that of Poorter (1981), Gower (1990), Park (1992) and Karlström et al. (2001) at ca. 1.3 Ga. Amazonia is here placed in a contiguous position with Laurentia–Baltica following the models of Hudsonland in Figs. 7–9. New palaeomagnetic data from Tohver et al. (2001, 2002) place Amazonia further south and west off the Llano uplift region of Texas.

The relative position of Baltica–Laurentia at this time is roughly the same as during 1.83 Ga, although it has rotated as a unity by 80° anticlockwise and drifted southwards. This configuration is independent of the polarity ambiguity since the data of 1.25-Ga mafic dykes from both continents are of single polarity (Pesonen and Neuvonen, 1981; Buchan et al., 2000).

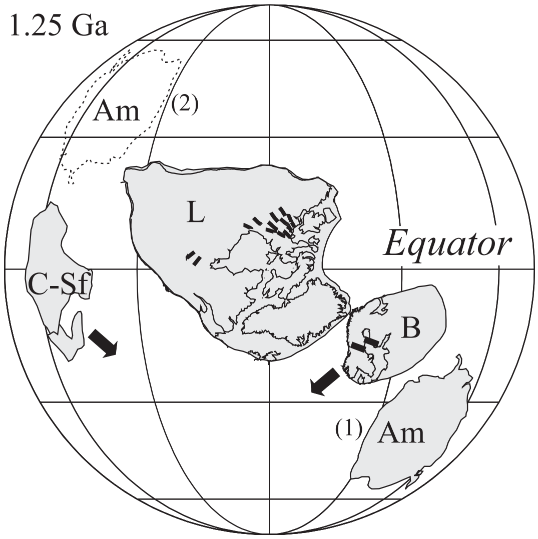


Fig. 11. The reconstruction of continents at 1.25 Ga. Data available from Laurentia, Baltica, Congo/São Francisco and Amazonia. The ca. 1.25 Ga dyke swarms in Laurentia (Mackenzie) and Baltica (Jotnian) are shown as black sticks. The thick arrows shows the drift direction of Congo/São Francisco and Baltica with respect to their position in the next configuration at 1.15 Ga (Fig. 13). For explanation, see Fig. 4.

The 1.25-Ga assembly of Baltica–Laurentia is supported by geological data. We have previously (Buchan et al., 2000; Pesonen and Mertanen, 2002) shown that the 1.71- to 1.65-Ga-old Labradorian–Gothian belts will be aligned in this configuration. The rift-related post-Jotnian dykes and sills in central Baltica are probably associated with the huge Mackenzie rifting and mafic dyke event in NE Laurentia. Ernst and Buchan (2001) have proposed that the fan-shaped Mackenzie dyke swarm could be a signature of a mantle plume occurring at 1.25 Ga in NW Laurentia. Elming and Mattson (2001) have shown that the Central Scandinavian dolerite activity is more widespread in Baltica than previously thought extending now into northwestern Sweden, towards Greenland (Figs. 11 and 12). The trends of dykes in Baltica (Jotnian dykes; Bylund and Pesonen, 1987) and Laurentia (Mackenzie dykes; Ernst and Buchan, 2001) become contiguous in this reconstruction (Fig. 11), although the former is distinctly less abundant than the latter (in Baltica the dolerites appear mainly as sills).

Elming and Mattson (2001) have shown that the lineation of the anisotropy of susceptibility (AMS), which is a measure of the magma flow direction, of the sills in Sweden and those in NE Greenland (the Midsommersö sill and Zig-Zag basalts; Marcussen and Abrahamsen, 1983) have different orientations in present-day configuration but becomes parallel when stored to the 1.25-Ga configuration (Fig. 12). These sills in Baltica and Laurentia have tholeiitic compositions and intra-continental origin, thus supporting a joint Laurentia–Baltica assembly at that time. The tensional regime reflected by the sill intrusions indicates that rifting between Laurentia and Baltica probably began at 1.25 Ga. This rifting is envisaged in several rift-related grabens in these continents, e.g., the Satakunta-Ulvö graben with red sandstones and mafic dyke intrusions in Finland and Sweden, the coeval Sibley red bed sequence and the

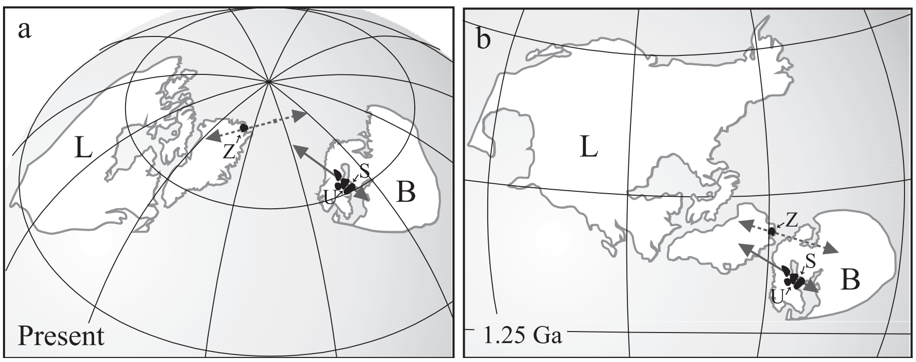


Fig. 12. The arrows show the axes of directions of the maximum susceptibility (AMS) in the 1.25-Ga-old diabase sills and basalts from Greenland and Baltica, in (a) present-day coordinates and (b) when restored to the 1.25-Ga reconstruction of Fig. 11. The symbols denote: Z, Zig-Zag basalts (Greenland); S, Satakunta-Ulvö sills (Baltica) (see Elming and Mattson, 2001).

Mackenzie-Sudbury dyke swarm in Canada. We propose that this rifting is a signature of the breakup of the Hudsonland landmass at 1.25 Ga and may have been enhanced by a mantle plume in the center of Hudsonland (Ernst and Buchan, 2001). In this respect, it is worthwhile to note that the 1.25-Ga dyke activity is a global one and is well documented in several continents (e.g., Kibaran intrusives in Congo, Western Gardar dykes in South Greenland, Midsommersö dolerites in North Greenland, Mount Isa dykes in Australia, Westfold Hills dykes in Antarctica, Wutai-Talhang dykes in S. China and the Gnowangerup dykes in India; see Ernst et al., 1996; Rogers and Santosh, 2002). Unfortunately, palaeomagnetic data from dykes are only available from Laurentia–Baltica to see if the dykes support the mantle plume model.

7.9. Reconstruction at 1.15 Ga

Only three continents, Laurentia, Australia and Kalahari yielded reliable data for the 1.15-Ga reconstruction (Fig. 13, Table 1). The rapid southward drift of Laurentia is defined by the sequence of 1.14–1.00 Ga palaeomagnetic data (e.g., Halls and Pesonen, 1982; Buchan et al., 2001; Weil et al., 1998; Powell and Li, 1994; Meert and Torsvik, 2003). We position Australia closer to the AUSWUS model of Karlström et al. (2001) for this time period; however, recent palaeomagnetic data from the Bangemall Basin in western Australia suggest that neither AUSWUS nor SWEAT may be valid for this time period (Wingate et al., 2002).

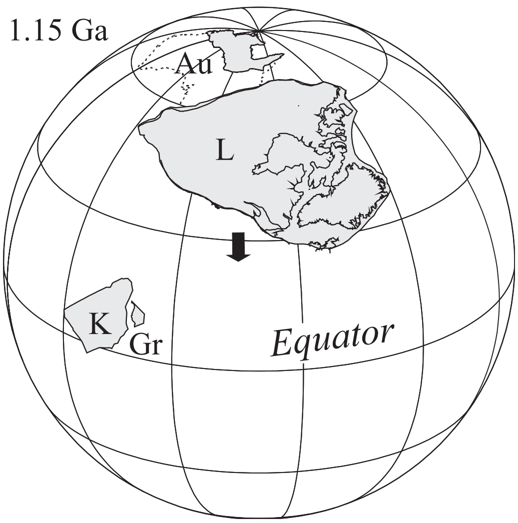


Fig. 13. The reconstruction of continents at 1.15 Ga. Data available from Laurentia, Australia, Kalahari and Grunehogna. The arrow indicates the onset of the rapid southward movement of Laurentia during the Keweenawan times, just before the assembly of continents into Rodinia. For explanation, see Fig. 4.

7.10. Reconstruction at 1.10 Ga—the onset of Rodinia

After 1.25 Ga, Baltica separated from Laurentia and started its journey to southern hemisphere. This separation marks the opening of the hypothetical Congo Sea between Laurentia and Baltica (e.g., Pesonen et al., 2001a,b; Fig. 14). The southerly drift of Baltica between 1.25 and 1.10 Ga is associated with a ca. 80° clockwise rotation and ca. 15° southward movement. This rotation, suggested by Poorter (1975), Patchett and Bylund (1977) and Pesonen and Neuvonen (1981), is based on palaeomagnetic data from the Sveconorwegian Province. The agreement of dyke poles from Northern Baltica (Laanila-Ristijärvi dykes, and the Kautokeino-Karasjokk dykes; see Mertanen et al., 1996) with the poles from the Sveconorwegian terrane of SW Baltica is in contrast with Romer (1996) who interprets the Sveconorwegian APW track by local tectonism in the Sveconorwegian province. Moreover, the shape of the Grenvillian and Sveconorwegian APW tracks (see e.g., Powell et al., 2001) are strikingly similar, which is unlikely to be the case if local block movements have taken place.

Figs. 11 and 14 show that, unlike Baltica, the orientation of Laurentia remains constant from 1.25 to 1.10 Ga, with only latitudinal drift taking place, supporting the independent drift of Laurentia and Baltica during 1.25–1.10 Ga. Congo/São Francisco also began to drift to southern hemisphere at ca. 1.25 Ga, (Fig. 11), while Amazonia started to move northwest towards Laurentia (Fig. 11).

At about 1.10 Ga, several continents amalgamated together (Fig. 14). This time records the "first phase" of Rodinia collisions and occur at 1.10 Ga, constrained by palaeomagnetic data from Laurentia, Baltica, Congo/São Francisco, Kalahari-Grunehogna, Coats Land and Australia. Although no reliable 1.10- to 1.00-Ga-old data from Amazonia are yet available, we have tentatively placed Amazonia along the southern margin of Laurentia in Hoffman's (1991)

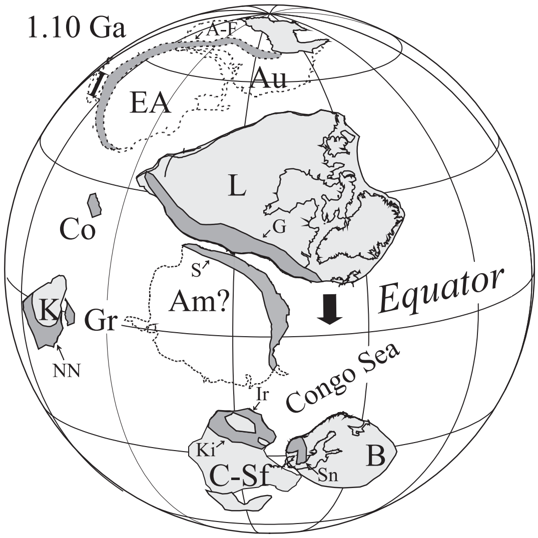


Fig. 14. The reconstruction of continents at 1.10 Ga denoting the assembly time of Rodinia. Data are available from Laurentia, Baltica, Congo/São Francisco, Australia, Kalahari, Grunehogna and Coats Land. The East Antarctica and India are plotted in their Gondwana reconstruction. Amazonia is plotted as dashed lines since no palaeomagnetic data are available. The Grenvillian age collision belts formed during the assembly of Rodinia are shown with dark shading and they are: G, Grenville belt (Laurentia); Sn, Sveconorwegian belt (Baltica); Ki, Kibaran belt and Ir, Irumide belt (both in Congo); S, Sunsas belt (Amazonia); NN, Natal-Namaqua belt (Kalahari) and A-F, Albany-Fraser belt (Australia). For explanation, see Fig. 4.

Rodinia configuration. Recent palaeomagnetic data from Amazonia during 1.60–1.00 Ga (D'Agrella-Filho et al., 2001a,b) support this interpretation although the new data of Tohver et al. (2002) would require significant shear motion along the Laurentian margin to reach the Hoffman configuration. We have maintained the position of Australia in a position intermediate between the SWEAT and AUSWUS configurations and note that neither may be accurate (see also Meert and Torsvik, 2003).

Fig. 14 depicts several continent–continent collisions at 1.10 Ga. The Congo/São Francisco craton collides with Baltica causing the "early" Grenvillian–Sveconorwegian orogenic belts in these continents. This is a new tectonic model for the assembly of Rodinia since previously Congo/São Francisco craton has been thought to collide with Laurentia or with Amazonia (Weil et al., 1998; Hoffman, 1991; Dalziel, 1997; see also Meert and Torsvik, 2003). For the Congo/São Francisco craton, possible candidates for the collisional belt include either the Kibaran (Ki) or the Irumide (Ir) belts surrounding the Congo–Tanzania craton (Fig. 14; e.g., Hoffman, 1991; Kröner et al., 1997; Jacobs et al., 1998). In our model, at about the same time when Baltica collides with Congo/São Francisco, Laurentia collides with Amazonia producing the early Grenvillian belt (G) in southern Laurentia and the coeval Sunsas-Aguapei (S) belt in Amazonia (Fig. 14). We note that all these "early" Grenvillian belts are marginal to the preceeding 1.83–1.40 Ga belts in Laurentia, Baltica and Amazonia (Fig. 8). A slightly different scenario to describe the continent–continent collisions and the formation of Rodinia is presented by Pisarevsky et al. (2003).

South China and North China were not included in our Fig. 12 since no palaeomagntic data are available. The large East Gondwana landmass, comprising Australia, East Antarctica and India, was located to the north of the western coast of Laurentia (Fig. 14) with Australia at high northern latitudes. Palaeomagnetic data are available only from Australia (Table 1). The East Antarctic craton and India are plotted together with Australia in their Gondwana configuration since no palaeomagnetic data are available from these continents. Meert et al. (1995) and Meert (2003) argue that East Gondwanaland was not combined until late Neoproterozoic or even early Cambrian (see also Fitzsimons, 2000b; Boger et al., 2001; Powell and Pisarevsky, 2002). If this is true, then these blocks should be treated as independent blocks at 1.10 Ga rather than as we present them here (see also Meert and Torsvik, 2003). Further palaeomagnetic and age data are needed to solve this problem.

Several other problems remain to be solved in this Rodinia model. First, unlike the majority of the orogenic belts, which are inboard in Rodinia (e.g., the Sunsas-Aguapei belt in Amazonia, Grenville belt in Laurentia, the Sceconorwegian belt in Baltica and the Albany-Fraser belt in Australia), the Musgrave belt crosses Australia in its centre, which may imply collisions between the Gawler and West Australian cratons of Australia at ca. 1.20 Ga (e.g. Dawson et al., 2003), which caused this intra-continent orogenic belt. Also, the coastal Namaqua-Natal belt (NN, Fig. 14) in Kalahari is facing oceanward in this Rodinia model

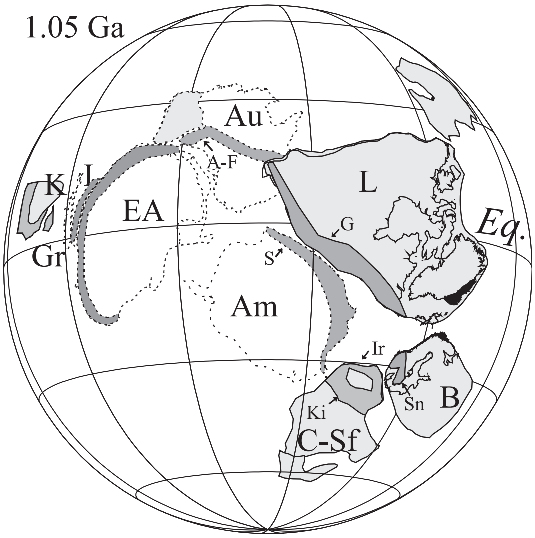


Fig. 15. The reconstruction of continents at 1.05 Ga showing the Rodinia configuration. Data available from Laurentia, Baltica, Congo/São Francisco, Siberia and Kalahari. The other continents are plotted in their Gondwana reconstruction. Grunehogna is treated together with Kalahari as explained in text and in Table 1. Siberia is now located close to Laurentia and Australia and in inverted position relative to its position in the 1.50 Ga configuration (Fig. 10). For explanation, see Fig. 4.

and not inboard (Powell et al., 2001; Meert and Torsvik, 2003). This position of Kalahari is well constrained by matching the 1.10- to 1.00-Ga APWP tracks of Laurentia (the Keweenawan track) and the coeval track of Kalahari (e.g., Weil et al., 1998; Buchan et al., 2001; Powell et al., 2001); however, the exact segment of the path is subject to some controversy (see Meert and Torsvik, 2003). The outboard orientation of NN may imply that it is unlikely to be explained by collisions of Kalahari with Amazonia or with Laurentia, as has been suggested (Dalziel et al., 2000). Our palaeomagnetic reconstruction may indicate that Kalahari was probably colliding with India or with those microcontinents of East Antarctica (Rayner, Prydz Bay, Maud), which have Grenvillian-age belts. Further palaeomagnetic data of these microcontinents are needed to better constrain their relative position in the 1.10-Ga Rodinia configuration and their possible association with Kalahari (Fitzsimons, 2000a; Pisarevsky et al., 2003; Meert and Torsvik, 2003).

7.11. Reconstructions at 1.05–1.0 Ga

Figs. 15 and 16 show the configuration of the continents during 1.05–1.00 Ga, respectively. The 1.05-Ga time bin marks the final assembly of Rodinia with possible minor adjustments taking place during 1.05–1.0 Ga. Data are available from Laurentia, Baltica, Kalahari, Congo/São Francisco, Australia (only for 1.05 Ga) and Siberia. The Congo Sea began to close sometime after 1.10 Ga by the movement of Laurentia/Amazonia landmass towards Congo/São Francisco–Baltica landmass (e.g., Pesonen et al., 2001a). These landmasses aggregated at ca. 1.05 Ga producing the "late" Grenvillian collisions (Fig. 15). This scenario predicts that late Grenvillian events should have occurred in NW Baltica, in Barentia (Svalbard) and in E Greenland due to the collision of NE Laurentia with Baltica. Recent U–Pb age data from East Geenland and from Svalbard reveal "late" Grenvillian ages, which in general support the model of Fig. 15, although these "late" Grenvillian ages may be somewhat younger (Peucat et al., 1989; Watt and Thrane, 2001; Henriksen et al., 2000; Kalsbeek et al., 2000). Similar late Grenvillian events should also be observed in NW Congo and NW Amazonia, since the model predicts that they collide at 1.05 Ga in their

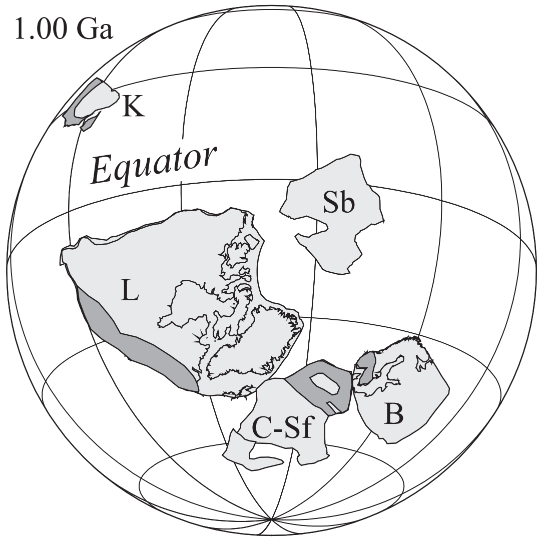


Fig. 16. The reconstruction of continents at 1.00 Ga. Data available from Laurentia, Baltica, Congo/Sã o Francisco, Kalahari and Siberia. See text for discussion. For explanation, see Fig. 4.

amalgamation into Rodinia. Although no palaeomagnetic data are available from the East Gondwanaland cratons, geologically many of them have suffered multiple Grenvillian events during 1.10–0.90 Ga (Clark et al., 2000; Li et al., 2001; but see also Hartz and Torsvik, 2002). The known major Grenvillian belt in SW Laurentia may continue from Laurentia across central Australia (Albany–Fraser belt, Cape Smith Belt and the Musgrave belt) and then around East Antarctica to Kalahari (NN belt) and then to India (Eastern Ghats).

Fig. 15 shows that Australia is further south and close to the AUSMEX fit of Wingate et al. (2002) at 1.05 Ga (see also Fitzsimmons, 2002). This could signify that our previous reconstructions (Figs. 8–10) were in error or that the assembly of Rodinia commenced with significant shear motion along the present-day coast of western Laurentia.

The position of Siberia in our Rodinia configuration is controversial. The position and orientation of Siberia at ca. 1.05 Ga (Fig. 15) is very different from that at 1.50 Ga (Fig. 10) indicating that at sometimes during 1.50–1.10 Ga Siberia broke away from Laurentia. The position of Siberia is also ~90° counterclockwise from the reconstruction of Sears and Price (2000). Siberia can be shifted closer to Australia along the western margin of Laurentia, which would make an Australia–Siberia–Laurentia connection possible. Other people places Siberia adjacent to the northern margin of Laurentia (e.g. Hoffman, 1991; Condie and Rosen, 1994; Pelechaty, 1996; Frost et al., 1998; Rainbird et al., 1998) but in a variety of orientations (see Pisarevsky and Natapov, 2003; Pisarevsky et al., 2003). We chose not to include Siberia as part of Rodinia during this time interval since the geological interpretations are controversial (e.g., Condie and Rosen, 1994; Rainbird et al., 1998) and since Siberia still lacks firm evidence of Grenvillian ages (Pisarevsky and Natapov, 2003).

Fig. 16 shows the Rodinia configuration at ca. 1.00 Ga based on palaeomagnetic data from Laurentia, Congo/São Francisco, Baltica, Kalahari and Siberia (Table 1). It is possible that some minor modifications within Rodinia took place during 1.05–1.0 Ga period, but considering the uncertainties in the pole positions and their ages, we interpret the 1.00 Ga assembly to be similar to that at 1.05 Ga, thus indicating that Rodinia was fully amalgamated at ca. 1.05 Ga. However, we note here that the positions of the East Gondwana blocks in Figs. 15 and 16 lack still reliable data and therefore this conclusion must be verified with palaeomagnetic data from these blocks.

8. Testing the reconstructions

8.1. Comparisons of drift curves and drift rates

One way to test the validity of the palaeomagnetically made reconstructions and proposed supercontinent models is to compare the drift patterns and drift rates of the member continents. If a supercontinent model is valid, the drift rates of the participating

Table 2
Drift rates of four cratons

Landmass	Period (Ga)	Laurentia (cm year^{-1})	Baltica (cm year^{-1})	Amazonia (cm year^{-1})	Congo-São-Fr. (cm year^{-1})
Break up of Kenorland	2.45–2.00	+1.1	–	–	–
	2.00–1.88	+1.2	–		–
	1.88–1.83	+0.1	+1.3	+0.02	–
Hudsonland	1.83–1.77	−3.8	−1.2		–
	1.77–1.65	+2.5	−0.9	+1.7	–
	1.65–1.50	−3.2	+0.8		–
	1.50–1.25	−0.04	−1.3	−1.3	–
	1.25–1.15	+5.2	–	–	–
	1.15–1.10	−4.1	–	–	–
Rodinia	1.10–1.05	−6.5	−0.5	–	−2.9
	1.05–1.00	−6.2	−2.1	–	−0.8

Drift rate = latitudinal drift rate. +(−) denotes drift from North to South (South to North). − indicates that no data are available. For Amazonia, the time periods are 2.00–1.83, 1.83–1.65 and 1.65–1.25 Ga (see also Fig. 17).

continents should be similar during the lifetime of the assembly. Due to the paucity of data, we have attempted this only for Laurentia, Baltica, Amazonia and Congo/São Francisco during 2.45–1.00 Ga. Fig. 17 portrays the temporal drift of these continents as interpreted in this paper. During the 1.83- to 1.25-Ga interval, the drift patterns of Laurentia, Amazonia and Baltica show some similar general characteristics. In spite of the many caveats noted throughout this paper, the drift patterns are not totally at odds with the notion of their inclusion in one or more supercontinents.

We also note that the calculated minimum drift rates for these continents (Table 2) during the 2.45–1.0 Ga interval are generally less than 3 cm year^{-1} and comparable to Cenozoic continental drift rates. The one exception is during the Keweenawan interval where rates may exceed 6 cm year^{-1} (Table 2). These higher velocities during the Keweenawan–Grenvillian interval have been noted by other authors (e.g., Powell et al., 2001; Meert and Torsvik, 2003). There are a number of possible explanations for these enhanced drift rates including errors introduced by persistent nondipolar fields (e.g., Pesonen and Nevanlinna, 1981; Kent and Smethurst, 1998; Van der Voo and Torsvik, 2001; but see also Ernst and Buchan, 1993; Gallet and Pavlov, 1996); true polar wander (Evans, 1998; Meert and Torsvik, 2003) or enhanced mantle plume activity (Meert and Tamrat, 2003).

9. Conclusions

(1) Palaeomagnetic data suggest that continents were located at low to intermediate latitudes for much of the period from 2.45 to 1.00 Ga. Whether this reflects a real bias, or a fundamental problem with the axial geomagnetic dipole hypothesis, is debatable. Sedimentological latitudinal indicators are generally consistent with this concept with the exception of the Early Proterozoic period where low-latitude continental glaciations have been noted.

(2) The data indicate the possibly three large landmasses existed during the Proterozoic. The configurations of Kenorland, Hudsonland and Rodinia depart from each other and also from the Pangaea 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. The oldest, a Neoarchaean Kenorland, broke up during protracted (or episodic) riftings ca. 2.45–2.15 Ga ago as manifested by mafic dyke activity with possibly mantle plume origin and developments of rift-related sedimentary basins.

(3) The Early Proterozoic Hudsonland was assembled at ca. 1.83–1.77 Ga. The configuration of Hudsonland is only tentatively known but comprises of Laurentia, Baltica, Amazonia, Australia, Siberia and North China. It is suggested that the core of the Hudsonland is the laterally contiguous Laurentia–Baltica–Amazonia landmass. Australia was probably part of Hudsonland and in juxtaposition with the western margin of Laurentia as suggested by Karlström et al. (2001). Palaeomagnetic data show that the configuration of Hudsonland differs from the proposed supercontinent Columbia. A characteristic feature of Hudsonland is a long-lasting accretion tectonism with new juvenile material added to its convergent margin. These accretions resulted to progressively younging, oceanward stepping orogenic belts in Laurentia, Baltica and Amazonia. The palaeomagnetic data at 1.65 Ga are, however, in contrast with this geological model, probably due to problems in the ages of the poles. The breakup of Hudsonland may be related to the extensional rapakivi–anorthosite magmatism at ca. 1.5–1.3 Ga ago as seen in Amazonia and Laurentia but more probably to a global wide rifting at 1.25 Ga, as manifested by mafic dykes, sedimentary basins, and graben formations.

(4) The Neoproterozoic supercontinent Rodinia began to assemble at 1.10 Ga and was fully amalgamated at ca. 1.05–1.00 Ga. It consists of most of the continents and is characterized by multiple Grenvillian continent–continent collisions. These belts are generally located inboard of the supercontinental boundaries with the exception of the Namaqua-Natal Belt (Kalahari craton) and the Musgrave Belt of Australia. A new model for these orogenic belts is proposed which involves multiple Grenvillian age collisions. The early phase of Grenvillian tectonism (1.10 Ga) may be related to the collision of the Congo/São Francisco with Baltica, and Amazonia with Laurentia. Subsequently, these combined continents assemble into their Rodinia configuration during a second, slightly younger set of collisions (1.05–1.00 Ga).

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