Available online at www.sciencedirect.com
SCIENCE DIRECT®

Tectonophysics 375 (2003) 261–288

TECTONOPHYSICS

www.elsevier.com/locate/tecto

The making and unmaking of a supercontinent: Rodinia revisited

Joseph G. Meert[a,*], Trond H. Torsvik[b]

[a] Department of Geological Sciences, University of Florida, 241 Williamson Hall, PO Box 11210 Gainesville, FL 32611, USA
[b] Academy of Sciences (VISTA), c/o Geodynamics Center, Geological Survey of Norway, Leif Eirikssons vei 39, Trondheim 7491, Norway

Received 11 April 2002; received in revised form 7 January 2003; accepted 5 June 2003

Abstract

During the Neoproterozoic, a supercontinent commonly referred to as Rodinia, supposedly formed at ca. 1100 Ma and broke apart at around 800–700 Ma. However, continental fits (e.g., Laurentia vs. Australia–Antarctica, Greater India vs. Australia–Antarctica, Amazonian craton [AC] vs. Laurentia, etc.) and the timing of break-up as postulated in a number of influential papers in the early–mid-1990s are at odds with palaeomagnetic data. The new data necessitate an entirely different fit of East Gondwana elements and western Gondwana and call into question the validity of SWEAT, AUSWUS models and other variants. At the same time, the geologic record indicates that Neoproterozoic and early Paleozoic rift margins surrounded Laurentia, while similar-aged collisional belts dissected Gondwana. Collectively, these geologic observations indicate the breakup of one supercontinent followed rapidly by the assembly of another smaller supercontinent (Gondwana). At issue, and what we outline in this paper, is the difficulty in determining the exact geometry of the earlier supercontinent. We discuss the various models that have been proposed and highlight key areas of contention. These include the relationships between the various 'external' Rodinian cratons to Laurentia (e.g., Baltica, Siberia and Amazonia), the notion of true polar wander (TPW), the lack of reliable paleomagnetic data and the enigmatic interpretations of the geologic data. Thus, we acknowledge the existence of a Rodinia supercontinent, but we can place only loose constraints on its exact disposition at any point in time.

Keywords: Rodinia; Paleomagnetism; Gondwana; Supercontinent; True polar wander

1. Introduction

The notion of a late Proterozoic supercontinent was postulated in the 1970s as geologists noted the existence of a number of 1100–1000 Ma 'mobile belts' (Dewey and Burke, 1973). J.D.A. Piper postulated, early on, that the available paleomagnetic data from all the continents could be fitted to a common apparent polar wander path (APWP). This led him to suggest that a supercontinent composed of most of the continental crust remained in a quasi-rigid configuration throughout the bulk of Precambrian time (Piper, 1976, 2000). Paleomagnetic poles published in the late 1970s and early 1980s generally had poor age control and allowed sufficient flexibility to fit almost any pole on the rather tortuous APWP proposed by Piper (see review in Van der Voo and Meert, 1991). Subsequent thoughts about Precambrian supercontinents by Bond et al. (1984)

---

* Corresponding author. Tel.: +1-352-846-2414; fax: +1-352-392-9294.

E-mail address: jmeert@geology.ufl.edu (J.G. Meert).

0040-1951/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0040-1951(03)00342-1

relied on evidence from passive margin sequences around the globe. They argued that the global presence of these margins heralded the breakup of a supercontinent at the end of the Proterozoic. In the early 1990s, Dalziel (1991), Moores (1991) and Hoffman (1991)—following the suggestion of McMenamin and McMenamin (1990)—adopted the name Rodinia for this Meso–Neoproterozoic supercontinent (see also Meert and Powell, 2001). The geometry of the Rodinia supercontinent has remained flexible, but generally most models have sought to develop the configuration around Grenvillian–Sveconorwegian–Kibaran aged metamorphic belts (~ 1350–1000 Ma) and link geologic provinces across cratonic margins (Fig. 1). In the 'archetypal' Rodinia reconstructions (e.g., Dalziel, 1997), Laurentia formed the core of the supercontinent with East Gondwana situated along its present-day western margin (SWEAT, Southwest U.S.–East Antarctic), and with Amazonia and Baltica positioned along its present-day eastern margin (Fig. 1).

Early paleomagnetic tests of the Rodinia configuration were broadly supportive of the idea (e.g., Powell et al., 1993; Torsvik et al., 1996), but the quality of the available data were insufficient to provide any rigorous test of the Rodinia paleogeography. In part, this was due to the fact that the older paleomagnetic studies on Proterozoic rocks were not tied to a specific radiometric age or were not completely analyzed for the possibility of younger over-

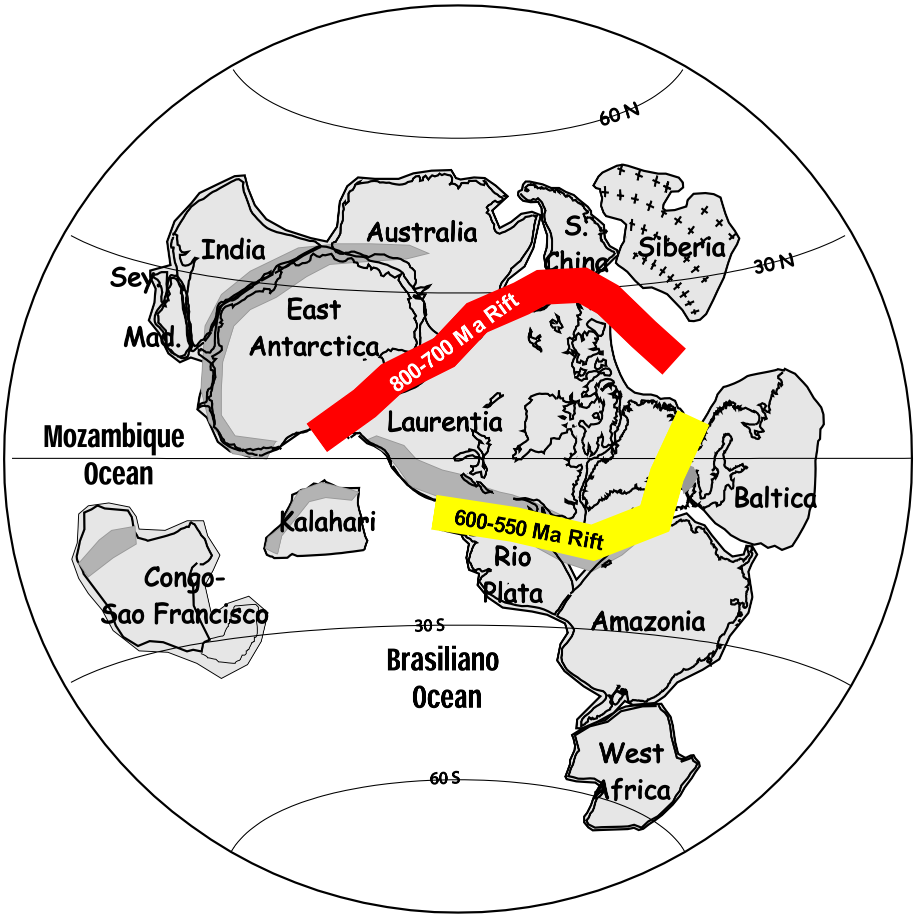


Fig. 1. The 'traditional' model of Rodinia adopted from Dalziel (1997) and Torsvik et al. (1996). The model posits two rifting events, one along the present-day western margin of Laurentia sometime between 800 and 700 Ma, and a second along the present-day eastern margin of Laurentia between 600 and 550 Ma.

printing. Of more recent vintage are paleomagnetic studies that are conducted in conjunction with radiometric studies in order to develop temporally and spatially defined APWPs. Nevertheless, current Proterozoic paleomagnetic studies are sufficient only to test paleogeographic relationships between two or three continents at discrete (and widely separated) intervals (Meert and Powell, 2001).

Despite a lack of paleomagnetic evidence in favour of the Rodinia supercontinent, geologic links between the various cratonic nuclei were held forth in support of widely varying reconstructions (Young, 1995; Pelechaty, 1996; Dalziel, 1997; Rainbird et al., 1998; Karlstrom et al., 1999; Sears and Price, 2000; Dalziel et al., 2000). Our review paper, a tribute to the pioneering work of Chris Powell, focuses on key intervals during the formation and breakup of the supercontinent and highlights several controversial aspects of those reconstructions. We wish to note, at the outset, that each reconstruction discussed below is based on a particular set of paleomagnetic poles and polarity options. At times, there are not so subtle differences between our choice of poles and those chosen by earlier authors. We do not have the space to develop a pole-by-pole comparison in this review paper and therefore our goal is to generate a set of paleogeographic maps for critical intervals of Neoproterozoic history and show how they differ from previous interpretations. At the same time, we recognize that the limited dataset creates a host of problems for previous interpretations. Because of the limitations of the paleomagnetic data, we highlight these problems for further consideration rather than attempting to rescue any particular reconstruction.

2. Paleomagnetic constraints on the Neoproterozoic supercontinent

The interval from ~ 1100 to 900 Ma marks a geologically important period during the formation of the Neoproterozoic supercontinent. The Grenvillian, Sveonorwegian and slightly older Kibaran orogenic belts are thought to mark the sutures between the various elements of the Rodinian supercontinent (see Dalziel, 1997; Meert and Powell, 2001; Powell et al., 2001; Pesonen et al., this volume). Meert and Powell (2001) noted that paleomagnetic data for this time period are lacking for many of the cratonic elements thought to comprise Rodinia. Therefore, any reconstruction developed for this time period must be extremely fluid as new data may create significant changes in the overall distribution of cratonic elements surrounding Laurentia. At the same time, any reconstruction for this period must also fit the paleogeographic constraints imposed by younger (pre-breakup) paleomagnetic data and they must be geologically reasonable. Table 1 lists available paleomagnetic results from the cratonic elements comprising Rodinia and, where possible, these poles are fitted to an APWP. All poles in Table 1 are calculated on the assumption that the time-averaged geomagnetic field is that of a geocentric axial dipole (GAD) field. Some recent studies cast doubts on this fundamental assumption (e.g., Kent and Smethurst, 1998; Van der Voo and Torsvik, 2001; Torsvik et al., 2001a), and this raises some concern about the detailed resolution power in palaeomagnetic reconstructions. For example, zonal non-dipole octupole contributions of 10–20% will introduce latitudinal discrepancies on the order of 750–1500 km at intermediate latitudes.

2.1. 1100–900 Ma: Laurentia and Baltica

The paleomagnetic database for Laurentia (Fig. 2a) and Baltica (e.g., Fig. 2b and c) during this interval has been reviewed by a number of different authors (see Weil et al., 1998; Walderhaug et al., 1999; Buchan et al., 2001; Powell et al., 2001). For a complete discussion of the individual poles and the shape/direction of the Laurentian apparent polar wander path please refer to the above-mentioned articles. Weil et al. (1998) and Walderhaug et al. (1999) discussed the enigma of clockwise, anticlockwise and no loops for the Grenvillian poles in North America and Baltica. Our path differs from that of Weil et al. (1998) because we draw the path through the ‘eastern’ group of Keewanawan paleomagnetic poles rather than through the ‘western’ group (see Fig. 2a). Hartz and Torsvik (2002) discuss the relationship of younger Baltica poles with Laurentia (~ 750 Ma) and suggest that Baltica might be inverted with respect to the more ‘traditional’ Rodinia fits (e.g., Fig. 1).

Fig. 2b shows the available paleomagnetic data from Baltica (assumed north poles) for the interval

Table 1
Selected paleomagnetic poles

Pole name	Symbol	Age (Ma)	Pole latitude	Pole longitude	A_{95} or dp/dm*	Q-value**	Reference
Laurentia							
Abitibi dikes	1	1141 ± 2	44°N	211°E	15°/12°	6	Ernst and Buchan, 1993
Seabrook Lake carbonatite	2	1113 ± 36	46°N	180°E	11°	6	Symons, 1992
Mean Logan sills	3	1109 ± 4/2	49°N	220°E	3°	5	Halls and Pesonen, 1982
Coldwell complex[a]	4	1108 ± 1	49°N	200°E	16.5	6	Lewchuk and Symons, 1990a
Keewanawan dikes N&R[b]	5	1102 ± 5	44°N	197°E	11°/11°	5	Green et al., 1987
Copper Harbor lavas	6	~ 1100	35°N	176°E	3°/5°	5	Halls and Palmer, 1981
Mean Logan dikes	7	~ 1100	35°N	181°E	10°	6	Halls and Pesonen, 1982
Upper Osler volcanics	8	1098 ± 3	34°N	178°E	10°	4	Halls, 1974
Portage Lake lavas	9	1095 ± 1	27°N	181°E	3°/2°	4	Halls and Pesonen, 1982
Powder mill reverse	10	< 1095	39°N	218°E	5°/6°	4	Palmer and Halls, 1986
Lake shore traps	11	1087 ± 2	22°N	181°E	7°/7°	4	Diehl and Haig, 1994
Clay-Howells carbonatite	12	1075 ± 15	27°N	179°E	7°	5	Lewchuk and Symons, 1990b
Nonesuch shale[c]	13	< LST	10°N	177°E	3°/6°	5	Henry et al., 1977
Freda sandstone[d]	14	< NS	1°N	180°E	1°/3°	4	Henry et al., 1977
Jacobsville sandstone mean[e]	15	< FS >1000	9°S	183°E	3°/6°	5	Roy and Robertson, 1978
K1 Fond du Lac sandstones	NU	~ 1020	16°N	160°E	4°	3	Watts, 1981
Eileen sandstones	NU	~ 1020	20°N	156°E	10°	3	Watts, 1981
Middle River sandstones	NU	~ 1020	25°N	148°E	9°	3	Watts, 1981
Haliburton intrusions	16	980 ± 10	36°S	143°E	6°	4	Hyodo and Dunlop, 1993
Nippissing diabase remag	17	975	27°S	141°E	8°	3	Hyodo et al., 1986
Granodiorites reset	18	960	37°S	150°E	8°	2	Hyodo et al., 1986
Gatineau Hills metamorphics	19	~ 900	32°S	155°E	5°	3	Irving et al., 1972
Little Dal (A + B)[f]	20	>778	9°N	320°E***	11°	6	Park, 1981a,b
Top Little Dal[f]	21	~ 778	24°S	339°E***	11°	3	Morris and Aitken, 1982
Tsezotene Fm[f]	22	>778	12°S	326°E***	8°	4	Park and Aitken, 1986
Tsezotene sills	23	778 ± 2	2°N	338°E***	5°	4	Park, 1981a,b
Franklin dikes	24	723 ± 3	9°S	332°E***	5°	7	Christie and Fahrig, 1983
Brock Inlier sills	25	723 ± 3	2°N	345°E***	16°	4	Park, 1981a,b
Long Range dikes “A”[g]	NU	615 ± 2	11°N	344°E	18°	3	Murthy et al., 1992
Long Range dikes “B”[g]	NU	615 ± 2	69°N	350°E	15°	3	Murthy et al., 1992
Callander complex	26	575 ± 5	46°N	301°E	6°/6°	6	Symons and Chiasson, 1991
Catoctin Basalts-A	27	564 ± 9	42°N	297°E	9°	6	Meert et al., 1994a,b
Sept-Îles Complex B[h]	28	564 ± 4	44°N	315°E	5°	5	Tanczyk et al., 1987
Sept-Îles Complex A[h]	NU	564 ± 4	20°S	321°E	8°	4	Tanczyk et al., 1987
Tapeats sandstone	29	~ 508	5°S	338°E	3°	5	Elston and Bressler, 1977
Late Cambrian mean	30	495	3°S	344°E	12°	7	Meert, 1999
Kalahari/Dronning Maud Land							
Premier Kimberlites	32	1165 ± 10	41°N	55°E	7°	4	Powell et al., 2001
Richterflya[i]	33	1130 ± 12	61°N	29°E	4°/4°	3	Jones et al., 1999
Coats Land Nunataks[i]	34	1112 ± 4	72°N	117°E	7°	4	Gose et al., 1997
Umkondo Igneous Province	35	1105 ± 2	66°N	37°E	3°/3°	4	Hargraves et al., 1994; Powell et al., 2001

Table 1 (*continued*)

Pole name	Symbol	Age (Ma)	Pole latitude	Pole longitude	A_{95} or dp/dm*	*Q*-value**	Reference
Kalahari/Dronning Maud Land							
Post-Waterberg diabase	36	1091 ± 15	65°N	51°E	8°	5	Jones and McElhinny, 1966
Kalkpunt Fm[f]	37	~ 1065	57°N	3°E	7°	3	Jones and McElhinny, 1966
Central Namaqua metamorphics	38	1015 ± 15	8°N	330°E	10°/10°	3	Onstott et al., 1986
Congo–Sao Francisco/Adjacent Pan–African Belts and Arabian Shield							
Post-Kibaran intrusives	39a	1236 ± 24	17°S	113°E	7°	4	Meert et al., 1994a,b
Olivenca Dikes-R (SFC)	39b	1078 ± 18	10°S	100°E	6°	4	D'Agrella-Filho et al., 1990
Itaju do Colonia (SFC)	40	~ 1050	8°N	111°E	6°	4	D'Agrella-Filho et al., 1990
Olivenca Dikes-N (SFC)	41	~ 1050	16°N	107°E	5°	4	D'Agrella-Filho et al., 1990
Ilheus dikes (SFC)	42	1012 ± 24	30°N	100°E	3°	4	D'Agrella-Filho et al., 1990
Nyabikere massif	NU	~ 935	43°N	137°E	14°	2	Meert et al., 1994a,b
Suakin gabbros (CC)	43	841 ± 4	25°N	134°E	8°	4	Reischmann et al., 1992
Gagwe lavas (CC)	44	795 ± 7	25°S	273°E	10°	5	Meert et al., 1995
Mbozi complex (CC)	45	755 ± 25	46°N	325°E	9°	6	Meert et al., 1995
Dokhan volcanics (ANS)[j]	46	593 ± 13, 602 ± 9	43°S	36.2°E	10°	4	Davies et al., 1980; Nairn et al., 1987
Sinyai dolerite (PA)	47	547 ± 4	28°S	319°E	5°	5	Meert and Van der Voo, 1996
Mirbat sandstone (ANS)	48	~ 550	32°S	334°E	7°	3	Kempf et al., 2000
Ntonya Ring structure (PA)	49	522 ± 3	28°N	355°E	2°	5	Briden et al., 1993
Mean Sao Francisco Pole (SFC)[k]	50	~ 520	19°N	330°E	13°	3	D'Agrella-Filho et al., 2000
Amazonian Craton							
Nova Floresta	51	1199 ± 5	25°N	165°E	6°	5	Tohver et al., 2002
Australia							
Mundine dikes	52	755 ± 3	45°N	135°E	4°	6	Wingate and Giddings, 2000
Angepena Fm[l]	53	~ 650	33°N	164°E	13°	2	McWilliams and McElhinny, 1980
Yaltipena Fm[l]	54	~ 600	44°N	173°E	11°	6	Sohl et al., 1999
Elatina[l]	55	~ 600	40°N	182°E	6°	6	Sohl et al., 1999
Brachina Fm[l]	56	~ 580	33°N	148°E	16°	5	McWilliams and McElhinny, 1980
Lower Arumbera/ Pertataka Fm[l]	57	~ 570	44°N	162°E	10°	6	Kirschvink, 1978
Upper Arumbera SS[l]	58	~ 550	46°N	157°E	4°	6	Kirschvink, 1978
Todd River	59	~ 530	43°N	160°E	7°	6	Kirschvink, 1978
Antrim plateau volcanics[m]	60	520 ± 9	9°N	160°E	13°	4	McElhinny and Luck, 1970
Hawker Group A	61	~ 520	21°N	195°E	11°	3	Klootwijk, 1980

(*continued on next page*)

Table 1 (*continued*)

Pole name	Symbol	Age (Ma)	Pole latitude	Pole longitude	A_{95} or dp/dm*	Q-value**	Reference
Australia							
Billy Creek, Aroona-Wirrealpa-A	62	~ 510	37°N	200°E	14°	3	Klootwijk, 1980
Lake Frome-A	63	~ 505	31°N	207°E	10°	3	Klootwijk, 1980
Giles Creek Dolomite-Lower	64	~ 505	38°N	205°E	10°	3	Klootwijk, 1980
Pertaoorta Group	65	~ 505	33°N	192°E	7°	4	Klootwijk, 1980
South China							
Liantuo	66	748 ± 12	4°S	341°E	13°	7	Evans et al., 2000
Nantuo Fm[f]	67	~ 740	0°N	331°E	5°	4	Rui and Piper, 1997
Meishucun Fm[f]	68	~ 525	9°N	31°E	10°	3	Lin et al., 1985
Tianheban Fm[f]	69	~ 511	7°S	10°E	23°	3	Lin et al., 1985
Hetang Fm[f]	70	~ 511	3°S	16°E	17°	3	Lin et al., 1985
Siberia							
Malgin pole	71	~ 1075	25°S	231°E	3°	6	Gallet et al., 2000
Sette-Daban Sills/ Kandyk Fm[n]	72	1005 ± 4; 974 ± 7	4°S	177°E	2°	3	Pavlov et al., 1992
Shaman Fm[o]	73	650–580	32°N	251°E	7°/14°	4	Kravchinsky et al., 2001
Minya Fm[o]	74	650–580	34°N	217°E	9°/15°	3	Kravchinsky et al., 2001
Cisbaikalia[o]	75	650–580	3°S	168°E	9°	5	Pisarevsky et al., 2000
Tsagan-Olom[o]	76	600–545	23°N	208°E	11°/22°	3	Kravchinsky et al., 2001
Kessyusa	77	~ 545	38°S	165°E	13°	4	Pisarevsky et al., 1998
Inican	78	~ 538	46°S	162°E	4°	3	Osipova, 1986
Ekreket Fm	79	~ 510	45°S	159°E	7°	4	Pisarevsky et al., 1998
Kulumbe River	80	~ 503	42°S	136°E	2°/3°	7	Pavlov and Gallet, 2001
Yuryakh Fm	81	~ 500	36°S	140°E	5°	4	Pisarevsky et al., 1998
Moyero River Seds	82	~ 490	37°S	139°E	6°	4	Gallet and Pavlov, 1996
Baltica							
Bamble intrusions (mean)[p]	83	1100–1040	3°S	37°E	15°	3	This study
Arby dolerite	84	~ 995	7°N	47°E	7°	3	Patchett and Bylund, 1977
Nilstorp dolerite	85	~ 984	9°S	59°E	10°	3	Patchett and Bylund, 1977
Falun dolerite	86	~ 966	6°N	58°E	6°	3	Patchett and Bylund, 1977
Mean pole[p]	87	~ 930	43°N	33°E	5°	4	This study
Hunnedalen dikes	88	~ 848	41°N	42°E	11°/12°	5	Walderhaug et al., 1999
Mean pole[q]	89	~ 750	28°S	17°E	8°	3	This study
Egersund dikes	90	~ 616	48°N	20°E	14°	7	Poorter, 1972; Torsvik et al., unpubl. data
Fen complex	91	583 ± 15	56°N	150°E	7°/10°	4	Meert et al., 1998
Tornetrask Fm	92	~ 535	56°N	116°E	12°/15°	4	Torsvik and Rehnström, 2001
Andarum limestone	93	~ 500	52°N	111°E	7°/10°	3	Torsvik and Rehnström, 2001
Madagascar							
Stratoid granite remag	94	521 ± 12	7°S	353°E	14°	4	Meert et al., 2003
Carion granite	95	509 ± 12	7°S	1°E	13°/17°	4	Meert et al., 2001
India/Seychelles							
Kaimur series (IND)[r]	96	~ 1200	82°N	286°E	6°	2	Sahasrabudhe and Mishra, 1966

Table 1 (*continued*)

Pole name	Symbol	Age (Ma)	Pole latitude	Pole longitude	A_{95} or dp/dm*	Q-value**	Reference
India/Seychelles							
Majhgawan Kimberlite (IND)[s]	97	1116 ± 12	39°N	217°E	31°	2	Miller and Hargraves, 1994
Lattavaram Kimberlite (IND)	98	1090 ± 20	45°S	238°E	11°	1	Miller and Hargraves, 1994
Harohalli dikes (IND)[t]	99	821 ± 12	27°N	79°E	9°	6	Radhakrishna and Joseph, 1996
Malani rhyolites (IND)	100	761 ± 10	75°N	71°E	10°	6	Torsvik et al., 2001a
Mahe granites (SEY)[u]	101	755 ± 1	77°N	23°E	2°	3	Torsvik et al., 2001b; Suwa et al., 1994
Mahe Dikes (SEY)[u]	102	750 ± 3	80°N	79°E	16°	4	Torsvik et al., 2001b; Hargraves and Duncan, 1990
Bhander-Rewa (IND)[s]	103	< 750	47°S	33°E	6°/6°	4	McElhinny et al., 1978

[a] Combined pole from all three intrusive episodes.

[b] Mean age.

[c] Overlies Lake shore traps.

[d] Overlies Nonesuch shale.

[e] Overlies Freda sandstone.

[f] Estimated age based on known isotopic and/or stratigraphic position.

[g] The Long Range dike study yielded four virtual geomagnetic poles (two are listed here). There is an ambiguous baked contact test reported on one of the "A" group dikes, but the baked direction does not closely resemble any of the four VGP directions from the dike (it is closest, but still some 50–60° different in declination from the "A" direction).

[h] The Sept-Îles "B" direction (after correction for minor tilt—see Symons and Chiasson, 1991) matches other ~ 570 Ma poles from Laurentia, while the "A" direction falls very close to the Cambro-Ordovician segment of the North American APWP (see Meert and Van der Voo, 2001).

[i] Rotated to African coordinates according to Lawver and Scotese (1987).

[j] New ages reported by Wilde and Youssef (2000). Nairn et al. (1987) argued that because the pre-tilt pole falls near the middle Cambrian segment of the Gondwana APWP the Dokhan volcanics may have been remagnetized at that time.

[k] Mean pole reported in Meert (1999).

[l] Estimated age based on stratigraphic information given in Pisarevsky et al. (2001) and stable isotope calibration given in Walter et al. (2000).

[m] New upper Concordia intercept age reported by Hanley and Wingate (2000); differs from their preferred age of 513 ± 12 Ma.

[n] Magnetic direction in the sills is identical to that reported in the Kandyk sedimentary rocks suggesting thermal overprint at the time of sill intrusion.

[o] All ages reported as 'Vendian' in original papers. Estimate is midpoint in published age ranges for these rocks. The Shaman, Minya and Cisbaikalia poles are taken from the Angara Block of the Siberian platform; the Tsagan-Olom pole is from the Tuva-Mongolian block. Kravchinsky et al. (2001) argued that the Siberian platform was not assembled until the Vendian–early Cambrian time.

[p] Mean of poles reported in Walderhaug et al. (1999) and Pesonen et al. (1991).

[q] Mean of poles reported in Torsvik et al. (1996).

[r] Age based on new geochronology and stable isotope curves reported in Rassmussen et al. (2002) and Ray et al. (2002) along with stratigraphic position.

[s] The Mahjgawan paleomagnetic pole is nearly identical to the assumed younger Bhander-Rewa pole hinting at possible problems with the age assignments of one or all of these units.

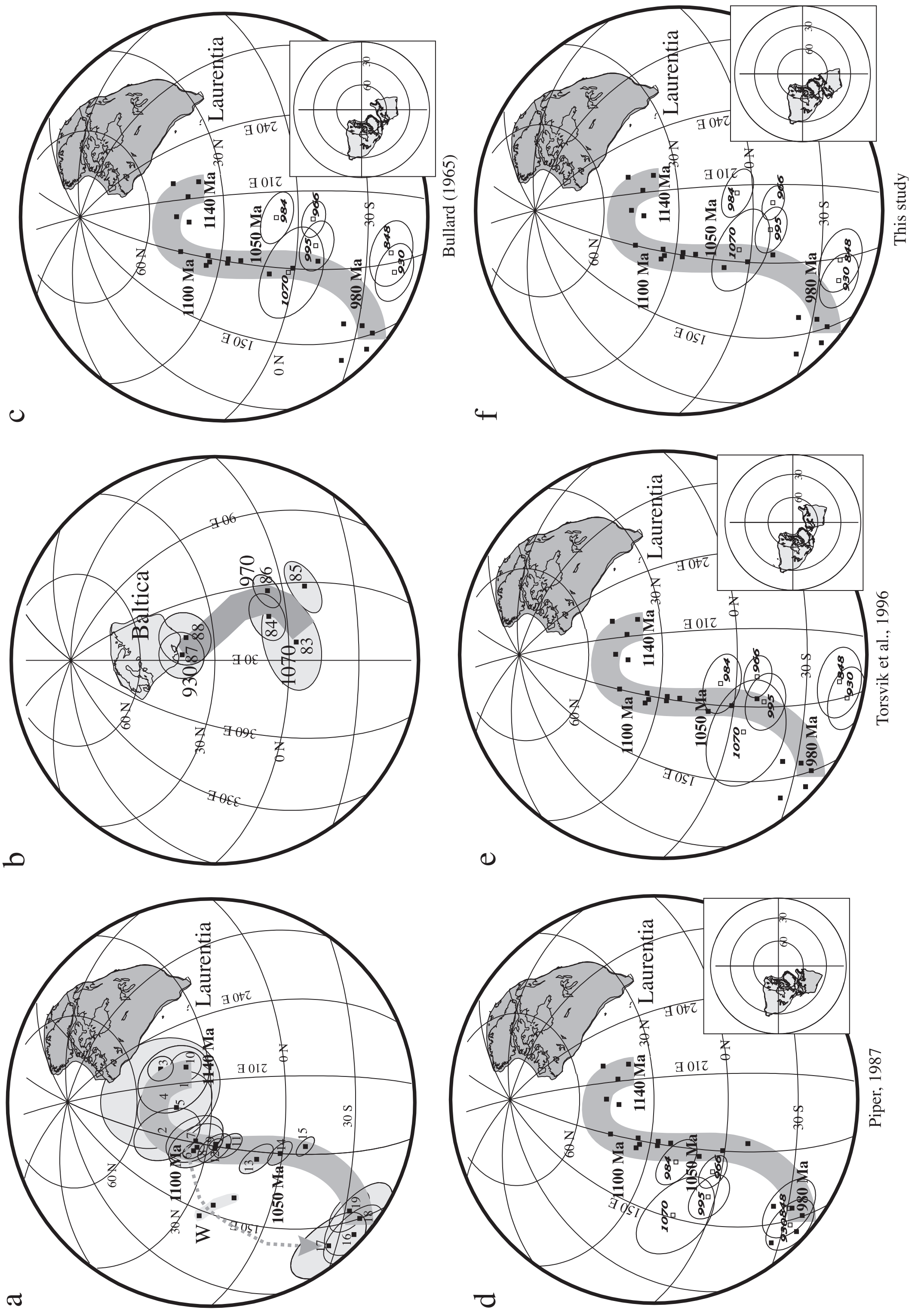
[t] Weighted mean of three Rb–Sr ages.

[u] Rotated to India according to Torsvik et al. (2001b).

* A_{95} = cone of 95% confidence about the mean pole; dp, dm = cone of 95% confidence about the paleomagnetic pole in the co-latitude direction (dp) and at a right angle to the co-latitude direction (dm).

** *Q*-value (quality factor) according to Van der Voo (1990).

*** These poles are sometimes considered to be of opposite polarity with respect to the Cambrian paleomagnetic poles (see Park, 1992). NU = Not used in the analysis. The Nyabikere VGP is based on only four samples.


a
b
c
d
e
f
Laurentia
Baltica
1100 Ma
1140 Ma
1050 Ma
980 Ma
930
970
1070
W
60 N
30 N
0 N
30 S
150 E
210 E
240 E
30 E
90 E
330 E
360 E
984
966
995
1070
930
848
Piper, 1987
Torsvik et al., 1996
Bullard (1965)
This study

from 1070 to 850 Ma (Table 1). These poles essentially define two groups (see Walderhaug et al., 1999), and Baltica moves from mid-low latitudes at 970 Ma to high northerly latitudes at ~ 930 Ma. Fig. 2a shows the available paleomagnetic data from Laurentia for this same interval of time (keyed to Table 1). Fig. 2c–e shows different fits of the Baltica poles to the Laurentian path based on the proposals of Bullard et al. (1965), Piper (1987) (see also Weil et al., 1998) and Torsvik et al. (1996). Although the Bullard et al. (1965) fit was proposed for much younger (Pangean) times, the most recent Rodinia models differ only slightly from the 1965 model. Torsvik et al. (1996) adopted a fit very close to the Bullard et al. (1965) model, but they also questioned the notion of a traditional Wilson (1966) cycle because it required a 180 degree rotation of Baltica during the initial opening of the Iapetus Ocean (Torsvik et al., 1996; Meert et al., 1998), followed by a return to nearly the same spot during the Paleozoic closure of the Iapetus ocean. We offer a slightly modified fit Baltica–Laurentia based on the paleomagnetic data listed in Table 1 (see Figs. 2f and 3) with the following caveats.

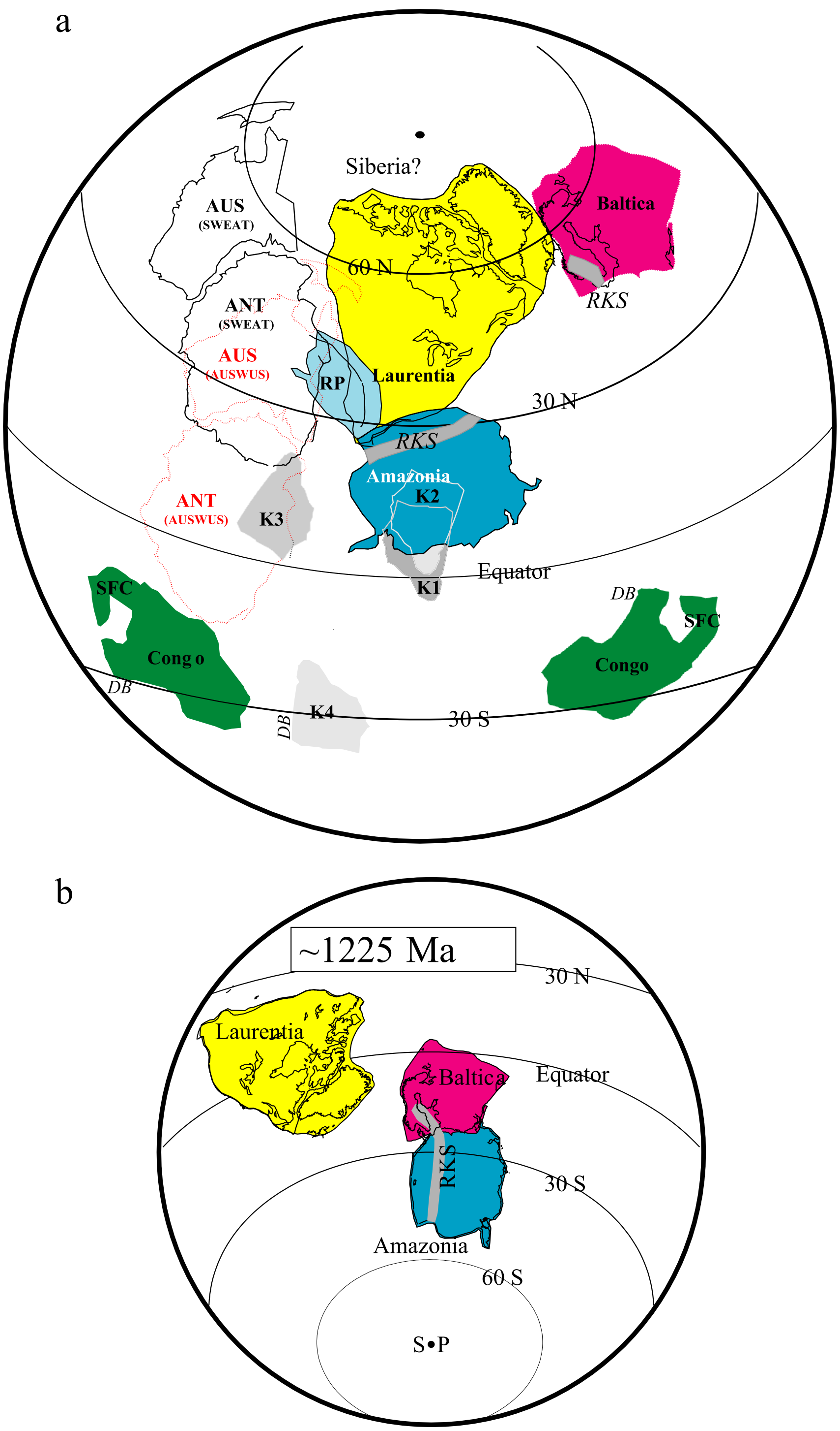
Hartz and Torsvik (2002) suggest that these 'traditional' fits of Baltica and Laurentia should be abandoned because they are largely based on incorrect geologic links between a small amount of 'Grenvillian' crystalline rocks in southern Baltica and Grenvillian Belts in Laurentia. They put forward the notion that Baltica was geographically inverted with respect to traditional fits at 750 Ma (see later). If their interpretation is correct (SPUEG fit), it means that the 'Grenvillian' linkages based on earlier interpretations of the APWP for Baltica are merely fortuitous or, alternatively, that the lengths and shapes of APWPs in the early Neoproterozoic result from a component of true polar wander (TPW) rather than motion of a single supercontinental plate. Indeed, the notion that Baltica and Laurentia were drifting independently is supported by the conclusions of Elming and Mattson (2001) who suggested that rifting between the two continents began at ~ 1.27 Ga, but differs from that of Pesonen et al. (this issue). It should be noted the SPUEG fit between Laurentia and Baltica can be reconciled with paleomagnetic data from the 1100 to 1000 Ma interval (Hartz and Torsvik, 2002) but it is incompatible with ca. 930–850 Ma poles.

2.2. 1100–900 Ma: Amazonian craton (AC)

The position of the AC within Rodinia was thought to be adjacent to the present-day eastern margin of Laurentia (Fig. 1), but this position was unconstrained by paleomagnetic data. Recent paleomagnetic data from the ~ 1200 Ma Nova Floresta Formation in Brazil (Tohver et al., 2002) provide an interesting and new position for the Amazonian craton adjacent to the Llano region of West Texas. This location for Amazonia provides evidence for the 'southern continent' that collided with Laurentia during the Grenvillian (see Mosher, 1998). Fig. 3a shows the alternative position for the Amazonian craton based on the Nova Floresta pole; if the AC collided with Laurentia along the Llano Grenvillian margin, then it has several interesting ramifications for Rodinia reconstructions.

The Rio Plata craton (RPC) is traditionally linked with the AC in Rodinia and earlier reconstructions (see Fig. 1 and also Rogers and Santosh, 2002). This connection is only weakly supported by geological data suggesting assembly of southern Amazonia and Rio Plata during the Trans-Amazonian orogen or through the comparison of younger sequences in both regions (Almeida et al., 2000; Texeira et al., 1999; Trompette, 1997). In contrast, Brito-Neves (2002) noted the existence of an oceanic segment between

Fig. 2. (a) Proposed APWP for Laurentia based on poles listed in Table 1. Individual poles (on all figures) are keyed to their numbered entry (key ages are listed on the figure) in the table. Note: shaded group of poles labeled "W" are poles used by Weil et al. (1998) to constrain the direction of the North American APWP. (b) Proposed APWP for Baltica (assumed north poles) from 1070 to 930 Ma based on the entries in Table 1. (c) Baltica poles rotated to the Laurentian APWP (shaded) using the fit of Bullard et al. (1965) (rotated 38° clockwise about an euler pole located at 88°N, 27°E). Inset figure shows the continental reconstruction (all inset figures show a North pole projection: Laurentia fixed). (d) Baltica poles rotated to the Laurentian APWP (shaded) using the fit of Piper (1987) (rotated 66.5° clockwise about an euler pole at 80.5°N, 274°E). Inset figure shows the continental reconstruction (e) Baltica poles rotated to the Laurentian APWP (shaded) using the fit of Torsvik et al. (1996) (rotated 50° clockwise about an euler pole located at 72°N, 43°E). Inset figure shows the continental reconstruction and (f) Baltica poles rotated to the Laurentian APWP (shaded) using an alternative fit (this study; rotated 35° clockwise about an euler pole located at 70°N, 211°E). Inset figure shows the continental reconstruction.


a
Siberia?
AUS
(SWEAT)
Baltica
60 N
RKS
ANT
(SWEAT)
AUS
(AUSWUS)
RP
Laurentia
30 N
RKS
Amazonia
K2
ANT
(AUSWUS)
K3
Equator
K1
DB
SFC
SFC
Cong o
Congo
DB
K4
DB
30 S
b
~1225 Ma
30 N
Laurentia
Baltica
Equator
RKS
30 S
Amazonia
60 S
S•P

the RPC and Amazonia during Brasiliano times, although the width of this ocean may have been quite small. A contiguous Rio de la Plata–Amazonian craton results in considerable overlap with Australia (in the AUSWUS configuration) and Antarctica in the SWEAT configuration (Fig. 3a).

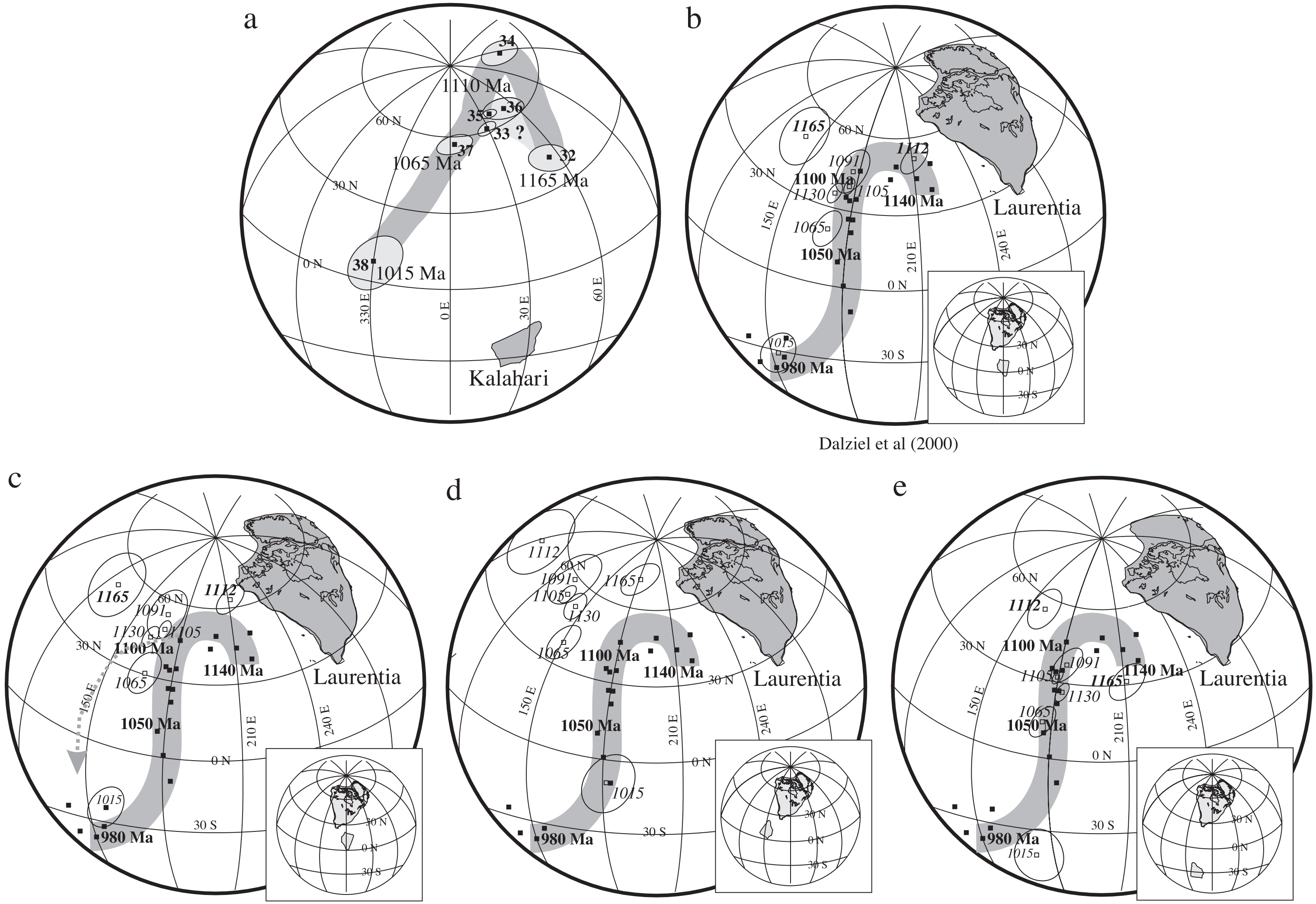
In discussing the geometric and geologic relationships between Laurentia, Baltica and Amazonia, Geraldes et al. (2001) suggested a genetic relationship between 1.55 and 1.60 Ga rapikivi and orogenic suites within Amazonia and those found in the Baltic shield (Åhäll et al., 2000). They suggested a continuation of these belts indicates close proximity between Amazonia and Baltica but not necessarily Laurentia (see also Pesonen et al., this issue). The Amazonia–Baltica connection is consistent with the paleomagnetic data up until ~1200 Ma (see Fig. 3b) but because of a lack of longitudinal control and choice of poles other options are equally valid (see Tohver et al., 2002; Pesonen et al., this issue).

2.3. 1100–900 Ma: Kalahari craton

Paleomagnetic poles from the Kalahari craton are shown in Fig. 4a (Table 1). The placement of the Kalahari craton within Rodinia is also the subject of considerable controversy. Many of the earlier reconstructions placed the Kalahari craton adjacent to the Grunehogna province of East Antarctica (Dalziel, 1997). Paleomagnetic data from Gose et al. (1997) along with geologic data described in Fitzsimons (2000) and Jacobs et al. (1998) demonstrated that there was no continuity between the larger East Antarctic craton and the Kalahari craton during the Neoproterozoic. Instead, the most recent Gondwana assembly models (Fitzsimons, 2000; Boger et al., 2002; Meert, 2003) suggest that the Grunehogna province was originally part of the Kalahari craton and was not juxtaposed with the East Antarctic craton until around 530 Ma. Dalziel et al. (2000) argued that the Kalahari craton is better placed outboard of the Llano region of Texas and that it behaved as a rigid indenter during the Grenvillian assembly of Rodinia (fit K2, Figs. 3a and 4b). According to their model and that of Mosher (1998), continental accretion in the Llano region began at ~1250 Ma with an arc–continent collision, followed by continent–continent collision between 1150 and 1120 Ma. The Dalziel et al. (2000) reconstruction is very similar to that proposed by Weil et al. (1998) (fit K1, Figs. 3a and 4c). Powell et al. (2001) countered that the Kalahari craton was, at closest, situated some 1000–2000 km away from the Laurentian margin using the most liberal estimates allowed by the paleomagnetic data. Powell and colleagues suggested that the Kalahari craton became attached to the Laurentian plate, but did not cause extensive deformation, sometime between 1060 and 1015 Ma in a position along-strike with the Llano Grenvillian Belt (see Figs. 3a and 4d; fit K3). This conclusion, while paleomagnetically valid, begs the question as to what continent caused the deformation observed in the Llano region. Deformation in the Namaqua–Natal belts along the Kalahari cratonic margin began between 1.22 and 1.07 Ga (Robb et al., 1999) with the accretion of island arcs along the Natal margin. Younger deformation, between 1060 and 980 Ma, consisted of NE–SW-directed convergence along the southern Kalahari craton (Jacobs et al., 1993, 1997). This may have involved continent–continent collision with unknown segments of Rodinia, which Powell et al. (2001) attributed to East Antarctica or further accretion of other smaller terranes to the Kalahari craton.

An alternative fit of paleomagnetic poles from the Kalahari craton is shown in Figs. 3a and 4e (fit K4). The shape and total length of APWPs for Kalahari and Laurentia are similar. This relationship was noted initially by Hartnady and Onstott (1992), and discussed at length by Weil et al. (1998) and Powell et al. (2001). By inverting the polarity of the Kalahari poles, our revised fit of Kalahari poles on the Laurentian track brings the 1165 Ma Premier Kim-

Fig. 3. (a) The disposition of various cratonic elements to Laurentia (present-day coordinates) discussed in this paper. Euler rotation parameters are given in the appendix and as captions in other figures with the exception of Amazonia. Amazonia was rotated to Laurentia using the data in Tohver et al. (2002). RKS = Mesoproterozoic Rapakivi suite of Geraldes et al. (2001). (b) Shows one possible reconstruction of Baltica and Amazonia at 1.225 Ga following the paleomagnetic data (see also Pesonen et al., this issue) and the suggestion by Geraldes et al. (2001). The paleomagnetic data in this paper would indicate that if the Baltica–Amazonia link proposed by Geraldes et al. (2001) for the Mesoproterozoic is correct and the relationship of Amazonia to Laurentia proposed by Tohver et al. (2002) is correct, then Baltica must have rifted from Amazonia between 1225 and 1100 Ma.



Dalziel et al (2000)

Weil et al (1998)

Powell et al (2001)

This study

berlite pole into reasonable agreement with similar-age poles from Laurentia (in contrast to the other fits described above). If we reconstruct Kalahari to Laurentia using this fit, it results in a ~50° separation between Laurentia and Kalahari. Our fit is admittedly at odds with the previous interpretations that sought to place the KC on the same 'plate' as Laurentia. While it is possible that our model places the KC on the same plate as Laurentia, we feel this is unlikely due to the large separation required in this particular reconstruction. However, we also note that the shape and length similarities may arise due to a component of true polar wander during this interval of time as discussed below, and that fitting different segments of the respective APWPs (or inverting the polarity choice) can bring the KC closer to the Laurentian margin.

2.4. 1100–900 Ma: Congo–Sao Francisco (CSF) craton

Weil et al. (1998) evaluated the APWP from the CSF craton (Fig. 5a). The contiguity of these two cratonic regions (Congo–Sao Francisco) was discussed in that paper and elsewhere (see also D'Agrella-Filho et al., 1990; Almeida et al., 2000). The interpretation by Weil et al. (1998) used combined paleomagnetic data from the CSF craton, and they argued that the path length and shape was similar to the North American APWP (assuming a counterclockwise Grenvillian loop, Fig. 5b and using the 'western' Keewanawan poles, Fig. 2a). The 'hinge' of the CSF loop is based on a virtual geomagnetic pole from only four samples in the Nyabikere massif of Burundi (Meert et al., 1994b), and the age assignment was taken from disturbed argon spectra ranging from 908 to 1004 Ma. This counterclockwise shape of the loop (in the Weil et al., 1998 fit) has additional weak support based on paleomagnetic studies of the 841 Ma Suakin Gabbro (Reischmann et al., 1992), and the 795 Ma Gagwe lavas (Meert et al., 1994a,b). The Suakin gabbro (Sudan), an island arc fragment within the Mozambique Ocean, is dated to 841 ± 4 Ma (^{40}Ar/^{39}Ar) and its pole falls midway between the 1012 Ma Iheus dikes and the 795 Ma Gagwe lavas pole and very close to the ~ 935 Ma VGP determined from the Nyabikere massif (see Fig. 5a). However, both the Suakin Gabbro pole and the Nyabikere pole fall close to younger ~560–550 Ma poles from elsewhere in Gondwana and may represent younger overprints. This is particularly true of the Suakin gabbro due to its location within the East African Orogenic belt (Stern, 1994).

Because of the uncertainty in the direction of the CSF APWP, we chose to fit the straight-line segment (1070–1012 Ma) of the CSF path in this paper (see Fig. 5c and d) which leads to alternative reconstructions of the CSF with Laurentia. The reconstruction shown in Fig. 5c results in a similar 'fit' between Laurentia and the CSF as that given in Weil et al. (1998) with a slightly larger separation between the cratons in our model (see Figs. 5b,c and 3a). Alternatively, we can invert the polarity of the Congo poles and then fit the CSF APWP to the Laurentian APWP (Fig. 5d). The resulting reconstruction places the Congo craton in the vicinity of Kalahari craton (K4) although rotated ~90° with respect to the Neoproterozoic Damara Belt (Fig. 3a). Interestingly, the Congo craton undergoes a 90°+ rotation during the 795–755 Ma interval as documented by paleomagnetic poles from the Gagwe lavas and Mbozi Complex (Meert et al., 1995). Unfortunately, there are no paleomagnetic data from the Kalahari craton to further constrain their relationship to each other during this same interval.

2.5. 1075–990 Ma Siberian craton

Perhaps the most enigmatic position of any craton within Rodinia is that of the Siberian craton. The

Fig. 4. (a) Proposed APWP for the Kalahari craton based on the poles listed in Table 1. Individual poles (on all figures) are keyed to their numbered entry in the list. (b) Kalahari poles rotated to the Laurentian APWP (shaded) using the fit of Dalziel et al. (2000) (rotated 138° clockwise about an euler pole located at 18.9°N, 23.9°W). Inset figure shows the continental reconstruction (all figures hold Laurentia-fixed in present-day coordinates). (c) Kalahari poles rotated to the Laurentian APWP (shaded) using the fit of Weil et al. (1998) (rotated 147° counterclockwise about an euler pole located at 15°S, 156°E). Note that Weil et al. (1998) use the alternative path shown as a dashed line in the figure. Inset figure shows the continental reconstruction and (d) Kalahari poles rotated to the Laurentian APWP (shaded) using the fit of Powell et al. (2001) (rotated 152.3° clockwise about an euler pole located at 63°N, 92.7°E). Inset figure shows the continental reconstruction and (e) Kalahari poles rotated to the Laurentian APWP (shaded) using an alternative fit (this study; rotated 164.6° clockwise about an euler pole located at 64°N, 142.6°E). Inset figure shows the continental reconstruction. Note: The polarities of the poles are inverted in (d) and (e) with respect to (b) and (c).

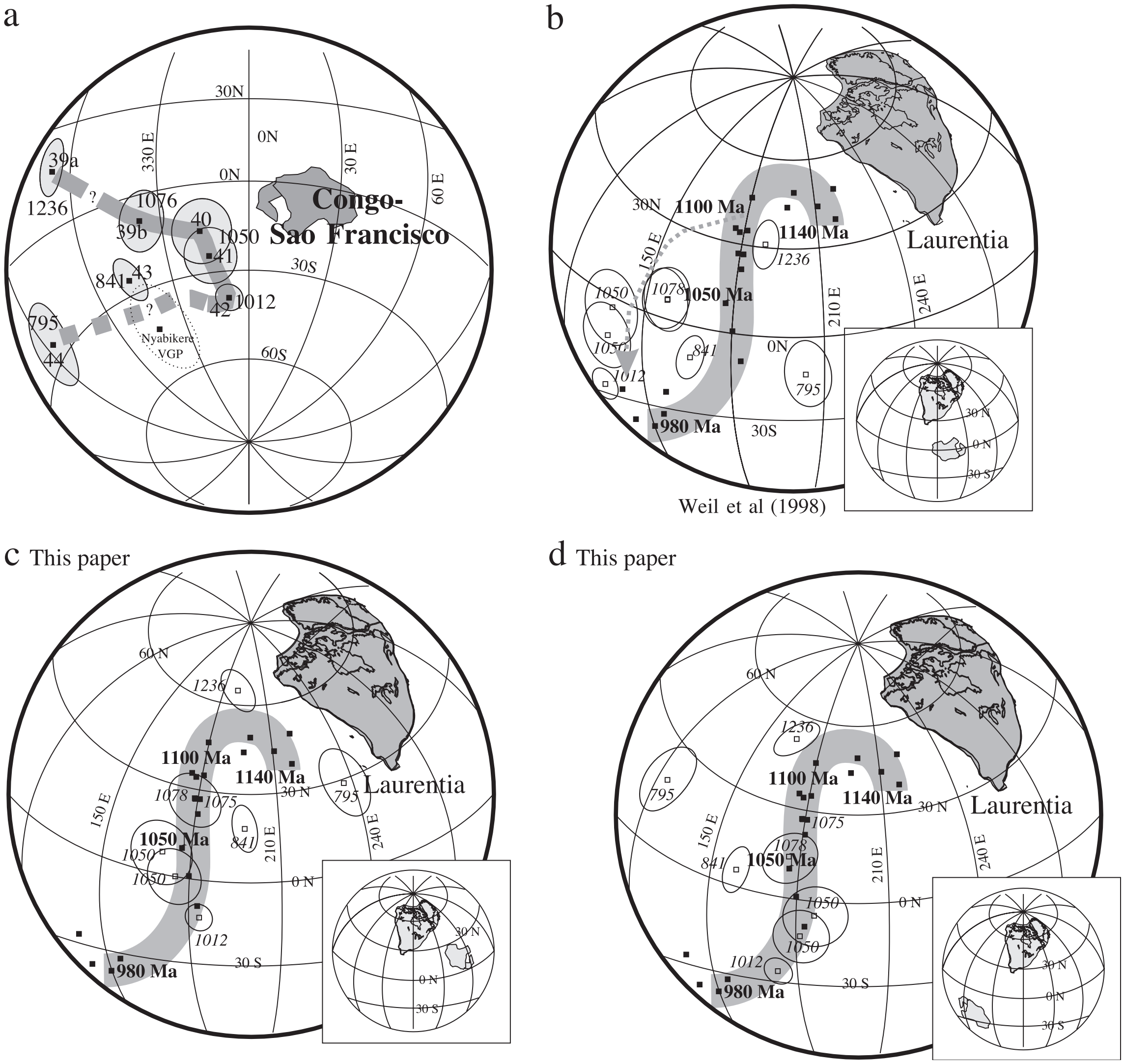


Fig. 5. (a) Proposed APWP for the CSF craton based on the poles listed in Table 1. Individual poles (on all figures) are keyed to their numbered entry in the list. (b) CSF poles rotated to the Laurentian APWP (shaded) using the fit of Weil et al. (1998) (rotated 185° clockwise about an euler pole located at 7°N, 150°E). Note: Weil et al. (1998) used the dashed path for Laurentia. Inset figure shows the continental reconstruction (all inset figures hold Laurentia fixed in present-day coordinates). (c) CSF poles rotated to the Laurentian APWP (shaded) using the polarity option given in Table 1 (this study; rotated 129.8° clockwise about an euler pole located at 10.1°N, 164.7°E). Inset figure shows the continental reconstruction and (d) CSF poles rotated to the Laurentian APWP (shaded) using the opposite polarity from (c) (this study; rotated 1511° clockwise about an euler pole located at 66.7°N, 278.1°E). Inset figure shows the continental reconstruction.

archetypal position of Siberia within Rodinia is along the present-day northern margin (Arctic margin) of Laurentia. In spite of a loose agreement regarding this northerly position, the orientation of Siberia and its geological correlation with Laurentia during the Proterozoic is hotly debated (see for example Hartz and Torsvik, 2002; Meert and Van der Voo, 2001; Meert and Powell, 2001; Sears and Price, 2000; Pisarevsky et al., 2000; Ernst et al., 2000; Rainbird et al., 1998; Frost et al., 1998; Pelechaty, 1996; Condie and Rosen, 1994; Hoffman, 1991). Paleomagnetic data from Siberia are sparse. Gallet et al. (2000) provide data from the

Malgin and Linok formations that were formerly assigned an age of ~750 Ma (Smethurst et al., 1998). Gallet et al. (2000) reviewed the available biostratigraphic and geochronologic age constraints on these formations and suggest that a better estimate for their age is between 1050 and 1100 Ma. Directional data from the Linok Formation may have been rotated by more than 20° during the opening of the Viljuy rift (Smethurst et al., 1998) and therefore was not used in this study. We assigned an age of ~1075 Ma to the Malgin Formation paleomagnetic pole.

Gallet et al. (2000) further argued that the Siberian craton could have been connected to northern Laurentia in a Rainbird et al. (1998) fit by assuming a south-pole option for the 1075 Ma segment of the Laurentian path given in Table 1 (Fig. 6a). Indeed, such a fit is permissible when using this single pole. Both Buchan et al. (2001) and Ernst et al. (2000) discuss the paleomagnetic data from the Sette Daban sills at the SE-margin of the Siberian craton. Smethurst et al. (1998) assumed an age of ~750 Ma for these dikes, but recent geochronologic work by Rainbird et al. (1998) indicates that the dikes are more likely between 950 and 1000 Ma. Pavlov et al. (1992) provided paleomagnetic data for these dikes that matches the magnetization observed in the host Kandyk sediments. Ernst et al. (2000) suggested that both the sediments and the sills are of similar age or that the magnetization of the sills and sediments were both reset. It is important to note that the pole position from both the Kandyk Sediments and the Sette Daban sills do match a younger (Vendian-age) pole from Cisbaikalia (Pisarevsky et al., 2000) although it is quite distinct from other published Vendian-age poles from Siberia (Kravchinsky et al., 2001; Table 1, Fig. 6a). We therefore tentatively accept the Sette-Daban pole as dating to ~990 Ma. Our acceptance of this pole has important ramifications for the paleoposition of Siberia with respect to Laurentia. We can fit the straight-line path between the two poles as we show in Fig. 6b by rotating the Siberian poles 93° clockwise about an euler pole located at 35.4°N, 356.2°E. This rotation results in a significant separation between Siberia and Laurentia and, if accepted at face value, would negate all previously proposed fits between Laurentia and Siberia.

Nevertheless, given that there are only two poles defining the straight path and that straight-line seg-

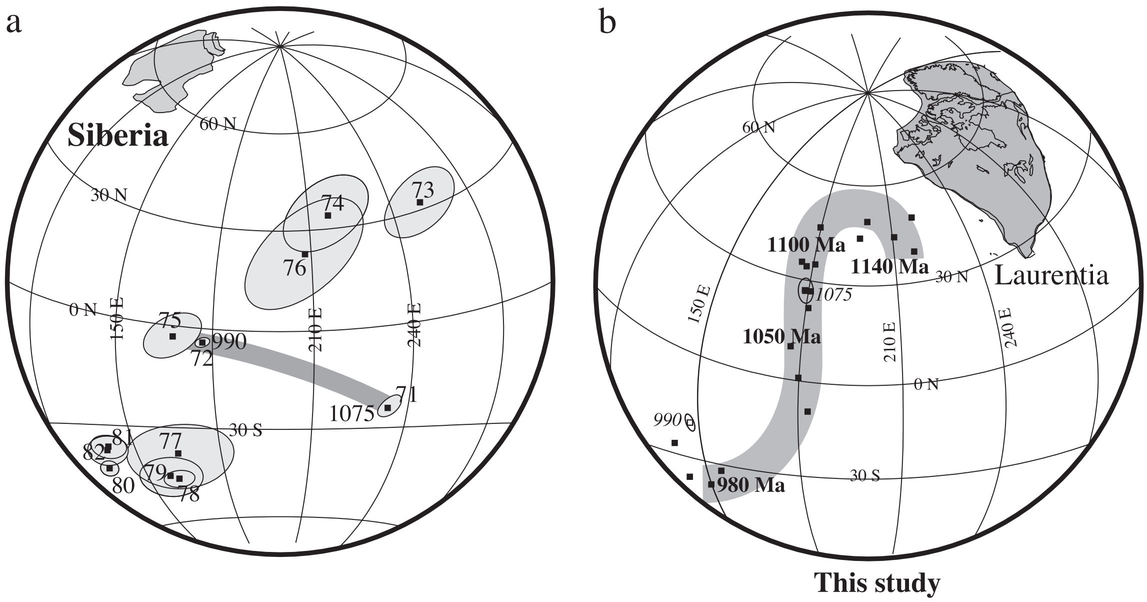


Fig. 6. (a) Proposed APWP for the Siberian craton based on the poles listed in Table 1. Individual poles (on all figures) are keyed to their numbered entry in the list. (b) Siberian craton poles rotated to the Laurentian APWP (shaded) attempting to fit the straight line segment of the 1075–990 Ma Siberian APWP (this study; rotated 94° counterclockwise about an euler pole located at 26.1°N, 351° E). Other rotations are possible as discussed in the text.

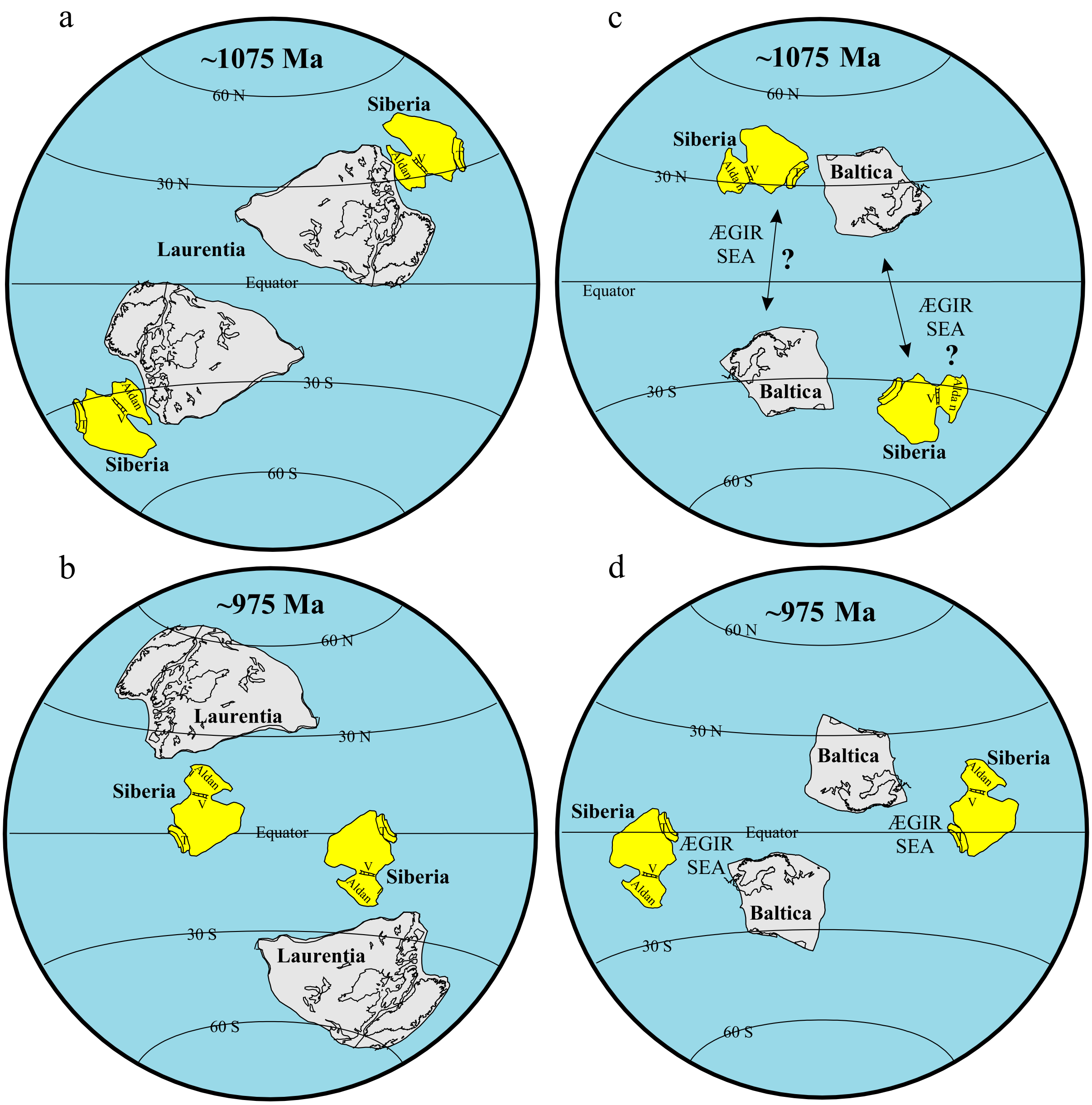


Fig. 7. (a) Possible 1075 Ma reconstructions of Laurentia and Siberia using the poles listed in Table 1 for both continents. Depending on the polarity choice for Laurentia and Siberia, this paleogeography closely approximates the fit advocated by Rainbird et al. (1998), although the Siberian craton is rotated with the Aldan shield parallel to the Arctic margin of Laurentia (compared with the orthogonal position advocated by Rainbird et al., 1998). Paleolongitudes are unconstrained in these reconstructions. (b) Possible 975 Ma reconstructions of Laurentia and Siberia using the Sette-Daban poles for Siberia (Table 1). Depending on the choice of polarity for the poles, this reconstruction matches the fit advocated by Sears and Price (2000) along the present-day western margin of Laurentia. (c) 1075 Ma reconstruction between Baltica and Siberia. Depending on polarity choice, this reconstruction indicates a possible wide separation between the two cratons (Ægir Sea; Hartz and Torsvik, 2002) and (d) 975 Ma reconstruction of Baltica and Siberia. Depending on polarity choice, this model closely approximates the reconstruction advocated by Hartz and Torsvik (2002) with Siberia and Baltica separated by the Ægir Sea.

ments can be fit using a number of different euler poles, we can instead estimate the closest approach of Siberia to Laurentia using coeval poles from Siberia and Laurentia. We are faced with polarity options for both sets of poles that lead to the options shown in Fig. 7a. The 1075 Ma reconstruction is broadly compatible with the suggestion of Rainbird et al. (1998), although, in the Rainbird et al. (1998) reconstruction, the Aldan Shield is orthogonal to the northern margin of Laurentia. In addition, we note that due to a lack of longitudinal control, a position for Siberia off the coast of present-day western Laurentia is equally permissible (see Sears and Price, 2000; Pesonen et al., this issue). The 975 Ma reconstruction poses more of a problem for traditional Rodinia fits (Fig. 7b) because it results in a latitudinal offset between Siberia and Laurentia.

Another alternative, argued by Hartz and Torsvik (2002), is that Siberia was not located near Laurentia at 750 Ma (and probably earlier times), but was situated close to Baltica and separated from it by the Ægir Sea. The APWPs for Baltica and Siberia for the interval from 1100 to 975 Ma are of different lengths although the geochronologic controls on both APWPs allow for considerable freedom. The different APW lengths suggest that Baltica and Siberia were drifting independently during this interval. Paleoreconstructions (Fig. 7c and d) based on the available poles show that Baltica may have had a close association with Siberia (dependent on the choice of polarity). Indeed, the reconstruction at 975 Ma (Fig. 7d) is similar to that advocated by Hartz and Torsvik (2002).

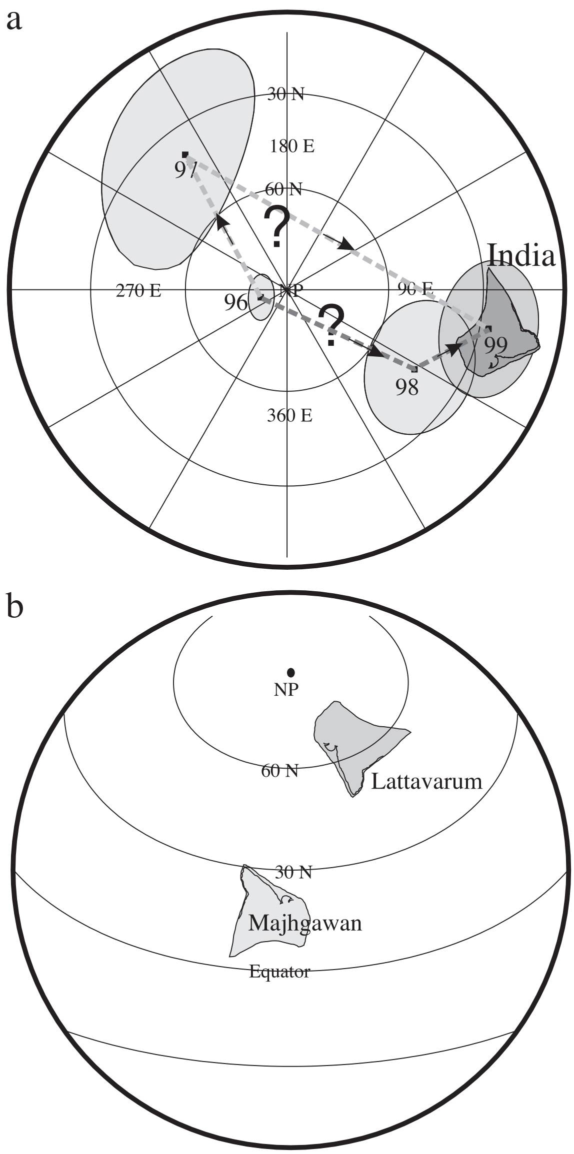


Fig. 8. 1200–813 Ma poles from India keyed to listing in Table 1. Assuming the Kaimur pole is representative of India at 1.2 Ga, two possible paths are possible. One through the Majhgawan kimberlite pole (97) and the other through the Lattavaram kimberlite pole (98). (b) Shows the difference in latitude and orientation based on the two ~ 1100 Ma poles.

2.6. India 1100–1000 Ma

The paleomagnetic database for the Indian subcontinent is sparsely populated and poorly resolved. There are two ~1100 Ma paleomagnetic poles from India that are separated by a minimum of 86° resulting in an uncertainty in the paleolatitudinal position of India (Table 1, Fig. 8a and b). The Majhgawan kimberlite pole is identical to a presumed younger paleomagnetic pole from the Bhander-Rewa series hinting at a possible problem with the age of one or both of those poles. A poorly documented paleomagnetic study of the Kaimur Series (Vindhyan Basin) by Sahasrabudhe and Mishra (1966) is also listed in Table 1. Although the directional data from the Kaimur Series is close to the expected present-day field direction in India, the section did exhibit a crude magnetic polarity sequence hinting that the pole might have retained a primary magnetization (Rao and

Bhalla, 1996). The age of the Kaimur is only poorly known. Recent geochronologic studies in the Vindhyan basin indicate that the upper part of the underlying Semri Group is roughly 1.6 Ga (Ray et al., 2002; Rassmussen et al., 2002). Both the Semri Group and the overlying Kaimur sandstone are intruded by the Majhgawan kimberlite dated between 1067 and 1140 Ma (Kumar et al., 1993). The age of the Kaimur must rest somewhere between 1.6 and 1.1 Ga. Carbon and strontium isotopic studies of the Semri Group indicate a possible 1.2 Ga age for the uppermost Rhotas limestone (Kumar et al., 2002). Therefore, we consider the Kaimur Series pole to lie somewhere in the interval from 1.1 to 1.2 Ga and have assigned an age of 1.2 Ga to this pole in our study. Because the data are so poor, no direct comparison to any APWP is attempted. More reliable late Neoproterozoic data for India are discussed below.

3. True polar wander?

As noted above, well-defined segments of the Laurentian and Kalahari APWP's show similar lengths of motion during the period from 1100 to 1000 Ma. The length of the APWP for the Congo craton is slightly less during this same interval of time. Although poorly constrained, the APWP for Siberia also shows nearly 60° of track length during this interval. The Baltica APWP also shows a significant track length, but for a slightly younger interval ~966–930 Ma although the age constraints are not as refined. Weil et al. (1998) suggested that not only were the path lengths similar for these continents, but the shapes were also similar and concluded that this resulted from all cratons lying within the same plate. Walderhaug et al. (1999) argued that there is no well-defined Grenvillian loop in the Baltica APWP. The loop in the Congo–Sao Francisco path in the Weil et al. (1998) paper is possible if the VGP from the poorly dated Nyabikere massif is accepted, but our TPW analysis uses only the straight-line segment of the APWP. Our Kalahari fit (discussed above) is quite different from previous analyses and collectively, the paleoreconstructions derived from matching the APWPs from the Congo, Kalahari and to a lesser extent Siberia cratons, suggest that the one plate model may not be valid for the 1100–900 Ma period.

Table 2
Analysis of APW lengths

Craton	Poles used[a]	Age range[b]	APW rate[c]
Laurentia-A	Mean 5–8 and 15	1100–1040 Ma	$8.2^{+13.8}_{-4.6}$
Laurentia-B	15 and 16	1040–980 Ma	$8.3^{+15.8}_{-4.1}$
Kalahari	35 and 38	1105–1015 Ma	$9.0^{+4.1}_{-2.8}$
Siberia	71 and 72	1075–990 Ma	$7.2^{+7.6}_{-2.7}$
Congo	39b and 42	1078–1012 Ma	$6.0^{+16.6}_{-2.8}$
Baltica-A	83 and 86	1040–966 Ma	$3.5^{+16.8}_{-3.3}$
Baltica-B[d]	86 and 87	966–930 Ma	$13.3^{+???}_{-9.2}$

[a] Keyed to Table 1.

[b] Where ages are estimated an error of ± 25 Ma is assigned.

[c] After Meert (1999).

[d] Age error is greater than the spread in ages.

A second possibility is that the similarity in path length for these cratons is due to true polar wander. Indeed, true polar wander has been proposed for other periods within the Neoproterozoic and early Paleozoic (Kirschvink et al., 1997; Evans, 1998) although the magnitude is hotly debated (Torsvik et al., 1998; Meert, 1999).

Rates of apparent polar wander for this interval can be calculated in a variety of ways. The most conservative estimate requires that APWP length is measured along the shortest path between successive poles. It is always possible to generate large APW by inverting polarities between successive poles, but this results in sometimes drastic changes to the paleogeography (Torsvik et al., 1998). Meert (1999) proposed a method for evaluating the relative magnitudes of APW and associated errors. Table 2 shows the results of that analysis for the cratons involved. The average rates of apparent polar wander listed in the table are moderate for large continents, but do not, in and of themselves, constitute strong evidence for true polar wander. On the other hand, since the rates are similar for all cratons during the same interval and since superposition of the APWPs suggest that the cratons do not all lie on the same plate, modest true polar wander for this period is a viable hypothesis.

4. The breakup of Rodinia: 800–700 Ma

The traditional Rodinia models argue that breakup of the supercontinent commenced with the 800–700 Ma opening of the Paleo-Pacific ocean between Laurentia and Australia–Antarctica (Fig. 1). Avail-

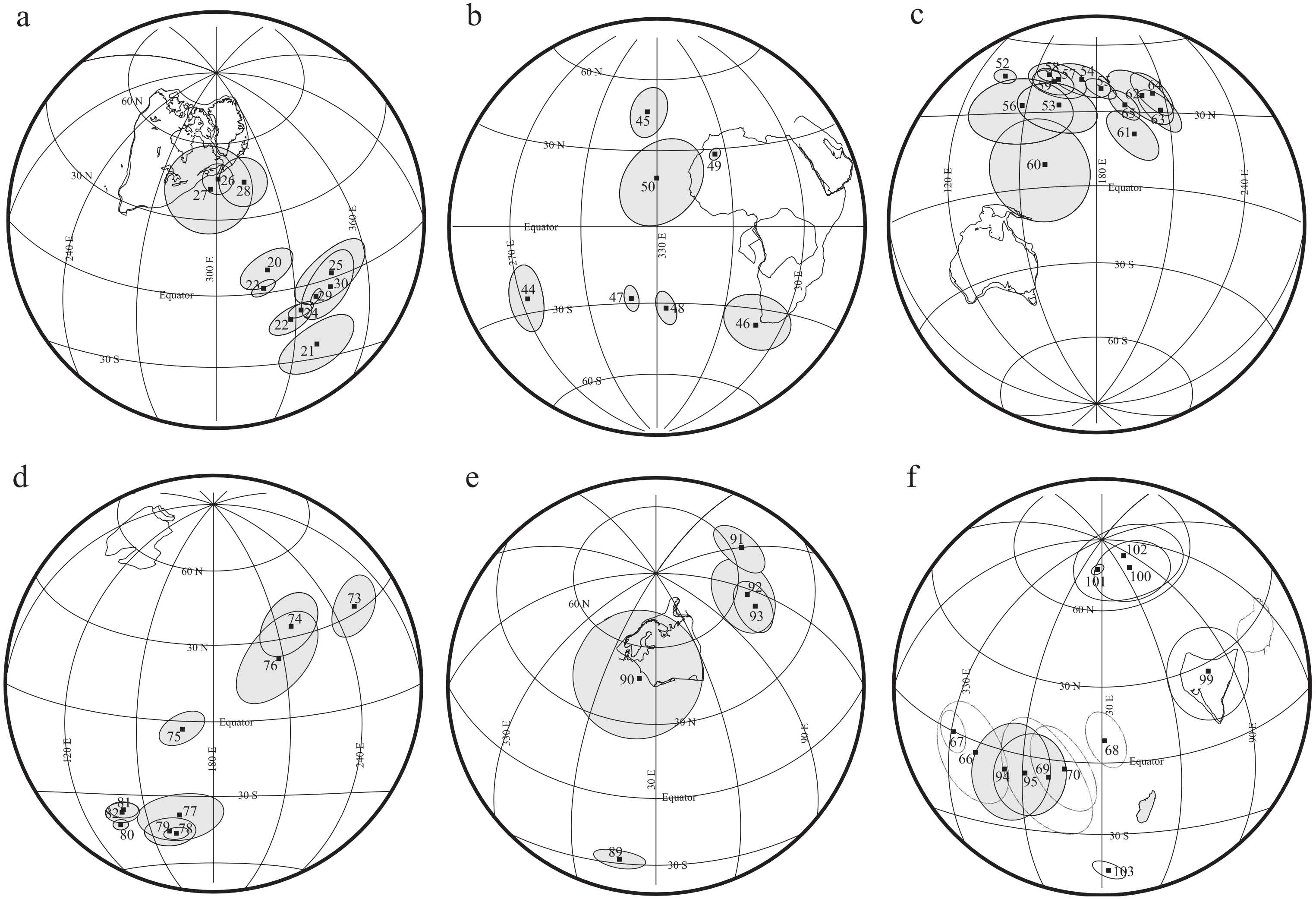


Fig. 9. (a) Late Neoproterozoic–Cambrian poles (778–495 Ma) from Laurentia keyed to listings in Table 1 (assumed south poles). (b) Late Neoproterozoic–Cambrian (795–520 Ma) poles from the CSF craton, Arabian shield and adjacent Pan–African belts keyed to the listings in Table 1 (assumed south poles). (c) Late Neoproterozoic–Cambrian poles (755–505 Ma) from Australia keyed to listings in Table 1 (assumed south poles). (d) Vendian–Cambrian poles (650–510 Ma) from Siberia keyed to listings in Table 1 (assumed south poles). (e) Late Neoproterozoic–Cambrian poles (750–500 Ma) from Baltica keyed to listings in Table 1 (assumed south poles). (f) Late Neoproterozoic–Cambrian poles (761–508 Ma) from India, South China and Madagascar keyed to listings in Table 1.

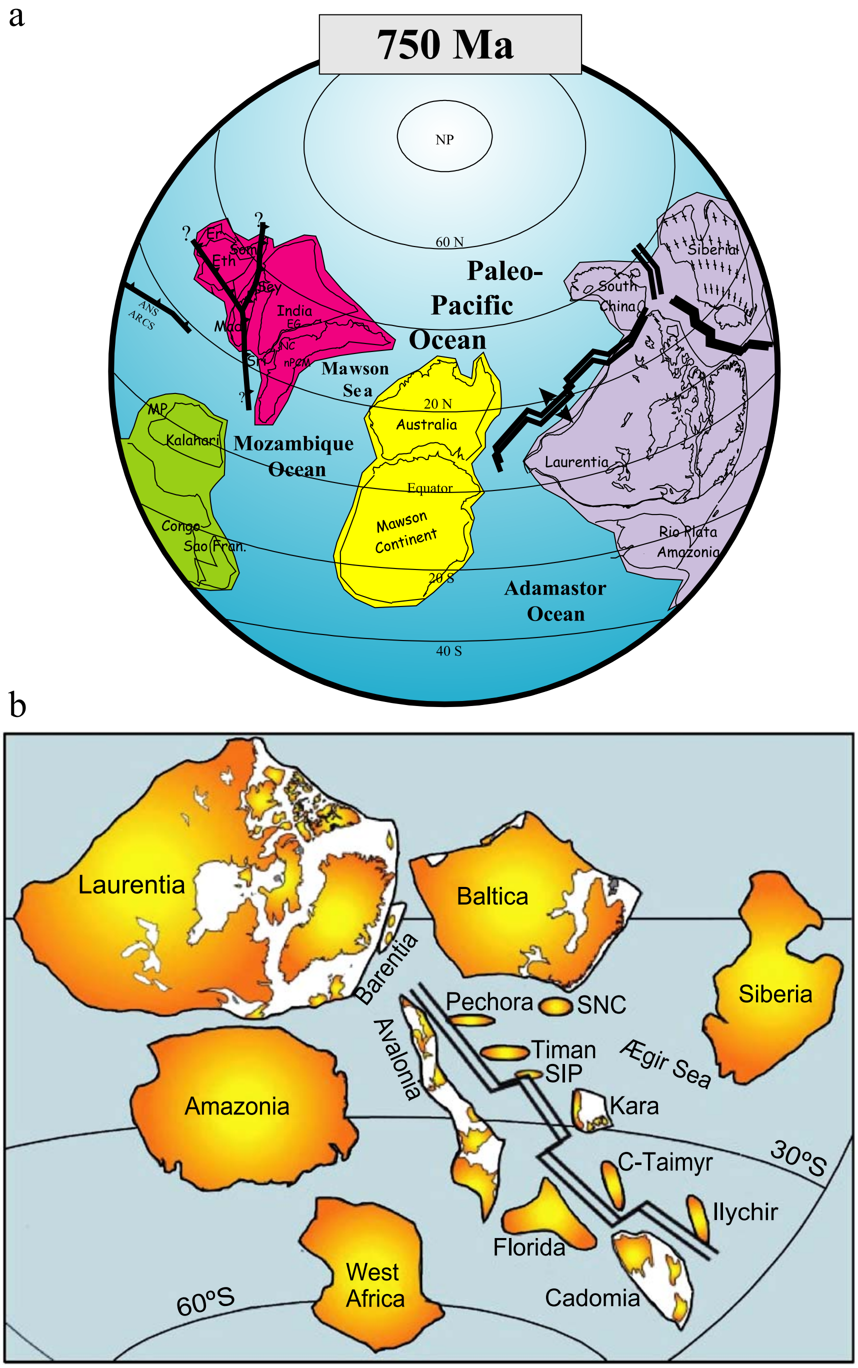


Fig. 10. (a) 750 Ma reconstruction modified from Meert (2003) showing the western margin breakup of the Rodinia supercontinent. In this reconstruction, eastern Gondwana is broken up into two large segments and (b) 750 Ma reconstruction based on the model of Hartz and Torsvik (2002) showing the relationship of landmasses along the eastern margin of Laurentia.

able paleomagnetic data from which these models can be tested are given in Table 1 and shown in Fig. 9a–f. This model is challenged by a number of recent authors who argued that the East Gondwana landmass was not a coherent block in mid-Neoproterozoic time (Meert, 2001, 2003; Boger et al., 2002; Powell and Pisarevsky, 2002; Foden et al., 2001; Torsvik et al., 2001b; Fitzsimons, 2000; Wingate and Giddings, 2000). In addition to those studies, Hartz and Torsvik (2002) argue that the position of Baltica alongside northeastern Laurentia should be inverted and they also challenged the position of Siberia within Rodinia. Tohver et al. (2002) suggest that Amazonia is better fitted along the southwestern margin of Laurentia within Rodinia as previously discussed. The positions of Australia and Antarctica within Rodinia remain problematic. Both AUSWUS and SWEAT models have been proposed and yet the largely Mesoproterozoic paleomagnetic data supporting those configurations is weak (Meert, 2002; Buchan et al., 2001; Karlstrom et al., 1999). We note that if the above postulates are correct and we adopt the AUSWUS configuration for Australo–Antarctica, then there is a considerable length of Neoproterozoic rifted margins surrounding Laurentia with no identifiable conjugates (Fig. 3). A recent study by Wingate et al. (2002) proposes an even more southerly fit of Australo–Antarctica against Mexico (AUSMEX). All of these paleomagnetic observations beg the question as to the existence and makeup of the Rodinia supercontinent. Fig. 10a shows the 750 Ma reconstruction given in Meert (2003) focused on the breakup along the western margin of Laurentia and the elements of East Gondwana. Fig. 10b shows the 750 Ma reconstruction from Hartz and Torsvik (2002) that focused on the eastern margin of Laurentia. Amazonia and Rio Plata are shown in their traditional Rodinia fits although the paper by Tohver et al. (2005) would suggest a more southwesterly connection with Laurentia (Llano uplift fit). However, it is probable that considerable sinsitral strike-slip motion between Amazonia and Laurentia took place resulting in a more 'archetypal' position of Amazonia alongside eastern Laurentia. New, high quality paleomagnetic data from India and Australia (Torsvik et al., 2001b; Wingate et al., 2000) show a clear latitudinal offset between these East Gondwana blocks and also an incompatibility with either AUSWUS or SWEAT models. India is located at mid to high latitudes during the 810–750 Ma interval (Torsvik et al., 2001b; Radhakrishna and Joseph, 1996) whereas Australia is thought to have remained in near equatorial position (Wingate et al., 2000; Pisarevsky et al., 2001). Fig. 9a is based on these new poles (see Table 1). There are no paleomagnetic data from Siberia for the 800–700 Ma interval and Hartz and Torsvik (2002) argue that geologic links between Laurentia and Siberia during this interval are not strong. Others (notably Pisarevsky et al., 2000; Pelechaty, 1996) maintain that Siberia and Laurentia remained in close proximity until the Cambrian.

Powell and Pisarevsky (2002) propose some alternative reconstructions for this time period with the Congo–Sao Francisco-Kalahari cratons attached to the Tarim craton and Australia at ca. 810 Ma. According to their model, Congo then rifted away from the Tarim craton and the KC at ca. 750 Ma only to reunite with the KC, in more or less the same position at ~ 610 Ma. The many and varied reconstructions for this time period highlight the need for better constrained paleomagnetic and geologic information for each of the cratonic blocks.

5. 580 Ma and younger reconstructions

The vestiges of the Rodinia supercontinent broke apart during the terminal Neoproterozoic and the timing of that breakup is broadly synchronous with the assembly of Gondwana (Meert, 2003; Powell and Pisarevsky, 2002; Boger et al., 2002; Meert, 2001; Torsvik et al., 1996). The existence of a younger, ephemeral supercontinent called Panottia is dependent on the time of rift-drift transition between Laurentia and the elements of western Gondwana (traditionally Amazonia–Rio Plata) and the final assembly of Gondwana. A number of authors have discussed the timing of final Gondwana assembly from a number of perspectives. Meert (2001) suggested, on the basis of paleomagnetic data, that final Gondwana assembly did not occur until sometime in the 550–530 Ma interval. This is consistent with a number of new geologic findings dividing East Gondwana into several different blocks (Fitzsimons, 2000; Boger et al., 2002; Meert, 2003). Fig. 11 is adopted from Meert (2003) and shows the position of the major continen-

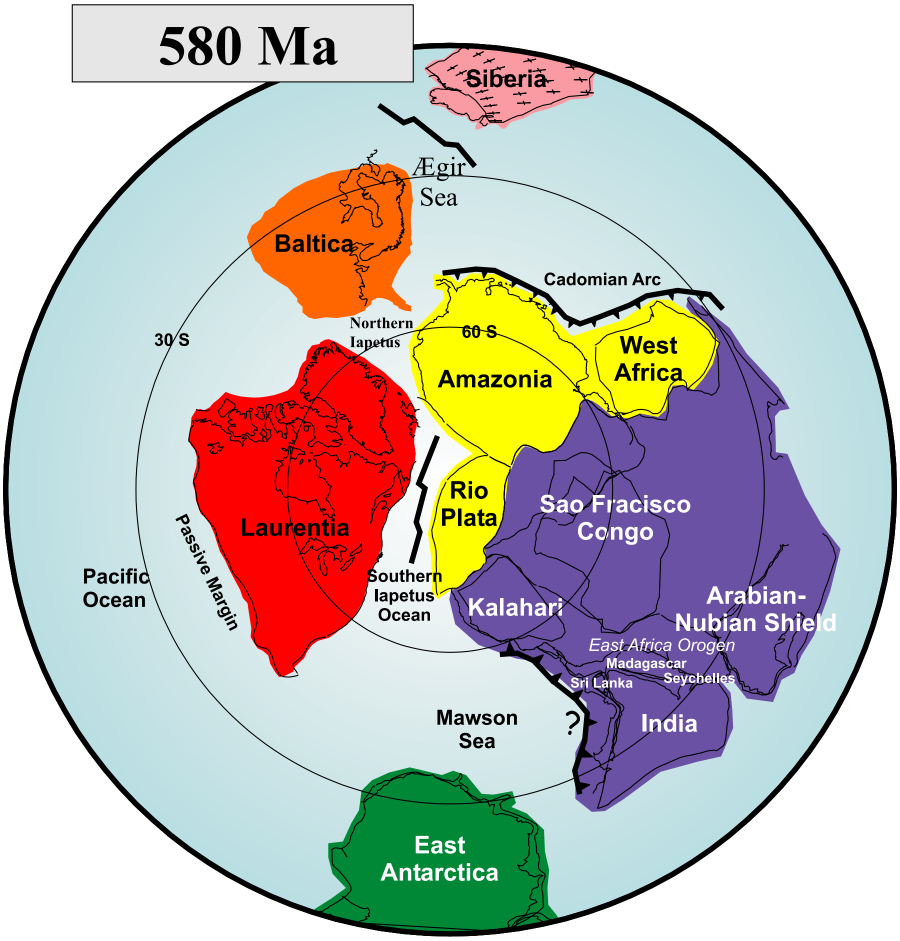


Fig. 11. 580 Ma reconstruction modified from Meert (2003), Torsvik and Rehnström (2001) and Hartz and Torsvik (2002).

tal blocks at 580 Ma. We note that in our reconstruction neither Australia nor the Mawson continent (East Antarctica, see Fitzsimons, 2000) have joined greater Gondwana and are separated from elements of eastern Gondwana by the Mawson Sea. Baltica and Siberia are shown in a slightly modified configuration advocated by Torsvik and Rehnström (2001), Rehnström et al. (2002) and Hartz and Torsvik (2002). Hartz and Torsvik (2002) suggest that the southern Iapetan Ocean opened by 550 Ma and was followed at around 535 Ma by the opening of the northern Iapetan Ocean. These models are critically dependent on the location of the Amazonian and Rio Plata cratons whose positions are largely unconstrained by paleomagnetic data although the model advocated by Tohver et al. (2002) would require a significant change to the paleogeography shown in Fig. 11 (requiring more than 4500 km of sinistral offset). On the other hand, preliminary data from the poorly dated Sierra de las Animas complex (Rio Plata craton) do support the reconstruction shown in Fig. 11 (Bettucci and Rapalini, 1997; Meert, 2001).

6. Conclusions

Meert and Powell (2001) highlighted the paucity of the paleomagnetic record in the latest Mesoproterozoic through Neoproterozoic time. New paleomagnetic data from the elements of Rodinia demonstrate the extremely fluid and controversial nature of 1100–500 Ma reconstructions. Our intent in this paper was to highlight the current status of paleomagnetic reconstructions for this time interval and to point out the extremely weak case for the Neoproterozoic supercontinent of Rodinia from those data. At the same time, we acknowledge that progress is made in small steps and paleomagnetism remains the only quantitative method for documenting plate motions and orientation during Neoproterozoic times. It is also important to note that the ambiguity in Proterozoic paleogeography is not confined to paleomagnetic models. Discussions regarding the makeup, position and orientation of many cratonic elements within the larger supercontinent of Rodinia are equally contentious. Nevertheless, a number of new high-quality paleomagnetic poles from Neoproterozoic and earlier times are providing new insights into the early geodynamic history of the earth.

Despite the uncertainty in the exact reconstruction, we can note that Laurentia is surrounded by Neoproterozoic rift margins and that similar-age collisional belts dissect Gondwana. Collectively, these observations are consistent with the notion of the breakup of one large continent and the subsequent assembly of another. Finally, we also note that although APWPs from several continents show similar lengths within the 1100–900 Ma interval, they do not necessarily provide strong evidence for the traditional Rodinia supercontinent, but are compatible with a component of true polar wander during that same interval.

Acknowledgements

Chris Powell spent most of the past 10 years studying the evolution of the late Proterozoic supercontinent. Chris, together with his colleagues at the Tectonics Research Centre, generated tremendous volumes of new data related to the formation and breakup of the supercontinent. Chris was both a good friend and an interesting scientific adversary. He always had time for lengthy discussions and was one of the most energetic scientists of our time. We will miss Chris and his contributions to our field and dedicate this work to his memory. We also wish to thank Sergei Pisarevsky, Rob Van der Voo and Mike McElhinny for their valuable comments on the manuscript.

Appendix A. Euler poles (clockwise)

Amazonia–Laurentia
This paper (modified from Tohver et al., 2002) 11.6, 286.6, −147.1 (Fig. 3a)
Tohver et al. (2002) 8.6, 280.2, −156.5

Antarctica–Laurentia fit
Karlstrom et al. (2001)—AUSWUS 34.4, 101.6, 123.5 (Fig. 3a)
Dalziel (1997)—SWEAT 12.8, 119.9, 134.8 (Fig. 3a)

Australia–Laurentia fit
Karlstrom et al. (2001)—AUSWUS 51.5, 106.7, 114.3 (Fig. 3a)
Dalziel (1997)—SWEAT 28.9, 126.1, 132.1 (Fig. 3a)

Baltica–Laurentia
Bullard et al. (1965) 88 N, 27 E, −38 (Fig. 2c)
Piper (1987) 80.5 N, 274 E, −66.5 (Fig. 2d)
Torsvik et al. (1996) 72, 43, −50 (Fig. 2e)
This study 70, 211, −35 (Fig. 2f)

Congo–Laurentia
Weil et al. (1998) 7 N, 150 E, −185 (Fig. 5b)
This study: 10.1 N, 164.7 E, −129.8 (Fig. 5c)
Alternative 2: 66.7 N, 278.1 E, −151.1 (Fig. 5d)

Kalahari–Laurentia
Weil et al. (1998) 15 S, 156 E, 147 (Fig. 4c)
Dalziel et al. (2000) 18.9 N, 23.9 W, −138 (Fig. 4d)
Powell et al. (2001) 63 N, 92.7 E, −152.3 (Fig. 4d)
This study: 64 N, 142.6 E, −164.6 (Fig. 4f)

Siberia–Laurentia
Dalziel (1997) 24.1, 17.2, 19.77 (Fig. 1)
This study 26.1, 351, −94 (Fig. 6d)

References

Åhäll, K.I., Connelly, J.N., Brewer, T.S., 2000. Episodic rapikivi magmatism due to distal orogenesis?: correlation of 1.69–1.50 Ga orogenic and inboard, 'anorogenic' events in the Baltic shield. Geology 28, 823–826.

Almeida, F.F., Brito Neves, B.B., Carneiro, C.D.R., 2000. The origin and evolution of the South American platform. Earth Sci. Rev. 50, 77–111.

Bettucci, L.S., Rapalini, A.E., 1997. Preliminary paleomagnetic data from the Sierra de las Animas complex, Uruguay and their implications in the Gondwana assembly. Terrane Dynamics, Christchurch, New Zealand, pp. 154–156. Extended abstracts.

Boger, S.D., Carson, C.J., Fanning, C.M., Hergt, J.M., Wilson, C.J.L., Woodhead, J.D., 2002. Pan-African intraplate deformation in the northern Prince Charles Mountains, east Antarctica. Earth Planet. Sci. Lett. 195, 195–210.

Bond, G.C., Nickeson, P.A., Kominz, M.A., 1984. Breakup of a supercontinent between 625 and 555 Ma: new evidence and implications for continental histories. Earth Planet. Sci. Lett. 70, 325–345.

Briden, J.C., McClelland, E., Rex, D.C., 1993. Proving the age of a paleomagnetic pole: the case of the Ntonya ring structure, Malawi. J. Geophys. Res. 98, 1743–1749.

Brito-Neves, B.B., 2002. Main stages of development of the sedimentary basins of South America and their relationship with the tectonics of supercontinents. Gondwana Res. 5, 175–196.

Buchan, K.L., Ernst, R.E., Hamilton, M.A., Mertanen, S., Pesonen, L.J., Elming, S.A., 2001. Rodinia: the evidence from integrated paleomagnetism and U–Pb geochronology. Precambrian Res. 110, 9–32.

Bullard, E.C., Everett, J.E., Smith, A.G., 1965. The fit of the continents around the Atlantic. Philos. Trans. R. Soc. Lond. (Ser. A.) 258, 41–51.

Christie, K.W., Fahrig, W.F., 1983. Paleomagnetism of the Borden dykes of Baffin island and its bearing on the Grenville Loop. Can. J. Earth Sci. 20, 275–289.

Condie, K.C., Rosen, O.M., 1994. Laurentia–Siberia connection revisited. Geology 22, 168–170.

D'Agrella-Filho, M.S., Pacca, I., Renne, P.R., Onstott, T.C., Texeira, W., 1990. Paleomagnetism of middle Proterozoic (1.01–1.08 Ga) mafic dykes in southeastern Bahia state, Sao Francisco craton, Brazil. Earth Planet. Sci. Lett. 101, 332–348.

D'Agrella-Filho, M.S., Babinski, M., Trindade, R.I.F., Van Schmus, W.R., Ernesto, M., 2000. Simultaneous remagnetization and U–Pb isotopes in Neoproterozoic carbonates of the Sao Francisco craton, Brazil. Precambrian Res. 99, 179–186.

Dalziel, I.W.D., 1991. Pacific margins of Laurentia and East Antarctica as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. Geology 19, 598–601.

Dalziel, I.W.D., 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis and environmental speculation. Geol. Soc. Am. Bull. 109, 16–42.

Dalziel, I.W.D., Mosher, S., Gahagan, L.M., 2000. Laurentia–Kalahari collision and the assembly of Rodinia. J. Geol. 108, 499–513.

Davies, J., Nairn, A.E.M., Ressetar, R., 1980. The paleomagnetism of certain late Precambrian and early Paleozoic rocks from the Red Sea Hills, eastern desert, Egypt. J. Geophys. Res. 85, 3699–3710.

Dewey, J.F., Burke, K.C.A., 1973. Tibetan, Variscan and Precambrian basement reactivation: products of continental collision. J. Geol. 81, 683–692.

Diehl, J.F., Haig, T.D., 1994. A paleomagnetic study of the lava flows within the Copper Harbor conglomerate, Michigan: new results and implications. Can. J. Earth Sci. 31, 369–380.

Elming, S.A., Mattson, H., 2001. Post-Jotnian basic intrusions in the Fennoscandian shield, and the break up of Baltica and from Laurentia: a paleomagnetic and AMS study. Precambrian Res. 108, 215–236.

Elston, D.P., Bressler, S.L., 1977. Paleomagnetic poles and polarity zonation from Cambrian and Devonian strata of Arizona. Earth Planet. Sci. Lett. 36, 423–433.

Ernst, R.E., Buchan, K.L., 1993. Paleomagnetism of the Abitibi dyke swarm, southern Superior Province, and its implications for the Logan Loop. Can. J. Earth Sci. 30, 1886–1897.

Ernst, R.E., Buchan, K.L., Hamilton, M.A., Okrugin, A.V., Tomshin, M.D., 2000. Integrated paleomagnetism and U–Pb geochronology of Mafic dikes of the Eastern Anabar shield region, Siberia: implications for Mesoproterozoic paleolatitude of Siberia and comparison with Laurentia. J. Geol. 108, 381–401.

Evans, D.A., 1998. True polar wander, a supercontinental legacy. Earth Planet. Sci. Lett. 157, 1–8.

Evans, D.A.D., Li, Z.X., Kirschvink, J.L., Wingate, M.T.D., 2000. A high-quality mid-Proterozoic paleomagnetic pole from South China, with implications for an Australia–Laurentia connection at 755 Ma. Precambrian Res. 100, 213–234.

Fitzsimons, I.C.W., 2000. A review of tectonic events in the East Antarctic shield, and their implications for Gondwana and earlier supercontinents. J. Afr. Earth Sci. 31, 3–23.

Foden, J., Barovich, K., Jane, M., O'Halloran, G., 2001. Sr-isotopic evidence for late Neoproterozoic rifting in the Adelaide geosyncline at 586 Ma; implications for Cu ore forming flux. Precambrian Res. 106, 291–308.

Frost, B.R., Avchenko, O.V., Chamberlin, K.R., Geldsetzer, H.H.J., 1998. Evidence for extensive Proterozoic remobilization of the Aldan shield and implications for Proterozoic plate tectonic reconstructions of Siberia and Laurentia. Precambrian Res. 89, 1–23.

Gallet, Y., Pavlov, V.E., 1996. Magnetostratigraphy of the Moyero River section (north-western Siberia): constraints on geomagnetic reversal frequency during the early Paleozoic. Geophys. J. Int. 125, 95–105.

Gallet, Y., Pavlov, V.E., Semikhatov, M.A., Petrov, P.Y., 2000. Late Mesoproterozoic magnetostratigraphic results from Siberia: paleogeographic implications and magnetic field behavior. J. Geophys. Res. 105, 16, 481–16, 500.

Geraldes, M.C., Van Schmus, W.R., Condie, K.C., Bell, S., Texeira, W., Babinski, M., 2001. Proterozoic geologic evolution of the SW part of the Amazonian craton in Mato Grosso state, Brazil. Precambrian Res. 111, 91–128.

Gose, W.A., Helper, M.A., Connelly, J.N., Hutson, F.E., Dalziel, I.W.D., 1997. Paleomagnetic data and U–Pb isotopic age determinations from Coats Land, Antarctica: implications for Neoproterozoic plate reconstructions. J. Geophys. Res. 102, 7887–7902.

Green, J.C., Bornhorst, T.J., Chandler, V.W., Mudrey, M.D., Myers, P.E., Pesonen, L.J., Wilband, J.T., 1987. Keewanawan dykes of the Lake Superior region: evidence for evolution of the middle Proterozoic mid-continent rift in North America. In: Halls, H.C., Fahrig, W.F. (Eds.), Mafic Dyke Swarms, Geol. Assoc. Can. Spec., pp. 289–302.

Halls, H.C., 1974. A paleomagnetic reversal in the Osler Volcanic Group, northern Lake Superior. Can. J. Earth Sci. 11, 1200–1207.

Halls, H.C., Palmer, H.C., 1981. Remagnetization in Keewanawan rocks: Part II. Lava flows within the Copper Harbor Conglomerate. Can. J. Earth Sci. 18, 1395–1408.

Halls, H.C., Pesonen, L.J., 1982. Paleomagnetism of Keewanawan rocks. In: Wold, R.J., Hinze, W.J. (Eds.), Geology and Tectonics of the Lake Superior Basin. Geol. Soc. Am. Mem., vol. 156, pp. 173–201.

Hanley, L.M., Wingate, M.T.D., 2000. SHRIMP zircon age for an early Cambrian dolerite dyke: an intrusive phase of the Antrim

Plateau volcanics of northern Australia. Aus. J. Earth Sci. 47, 1029–1040.

Hargraves, R.B., Duncan, R.A., 1990. Radiometric age and paleomagnetic results from Seychelles dikes. In: Duncan, R.A., et al. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results Leg, vol. 115, pp. 119–122.

Hargraves, R.B., Hattingh, P.J., Onstott, T.C., 1994. Paleomagnetic results of the Timbaratic gabbros in the Kruger National Park. S. Afr. J. Geol. 97, 114–118.

Hartnady, C.J.H., Onstott, T.C., 1992. A Mesoproterozoic geosuture link between North America and Southern Africa? Trans. Am. Geophys. Union EOS 73, 365.

Hartz, E.H., Torsvik, T.H., 2002. Baltica upside down: a new plate tectonic model for Rodinia and the Iapetus Ocean. Geology 30, 255–258.

Henry, S.G., Mauk, F.J., Van der Voo, R., 1977. Paleomagnetism of the Upper Keewanawan sediments: the Nonesuch shale and Freda sandstone. Can. J. Earth Sci. 14, 1128–1138.

Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside out? Science 252, 1409–1412.

Hyodo, H., Dunlop, D.J., 1993. Effect of anisotropy on the paleomagnetic contact test for a Grenville dyke. J. Geophys. Res. 98, 7997–8017.

Hyodo, H., Dunlop, D.J., McWilliams, M.O., 1986. Timing and extent of Grenvillian overprinting near Temagami. Geol. Soc. Can. Spec. Pap. 31, 119–126.

Irving, E., Park, J.K., Roy, J.L., 1972. Paleomagnetism and the origin of the Grenville Front. Nature 236, 344–346.

Jacobs, J., Thomas, R.J., Weber, K., 1993. Accretion and indentation tectonics at the southern edge of the Kaapvaal continent, south-east Africa. Geol. Rundsch. 83, 322–333.

Jacobs, J., Falter, M., Thomas, R.J., Kunz, J., Jeßburger, E.K., 1997. ^{40}Ar/^{39}Ar thermochronological constraints on the structural evolution of the Mesoproterozoic Natal metamorphic province, SE Africa. Precambrian Res. 86, 71–92.

Jacobs, J., Fanning, C.M., Henjes-Kunst, F., Olesch, M., Paech, H.J., 1998. Continuation of the Mozambique Belt into East Antarctica: Grenville-age metamorphism and polyphase Pan-African high-grade events in central Dronning Maude Land. J. Geol. 106, 385–406.

Jones, D.L., McElhinny, M.W., 1966. Paleomagnetic correlation of basic intrusions in the Precambrian of southern Africa. J. Geophys. Res. 71, 543–552.

Jones, D.L., Bates, M.P., Hodgkinson, G., Corner, B., Powell, C. McA., 1999. Paleomagnetic results from the mid-Proterozoic Richtersflya Supergroup of Queen Maud Lan, Antarctica–The Kalahari craton–Grunehogna Province connection. IUGG XXII General Assembly, Abstracts, Birmingham, UK., A309.

Karlstrom, K.E., Harlan, S.S., Williams, M.L., McClelland, J., Geissman, J.W., Åhäll, K.-I., 1999. Refining Rodinia: geologic evidence for the Australia–western US connection in the Proterozoic. GSA Today 9 (10), 1–7.

Karlstrom, K.E., Åhäll, K.-I., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., 2001. Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. Precambrian Res. 111, 5–30.

Kempf, O., Kellerhalls, P., Lowrie, W., Matter, A., 2000. Paleomagnetic directions in Precambrian/Cambrian glaciomarine sediments of the Mirbat sandstone formation, Oman. Earth Planet. Sci. Lett. 175, 181–190.

Kent, D.V., Smethurst, M.A., 1998. Shallow bias of paleomagnetic inclinations in the Paleozoic and Precambrian. Earth Planet. Sci. Lett. 160, 391–402.

Kirschvink, J.L., 1978. The Precambrian Cambrian boundary problem; magnetostratigraphy of the Amadeus Basin, central Australia. Geol. Mag. 115, 139–150.

Kirschvink, J.L., Ripperdan, R.L., Evans, D.A., 1997. Evidence for a large-scale reorganization of early Cambrian continental landmasses by inertial interchange true polar wander. Science 277, 541–545.

Klootwijk, C.T., 1980. Early Palaeozoic paleomagnetism in Australia. Tectonophysics 64, 249–332.

Kravchinsky, V.A., Konstantinov, K.M., Cogne, J.P., 2001. Paleomagnetic study of Vendian and early Cambrian rocks of South Siberia and Central Mongolia: was the Siberian platform assembled at this time? Precambrian Res. 110, 61–92.

Kumar, A., Kumari, P., Dayal, A.M., Murthy, D.S.N., Gopalan, K., 1993. Rb–Sr ages of Proterozoic kimberlites of India: evidence for contemporaneous emplacements. Precambrian Res. 62, 227–237.

Kumar, B., Das Sharma, S., Sreevinas, M.N., Dayal, A.M., Rao, N., Dubey, N., Chawla, B.R., 2002. Carbon, oxygen and strontium isotope geochemistry of Proterozoic carbonate rocks of the Vindhyan Basin, central India. Precambrian Res. 113, 43–64.

Lawver, L., Scotese, C.R., 1987. A revised reconstruction of Gondwanaland. In: McKenzie, G.D. (Ed.), Gondwana Six: StructureTectonics and Geophysics, Am. Geophys. Un. Mon., vol. 40, pp. 17–23.

Lewchuk, M.T., Symons, D.T.A., 1990a. Paleomagnetism of the late Precambrian Coldwell Complex, Ontario, Canada. Tectonophysics 184, 73–86.

Lewchuk, M.T., Symons, D.T.A., 1990b. Paleomagnetism of the Clay-Howell's carbonatite complex: constraints on Proterozoic motion in the Kapuskasing structural zone, Superior Province, Canada. Tectonophysics 172, 67–75.

Lin, J.L., Fuller, M.D., Zhang, W.Y., 1985. Paleogeography of the North and South China Blocks during the Cambrian. J. Geodyn. 2, 91–114.

McElhinny, M.W., Luck, G.R., 1970. The palaeomagnetism of the Antrim Plateau volcanics of northern Australia. Geophys. J. Roy. Astr. Soc. 20, 191–205.

McElhinny, M.W., Cowley, J.A., Edwards, D.J., 1978. Paleomagnetism of some rocks from peninsular India and Kashmir. Tectonophysics 50, 41–54.

McMenamin, M.A.S., McMenamin, D.L.S., 1990. The Emergence of Animals; The Cambrian Breakthrough. Columbia Univ. Press, New York. 217 pp.

McWilliams, M.O., McElhinny, M.W., 1980. Late Precambrian paleomagnetism in Australia in the Adelaide geosyncline. J. Geol. 88, 1–26.

Meert, J.G., 1999. A paleomagnetic analysis of Cambrian true polar wander. Earth Planet. Sci. Lett. 168, 131–144.

Meert, J.G., 2001. Growing Gondwana and rethinking Rodinia: a paleomagnetic perspective. Gondwana Res. 4, 279–288.

Meert, J.G., 2002. Paleomagnetic evidence for a Paleo-Mesoproterozoic supercontinent Columbia. Gondwana Res. 5, 207–216.

Meert, J.G., 2003. A synopsis of events related to the assembly of eastern Gondwana. Tectonophysics 362, 1–40.

Meert, J.G., Powell, C. McA., 2001. Introduction to the special volume on the assembly and breakup of Rodinia. Precambrian Res. 110, 1–8.

Meert, J.G., Van der Voo, R., 1996. Paleomagnetic and ^{40}Ar/^{39}Ar study of the Sinyai dolerite, Kenya: implications for Gondwana assembly. J. Geol. 104, 131–142.

Meert, J.G., Van der Voo, R., 2001. Comment: new palaeomagnetic result from the Vendian red sediments in Cisbaikalia and the problem of the relationship of Siberia and Laurentia in the Vendian by S.A. Pisarevsky et al. Geophys. J. Int. 146, 867–870.

Meert, J.G., Van der Voo, R., Payne, T., 1994a. Paleomagnetism of the Catoctin volcanic province: a new Vendian–Cambrian apparent polar wander path for North America. J. Geophys. Res. 99 (B3), 4625–4641.

Meert, J.G., Hargraves, R.B., Van der Voo, R., Hall, C.M., Halliday, A.N., 1994b. Paleomagnetic and ^{40}Ar/^{39}Ar studies of late Kibaran intrusives in Burundi, East Africa: implications for late Proterozoic supercontinents. J. Geol., 621–637.

Meert, J.G., Van der Voo, R., Ayub, S., 1995. Paleomagnetic investigation of the Neoproterozoic Gagwe lavas and Mbozi Complex, Tanzania and the assembly of Gondwana. Precambrian Res. 74, 225–244.

Meert, J.G., Torsvik, T.H., Eide, E.A., Dahlgren, S., 1998. Tectonic significance of the Fen Province, S. Norway: constraints from geochronology and paleomagnetism. J. Geol. 106, 553–564.

Meert, J.G., Nédélec, A., Hall, C., Wingate, M.T.D., Rakotondrazafy, M., 2001. Paleomagnetism, geochronology and tectonic implications of the Cambrian-age Carion granite, central Madagascar. Tectonophysics 340, 1–21.

Meert, J.G., Nédélec, A., Hall, C., 2003. The stratoid granites of central Madagascar: paleomagnetism and further age constraints on Neoproterozoic deformation. Precambrian Res. 120, 101–129.

Miller, K.C., Hargraves, R.B., 1994. Paleomagnetism of some Indian kimberlites and lamproites. Precambrian Res. 69, 259–267.

Moores, E.M., 1991. Southwest U.S.–East Antarctic (SWEAT) connection: a hypothesis. Geology 19, 425–428.

Morris, W.A., Aitken, J.D., 1982. Paleomagnetism of the Little Dal Lavas, McKenzie Mountains, Northwest Territories, Canada. Can. J. Earth Sci. 19, 2020–2027.

Mosher, S., 1998. Tectonic evolution of the southern Laurentian Grenville orogenic belt. Geol. Soc. Am. Bull. 110, 1357–1375.

Murthy, G., Gower, C., Turrett, M., Pätzold, R., 1992. Paleomagnetism of the Eocambrian Long Range dykes and Double Mer Formation from Labrador, Canada. Can. J. Earth Sci. 29, 1224–1234.

Nairn, A.E.M., Perry, T.A., Ressetar, R., Rogers, S., 1987. A paleomagnetic study of the Dokhan volcanic formation and younger granites, eastern desert of Egypt. J. Afr. Earth Sci. 6, 353–365.

Onstott, T.C., Hargraves, R.B., Joubert, P., 1986. Constraints on the evolution of the Namaqua Province II: reconnaissance paleomagnetic and ^{40}Ar/^{39}Ar results from the Namaqua Province and the Kheis Belt. Trans. Geol. Soc. S. Afr. 89, 143–170.

Osipova, E.P., 1986. Pole number 12060. In: Khramov, A.N. (Ed.), Paleomagnetic directions and paleomagnetic poles. Data for the USSR, Issue 6. Materials of the WDC-B, Moscow, p. 20 and 35 (in Russian).

Palmer, H.C., Halls, H.C., 1986. Paleomagnetism of the Powder Mill Group, Michigan and Wisconsin: a reassessment of the Logan Loop. J. Geophys. Res. 91, 11571–11580.

Park, J.K., 1981a. Paleomagnetism of basic intrusions from the Brock inlier, Northwest Territories, Canada. Can. J. Earth Sci. 18, 1637–1641.

Park, J.K., 1981b. Analysis of multicomponent magnetization of the Little Dal Group, Mackenzie Mountains, Northwest Territories, Canada. J. Geophys. Res. 86, 5134–5146.

Park, J.K., 1992. Did Laurentia pass over the south pole during earliest Cambrian time? Geol. Surv. Can. Pap. 92-1E, 11–22 (in Current Research, Part E).

Park, J.K., Aitken, J.D., 1986. Paleomagnetism of the late Proterozoic Tsezotene Formation of northwest Canada. J. Geophys. Res. 91, 4955–4970.

Patchett, P.J., Bylund, G., 1977. Age of Grenville Belt magnetization: Rb–Sr and paleomagnetic evidence from Swedish dolerites. Earth Planet. Sci. Lett. 35, 92–104.

Pavlov, V., Gallet, Y., 2001. Middle Cambrian high magnetic reversal frequency (Kulumbe River section, northwestern Siberia) and reversal behavior during the early Paleozoic. Earth Planet. Sci. Lett. 185, 173–183.

Pavlov, V., Burakov, K.S., Tsel'movich, V.A., Zhuralev, D.Z., 1992. Paleomagnetism of sills of the Uchur-Maya region and estimation of geomagnetic field strength in the late Riphean. Izvestiya 28, 72–79.

Pelechaty, S.M., 1996. Stratigraphic evidence for the Siberia–Laurentia connection and early Cambrian rifting. Geology 24, 719–722.

Pesonen, L.J., Bylund, G., Torsvik, T.H., Elming, S.A., Mertanen, S., 1991. Catalogue of palaeomagnetic directions from Fennoscandia: Archean to Tertiary. Tectonophysics 195, 151–207.

Piper, J.D.A., 1976. Palaeomagnetic evidence for a Proterozoic supercontinent. Philos. Trans. R. Soc. Lond. A280, 469–490.

Piper, J.D.A., 1987. Palaeomagnetism and the Continental Crust. Open Univ. Press, Milton Keynes. 434 pp.

Piper, J.D.A., 2000. The Neoproterozoic supercontinent: Rodinia or Palaeopangea? Earth Planet. Sci. Lett. 176, 131–146.

Pisarevsky, S.A., Gurevich, E.L., Khramov, A.N., 1998. Paleomagnetism of lower Cambrian sediments from the Olenek River section (northern Siberia): paleopoles and the problem of magnetic polarity in the early Cambrian. Geophys. J. Int. 130, 746–756.

Pisarevsky, S.A., Komissarova, R.A., Khramov, A.N., 2000. New paleomagnetic result from Vendian red sediments in Cisbaikalia and the problem of the relationship of Siberia and Laurentia in the Vendian. Geophys. J. Int. 140, 598–610.

Pisarevsky, S.A., Li, Z.X., Grey, K., Stevens, M.K., 2001. A palaeomagnetic study of Empress 1A, a stratigraphic drillhole in the Officer Basin: evidence for a low-latitude position of Australia in the Neoproterozoic. Precambrian Res. 110, 93–108.

Poorter, R.P.E., 1972. Paleomagnetism of the Rogaland Precambrian (southwestern Norway). Phys. Earth Planet. Int. 5, 167–176.

Powell, C. McA., Pisarevsky, S., 2002. Late Neoproterozoic assembly of East Gondwana. Geology 30, 3–6.

Powell, C. McA., McElhinny, M.W., Li, Z.X., Meert, J.G., Park, J.K., 1993. Paleomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana. Geology 21, 889–892.

Powell, C. McA., Jones, D.L., Pisarevsky, S., Wingate, M.T.D., 2001. Paleomagnetic constraints on the position of the Kalahari craton in Rodinia. Precambrian Res. 110, 33–46.

Radhakrishna, T., Joseph, M., 1996. Late Precambrian (850–800 Ma) paleomagnetic pole for the south Indian Shield from the Harohalli alkaline dykes; geotectonic implications for Gondwana reconstructions. Precambrian Res. 80, 77–87.

Rainbird, R.H., Stern, R.A., Khudoley, A.K., Kropachev, A.P., Heamon, L.M., Sukhorukov, V.I., 1998. U–Pb geochronology of Riphean sandstone and gabbro from southeast Siberia and its bearing on the Laurentia–Siberia connection. Earth Planet. Sci. Lett. 164, 409–420.

Rao, G.V.S.P., Bhalla, M.S., 1996. Magnetostratigraphy of the Vindhyan Supergroup. J. Geol. Soc. India 47, 29–32.

Rassmussen, B., Bose, P.K., Sarkar, S., Banerjee, S., Fletcher, N.J., MacNaughton, N.J., 2002. 1.6 Ga U–Pb zircon age for the Chorhat sandstone, lower Vindhyan, India: possible implications for early evolution of animals. Geology 30, 103–106.

Ray, J.S., Martin, M.W., Veizer, J., Bowring, S.A., 2002. U–Pb zircon dating and Sr isotope systematics of the Vindhyan Supergroup, India. Geology 30, 131–134.

Rehnström, E.F., Corfu, F., Torsvik, T.H., 2002. Evidence of a late Precambrian (637 Ma) deformational event in the Caledonides of northern Sweden. J. Geol. 110, 591–601.

Reischmann, Th., Bachtadse, V., Kroner, A., Layer, P., 1992. Geochronology and paleomagnetism of a late Proterozoic island arc terrane from the Red Sea Hills, northeast Sudan. Earth Planet. Sci. Lett. 114, 1–15.

Robb, L.J., Armstrong, R.A., Waters, D.J., 1999. The history of granulite facies metamorphism and crustal growth from single zircon U–Pb geochronology: Namaqualand, South Africa J. Petrol. 40, 1747–1770.

Rogers, J.J.W., Santosh, M., 2002. Configuration of Columbia, a Mesoproterozoic supercontinent. Gondwana Res. 5, 5–22.

Roy, J.L., Robertson, W.A., 1978. Paleomagnetism of the Jacobsville Formation and the apparent polar wander path for the interval 1100–670 m.y. for North America. J. Geophys. Res. 83, 1289–1304.

Rui, Z.Q., Piper, J.D.A., 1997. Paleomagnetic study of Neoproterozoic glacial rocks of the Yangzi Block; paleolatitudes and configuration of South China in the late Proterozoic supercontinent. Precambrian Res. 85, 173–199.

Sahasrabudhe, P.W., Mishra, D.C., 1966. Paleomagnetism of Vindhyan rocks of India. Bull. NGRI 4, 49–55.

Sears, J.W., Price, R.A., 2000. New look at the Siberian connection: no SWEAT. Geology 28, 423–426.

Smethurst, M.A., Khramov, A., Torsvik, T.H., 1998. Paleomagnetic constraints on the Neoproterozoic–Palaeozoic drift history of the Siberian platform: Rodinia to Pangea. Earth Sci. Rev. 43, 1–24.

Sohl, L.E., Christie-Blick, N., Kent, D.V., 1999. Paleomagnetic polarity reversals in Marinoan (~ 600 Ma) glacial deposits of Australia: implications for the duration of low-latitude glaciation in the Neoproterozoic. Bull. Geol. Soc. Am. 111, 1120–1139.

Stern, R.J., 1994. Arc assembly and continental collision in the Neoproterozoic East African Orogen: implications for the assembly of Gondwanaland. Annu. Rev. Earth Planet. Sci. 22, 319–351.

Suwa, K., Tokieda, M., Hoshino, M., 1994. Paleomagnetic and petrological reconstruction of the Seychelles. Precambrian Res. 69, 281–292.

Symons, D.T.A., 1992. Paleomagnetism of the Keewanawan Chipman Lake and Seabrook Lake carbonatite complexes, Ontario. Can. J. Earth Sci. 29, 1215–1223.

Symons, D.T.A., Chiasson, A.D., 1991. Paleomagnetism of the Callander Complex and the Cambrian apparent polar wander path for North America. Can. J. Earth Sci. 28, 355–363.

Tanczyk, E.I., Lapointe, P., Morris, W.A., Schmidt, P.W., 1987. A paleomagnetic study of the layered mafic intrusions at Sept-Iles, Quebec. Can. J. Earth Sci. 24, 1431–1438.

Texeira, W., Renne, P.R., Bossi, J., Campal, N., D'Agrella-Filho, M.S., 1999. ^{40}Ar/^{39}Ar and Rb–Sr geochronology of the Uruguayan dike swarm, Rio de la Plata craton and implications for Proterozoic intraplate activity in western Gondwana. Precambrian Res. 93, 153–180.

Tohver, E., van der Pluijm, B.A., Van der Voo, R., Rizzoto, G., Scandolara, J.E., 2002. Paleogeography of the Amazon craton at 1.2 Ga: early Grenvillian collision with the Llano segment of Laurentia. Earth Planet. Sci. Lett. 199, 185–200.

Torsvik, T.H., Rehnström, E.F., 2001. Cambrian paleomagnetic data from Baltica: implications for true polar wander and Cambrian paleogeography. J. Geol. Soc. Lond. 158, 321–329.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Sturt, B.A., Brasier, M.D., Walderhaug, H.J., 1996. Continental breakup and collision in the Neoproterozoic and Paleozoic—a tale of Baltica and Laurentia. Earth Sci. Rev. 40, 229–258.

Torsvik, T.H., Meert, J.G., Smethurst, M.A., 1998. Polar wander and the Cambrian. Science 279, 9a.

Torsvik, T.H., Mosar, J., Eide, E.A., 2001a. Cretaceous–Tertiary Geodynamics: a North Atlantic exercise. Geophys. J. Int. 146, 850–867.

Torsvik, T.H., Carter, L.M., Ashwal, L.D., Bhushan, S.K., Pandit, M.K., Jamtveit, B., 2001b. Rodinia refined or obscured: paleomagnetism of the Malani igneous suite (NW India). Precambrian Res. 108, 319–333.

Trompette, R., 1997. Neoproterozoic (~ 600 Ma) aggregation of Western Gondwana: a tentative scenario. Precambrian Res. 82, 101–112.

Van der Voo, R., 1990. The reliability of paleomagnetic data. Tectonophysics 184, 1–9.

Van der Voo, R., Meert, J.G., 1991. Late Proterozoic paleomagnetism and tectonic models: a critical appraisal. Precambrian Res. 53, 149–163.

Van der Voo, R., Torsvik, T.H., 2001. Evidence for Permian and

Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems. Earth Planet. Sci. Lett. 187, 71–81.

Walderhaug, H.J., Torsvik, T.H., Eide, E.A., Sundvoll, B., Bingen, B., 1999. Geochronology and paleomagnetism of the Hunnedalen dykes, SW Norway: implications for the Sveconorwegian apparent polar wander loop. Earth Planet. Sci. Lett. 169, 71–83.

Walter, M.R., Veevers, J.J., Calver, C.R., Gorjan, P., Hill, A.C., 2000. Dating the 840–544 Ma Neoproterozoic interval by isotopes of strontium, carbon and sulfur in seawater, and some interpretative models. Precambrian Res. 100, 371–432.

Watts, D.P., 1981. Paleomagnetism of the Fond du Lac formation and the Eileen and Middle River sections with implications for Keewanawan tectonics and the Grenville problem. Can. J. Earth Sci. 18, 829–841.

Weil, A.B., Van der Voo, R., MacNiocall, C., Meert, J.G., 1998. The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1100–800 Ma. Earth Planet. Sci. Lett. 154, 13–24.

Wilde, S.A., Youssef, K., 2000. Significance of SHRIMP dating of the Imperial Porphry and associated Dokhan volcanics, Gebel Dokhan, northeastern Egypt. J. Afr. Earth Sci. 31, 403–413.

Wilson, J.T., 1966. Did the Atlantic close and then re-open? Nature 211, 676–681.

Wingate, M.T.D., Giddings, J.W., 2000. Age and paleomagnetism of the Mundine Well dyke swarm, western Australia: implications for an Australia–Laurentia connection at 750 Ma. Precambrian Res. 100, 335–357.

Wingate, M.T.D., Pisarevsky, S.A., Evans, D.A.D., 2002. Rodinia connections between Australia and Laurentia: no SWEAT, no AUSWUS? Terra Nova 14, 121–128.

Young, G.M., 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to the fragmentation of two supercontinents? Geology 23, 153–156.