Models of Rodinia assembly and fragmentation

SERGEI A. PISAREVSKY, MICHAEL T. D. WINGATE, CHRIS MCA. POWELL, SIMON JOHNSON & DAVID A. D. EVANS

Tectonics Special Research Centre, Department of Geology and Geophysics, The University of Western Australia, 35 Stirling Highway, Crawley, 6009, WA, Australia.
(e-mail: spisarev@tsrc.uwa.edu.au)

Abstract: Amongst existing palaeogeographic models of the Rodinia supercontinent, or portions thereof, arguments have focused upon geological relations or palaeomagnetic results, but rarely both. A new model of Rodinia is proposed, integrating the most recent palaeomagnetic data with current stratigraphic, geochronological and tectonic constraints from around the world. This new model differs from its predecessors in five major aspects: cratonic Australia is positioned in the recently proposed AUSMEX fit against Laurentia; East Gondwanaland is divided among several blocks; the Congo–São Francisco and India–Rayner Cratons are positioned independently from Rodinia; Siberia is reconstructed against northern Laurentia, although in a different position than in all previous models; and Kalahari–Dronning Maud Land is connected with Western Australia. The proposed Rodinia palaeogeography is meant to serve as a working hypothesis for future refinements.

There is general agreement that the Earth's continental crust may have been assembled to form the supercontinent, Rodinia, in the Late Mesoproterozoic and Early Neoproterozoic. Rodinia is thought to have been produced by collisional events of broadly Grenvillian (Late Mesoproterozoic) age, and to have been relatively long-lived (*c.* 1100–750 Ma) (McMenamin & McMenamin 1990; Hoffman 1991).

Nonetheless, there are several versions of its composition and configuration (e.g. Hoffman 1991; Dalziel 1997; Weil *et al.* 1998). Laurentia is thought to have formed the core of Rodinia because it is surrounded by passive margins formed during Late Neoproterozoic breakup of the supercontinent (Bond *et al.* 1984). Most Rodinia models propose that Australia, Antarctica and possibly South China (Li *et al.* 1999) may have been situated along Laurentia's western margin (unless otherwise stated, all geographic references are in present coordinates); Baltica and Amazonia, and the Rio de la Plata Craton may have lain along its eastern margin. The precise position of Siberia is disputed, but it is generally shown as lying along either the northern or the western margin of Laurentia. The position of the Congo and Kalahari Cratons is uncertain, with at least four reconstructions having been shown for Kalahari in the last few years (Powell *et al.* 2001). An alternative Neoproterozoic supercontinent, Palaeopangaea, was proposed by Piper (2000), based mainly on palaeomagnetic data. This model is similar to earlier reconstructions by the same author (Piper 1987 and refs cited therein), which were criticized by both Van der Voo & Meert (1991) and Li & Powell (1999). In addition, the recent publication about Palaeopangaea (Piper 2000) contains no references for the poles employed, making the model difficult to assess. For these reasons, it will not be discussed further in this paper.

Several important results have been published recently that provide new geological, geochronological and palaeomagnetic constraints on Mesoproterozoic–Early Neoproterozoic palaeogeography. Palaeomagnetic data are necessary for quantitative constraints on Precambrian reconstructions. Unfortunately, these data are distributed very non-uniformly in time and space (Meert & Powell 2001 table 1). The majority of palaeomagnetic results for the interval during which Rodinia may have existed (*c.* 1100–750 Ma) come from Laurentia and Baltica, and fragments of apparent polar wander paths (APWP) can be constructed for these two blocks. Data from other cratons are sparse, making it impossible to construct an APWP for each block. The palaeopositions of these blocks are based on comparisons of individual palaeopoles, hence relative palaeolongitudes are not constrained.

The objective of this paper is to create a new model of the Rodinia supercontinent. Palaeomagnetism has been used to determine permissible fits for Rodinia; geological constraints, such as continuity of tectonic belts, and the presence of passive or active continental margins have been used to refine permissible fits into plausible reconstructions. There is also the global balance of Late Neoproterozoic rifted margins that needs to be accounted for in any acceptable reconstruction.

Selection of reliable palaeomagnetic data is the key issue for many Mesoproterozoic–Neoproterozoic reconstructions (e.g. Powell *et al.*

From YOSHIDA, M., WINDLEY, B. F. & DASGUPTA, S. (eds) 2003. *Proterozoic East Gondwana: Supercontinent Assembly and Breakup*. Geological Society, London, Special Publications, **206**, 35–55. 0305-8719/03/$15

1993; Torsvik *et al.* 1996; Smethurst *et al.* 1998; Weil *et al.* 1998; Piper 2000). In the present synthesis (Table 1), only palaeomagnetic results with $Q \geq 4$ are used (Van der Voo 1990). There are few exceptions where less reliable data is referred to and all such cases are explained individually. However, existing data are insufficient to provide robust reconstructions for all cratons except Laurentia and Baltica. In addition, there are no reliable palaeomagnetic data for Amazonia, West Africa and Rio de la Plata in the interval 1100–700 Ma.

In attempting to reconstruct Rodinia, available information from the majority of Precambrian continental blocks was used. Because very little is known about the Rodinian connections of North China, NE Africa and Arabia, Avalonia, Cadomia, Omolon, and other fragments of continental crust from the Russian Far East, northern Alaska and southeastern

Table 1. *Palaeomagnetic poles at 1100–700 Ma*

Object	Age (Ma)	Pole (°N)	Pole (°E)	A_{95} (°)	*Q*	Reference
Laurentia						
Franklin Dykes	723+4/−2	5	163	5	II–IIII 6	Heaman *et al.* 1992; Park 1994
Natkusiak Formation	723+4/−2	6	159	6	III–III 6	Palmer *et al.* 1983; Heaman *et al.* 1992
Tsezotene sills and dykes	779±2	2	138	5	III–I–I 5	Park *et al.* 1989; LeCheminant & Heaman 1994
Wyoming Dykes	782±8 785±8	13	131	4	III–I–I 5	Harlan *et al.* 1997
Haliburton Intrusions A	980±10	−36	143	10	III– – –I 4	Buchan & Dunlop 1976
Chequamegon Sandstone	*c.* 1020*	−12	178	5	–II–I–I 4	McCabe & Van der Voo 1983
Jacobsville Sandstone J (A+B)	*c.* 1020*	−9	183	4	–II–I–I 4	Roy & Robertson 1978
Freda Sandstone	1050±30	2	179	4	–IIII–I 5	Henry *et al.* 1977; Wingate *et al.* 2002
Nonesuch Shale	1050±30	8	178	4	–IIII–I 5	Henry *et al.* 1977; Wingate *et al.* 2002
Lake Shore Traps	1087±2	22	181	5	IIIII–I 6	Diehl & Haig 1994; Davis & Paces 1990
Portage Lake Volcanics	1095±2	27	181	2	II– –I–I 4	Halls & Pesonen 1982; Davis & Paces 1990
Upper North Shore Volcanics	1097±2	32	184	5	II– –III 5	Halls & Pesonen 1982; Davis & Green 1997
Logan Sills R	1109+4/−2	49	220	4	II–IIII 6	Halls & Pesonen 1982; Davis & Sutcliffe 1985
Abitibi Dykes	1141±2	43	209	14	IIII–I– 5	Ernst & Buchan 1993
Baltica						
Hunnedalen Dykes	≥848	−41	222	10	III–I–I 5	Walderhaug *et al.* 1999
Egersund Anorthosite	929–932	−44	214	4	III–III 6	Stearn & Piper 1984; Torsvik & Eide 1997
Pyätteryd Amphibolite	933–945	−43	214	11	III–I–I 5	Pisarevsky & Bylund 1998; Wang *et al.* 1996; Wang & Lindh 1996
Känna Gneiss	948–974	−50	225	17	III–I–I 5	Pisarevsky & Bylund 1998; Wang et al. 1996; Wang & Lindh 1996
Gällared Amphibolite	956?	−46	214	19	III–I–I 5	Pisarevsky & Bylund 1998; Möller & Söderlund 1997
Gällared Granite Gneiss	980–990	−44	224	6	III–I–I 5	Pisarevsky & Bylund 1998; Möller & Söderlund 1997

Table 1. (*cont.*)

Object	Age (Ma)	Pole (°N)	Pole (°E)	A_{95} (°)	*Q*	Reference
Laanila Dolerite	1045±50	−2	212	15	III–I–I 5	Mertanen *et al.* 1996
India						
Mahe Dykes, Seychelles†	748–755	80	79	11	III– – –I 4	Torsvik *et al.* 2001*a*
Malani Igneous Suite	751–771	68	88	8	IIIII–I 6	Torsvik *et al.* 2001*b*
Harohalli Dykes	814±34	27	79	18	III–III 6	Radhakrishna & Mathew 1996
Wajrakarur Kimberlites	1079?	45	59	11	I–I–I–I 4	Miller & Hargraves 1994
Australia						
Mundine Well Dykes	755±3	45	135	4	IIIII–I 6	Wingate & Giddings 2000
Bangemall Basin Sills	1070±6	34	95	8	IIIIIII 7	Wingate *et al.* 2002
Congo						
Mbozi Complex, Tanzania	755±25	46	325	9	III–III 6	Meert *et al.* 1995; Evans 2000.
Gagwe lavas, Tanzania	795±7	25	93	10	III–I–I 5	Meert *et al.* 1995; Deblond *et al.* 2001
São Francisco						
Ilheus Dykes	1011±24	30	100	4	III–I–I 5	D'Agrella-Filho *et al.* 1990; Renne *et al.* 1990
Olivenca Dykes, normal	*c.* 1035*	16	107	8	III–I–I 5	D'Agrella-Filho *et al.* 1990; Renne *et al.* 1990
Itaju de Colonia	*c.* 1055*	8	111	10	III–III 6	D'Agrella-Filho *et al.* 1990; Renne *et al.* 1990
Olivenca Dykes, reverse	1078±18	−10	100	9	III–I–I 5	D'Agrella-Filho *et al.* 1990; Renne *et al.* 1990
Kalahari‡						
Ritscherflya Supergroup (rotated to Kalahari)	1130±12	61	29	4	II– –I–I 4	Powell *et al.* 2001
Umkondo Igneous Province	1105±5	66	37	3	II– –III 5	Powell *et al.* 2001; Wingate 2001
Kalkpunt Formation	*c.* 1065?	57	3	7	II– –III 5	Briden *et al.* 1979; Powell *et al.* 2001
Central Namaqua	*c.* 1030–1000	8	330	10	III–III 6	Onstott *et al.* 1986; Robb *et al.* 1999
Siberia						
Uchur–Maya sediments	*c.* 990–1150	−25	231	3	–IIIIII 6	Gallet *et al.*, 2000
Turukhansk sediments	*c.* 975–1100	−15	256	8	–II–III 5	Gallet *et al.* 2000
South China						
Liantuo Formation	748±12	4	161	13	IIIIIII 7	Evans *et al.* 2000
Oaxaquia						
Oaxaca Anorthosite	*c.* 950	47	267	23	–II–III 5	Ballard *et al.* 1989

* Age based on apparent polar wander path interpolation.
† Rotated to India 28° counterclockwise around the pole of 25.8° N, 330°E (Torsvik *et al.* 2001*a*).
‡ For ages see Powell *et al.* (2001 and refs cited therein).
SA, South Australia; NT, Northern Territory; WA, Western Australia.

Asia, they are not included in the present reconstructions.

Configuration of Rodinia

Laurentia and Baltica

The majority of reliable Late Mesoproterozoic–Neoproterozoic palaeomagnetic data are from Laurentia (Table 1). The Laurentian APWP can be traced within the *c.* 1140–1020 Ma time interval, but younger poles are sparse. It is obvious that the poles between 1020 and 720 Ma circumscribe a 'Grenville Loop', although the shape and 'direction' of this loop is debated (e.g. Park & Aitken 1986; Hyodo & Dunlop 1993; Alvarez & Dunlop 1998; Weil *et al.* 1998; McElhinny & McFadden 2000). Alvarez & Dunlop (1998) analysed palaeopoles from the Grenville Province, generated from rocks remagnetized during post-Grenvillian exhumation between 1000 and 900 Ma. Some of these overprints are calibrated by ^{40}Ar–^{39}Ar ages that support a clockwise Grenville Loop of poles in the Pacific Ocean (Fig. 1). Following a similar approach, McElhinny & McFadden (2000, table 7.4) also constructed a clockwise loop. However, the data they used for the mean poles between 940 and 800 Ma are poorly dated, so this part of the loop has been simplified with an interpolation between reliable poles, as listed in Table 1.

Similarly, Early Neoproterozoic palaeomagnetic data from Baltica (not shown in Table 1) reflect a Sveconorwegian (Grenvillian) to post-Sveconorwegian overprint (e.g. Bylund 1992; Pisarevsky & Bylund 1998; Walderhaug *et al.* 1999 and refs cited therein). A large group of poles with ages *c.* 980 – 930 Ma is situated in a relatively small area at *c.* 45°S, 235°E, whereas poles with older and younger ages occupy near-equatorial positions (Fig. 1). These poles constitute the 'Sveconorwegian Loop' on the APWP for Baltica between *c.* 1000 and 800–850 Ma. As with the Grenville Loop, opinions about its shape and 'direction' are divided (e.g. Bylund 1985; Elming *et al.* 1993; Mertanen *et al.* 1996; Pisarevsky & Bylund 1998). Most data in Table 1 belong to the 980–930 Ma group, with the progression of ages more in favour of a clockwise loop. A clockwise loop is also supported by remanence directions obtained from a series of cross-cutting dykes in a single quarry within the northern part of the Protogine Zone, southern Sweden (Bylund & Pisarevsky 2002).

An exception to this general scenario is the interpretation of Walderhaug *et al.* (1999) concerning the Hunnedalen Dykes (Fig. 1). Based on ages of 848±27 (Ar–Ar on biotite) and 855±59 Ma (Sm–Nd mineral/whole-rock isochron), and on the similarity between the Hunnedalen Dyke Pole and those from 930 Ma plutonic rocks in SW Norway, these authors proposed that all of these rocks were remagnetized during a 'late unroofing' event at 850 Ma. However, because the Ar closure temperature for biotite is *c.* 400°C (Berger & York 1981), significantly lower than the dykes' palaeomagnetic unblocking temperatures (>520°C), and because these dykes were emplaced at moderate depth (Walderhaug *et al.* 1999), it is proposed here that intrusion of Hunnedalen Dykes and fixation of the stable remanence could have occurred long before 850 Ma. The uncertainty of the Sm–Nd age is also compatible with dyke emplacement at ≥900 Ma (perhaps consanguineous with the Egersund Anorthosite) followed by unroofing or mild reheating at 850 Ma. In the present model (Fig. 1), a simplified clockwise Sveconorwegian Loop, with the traditionally accepted age of *c.* 950 Ma at its vertex, was used.

The Grenville and Sveconorwegian APWP Loops coincide reasonably well after a 59° clockwise rotation of Baltica around an Euler pole at 75.8°N, 95.8°W. These rotation parameters were used for the Rodinia juxtaposition of Laurentia and Baltica, a suggestion implying that Baltica and Laurentia were joined as a single entity at between least 1000 and 850 Ma. The configuration proposed by Dalziel (1997), in which west Scandinavia was connected to East Greenland, is not supported by the palaeomagnetic data. One of the arguments used for such a position for Baltica was the juxtaposition of a possible Late Mesoproterozoic orogenic belt in East Greenland with the Sveconorwegian Belt in southern Scandinavia. However, a recent SHRIMP study of detrital zircons in pre-Caledonian rocks of East Greenland by Kalsbeek *et al.* (2000) showed that 'if present at all, a "Grenvillian" orogen in East Greenland would be of very different character than in North America and southern Scandinavia'.

The best fit between APWP loops implies a small gap between Laurentia and Baltica, sufficient to accommodate the Rockall submarine plateau. This region of submerged continental crust has yielded U–Pb and Sm–Nd crystallization ages of between 1750 (Daly *et al.* 1994) and 1625 Ma (Morton & Taylor 1991), comparable to those in the Trans-Scandinavian Igneous Belt (Larson & Berglund 1992) or the Ketilidian Orogen of southern Greenland (Rainbird *et al.* 2001). The southern part of Rockall was possibly reworked during latest Grenvillian times [Ar–Ar on granulite at 997±5 Ma (Miller *et al.* 1973), which was recalculated according to Dalrymple (1979)], which is comparable to ages for the Sveconorwegian Orogeny (e.g. Gorbatschev & Bogdanova 1993). The present proposed fit also includes a palinspastic reconstruction

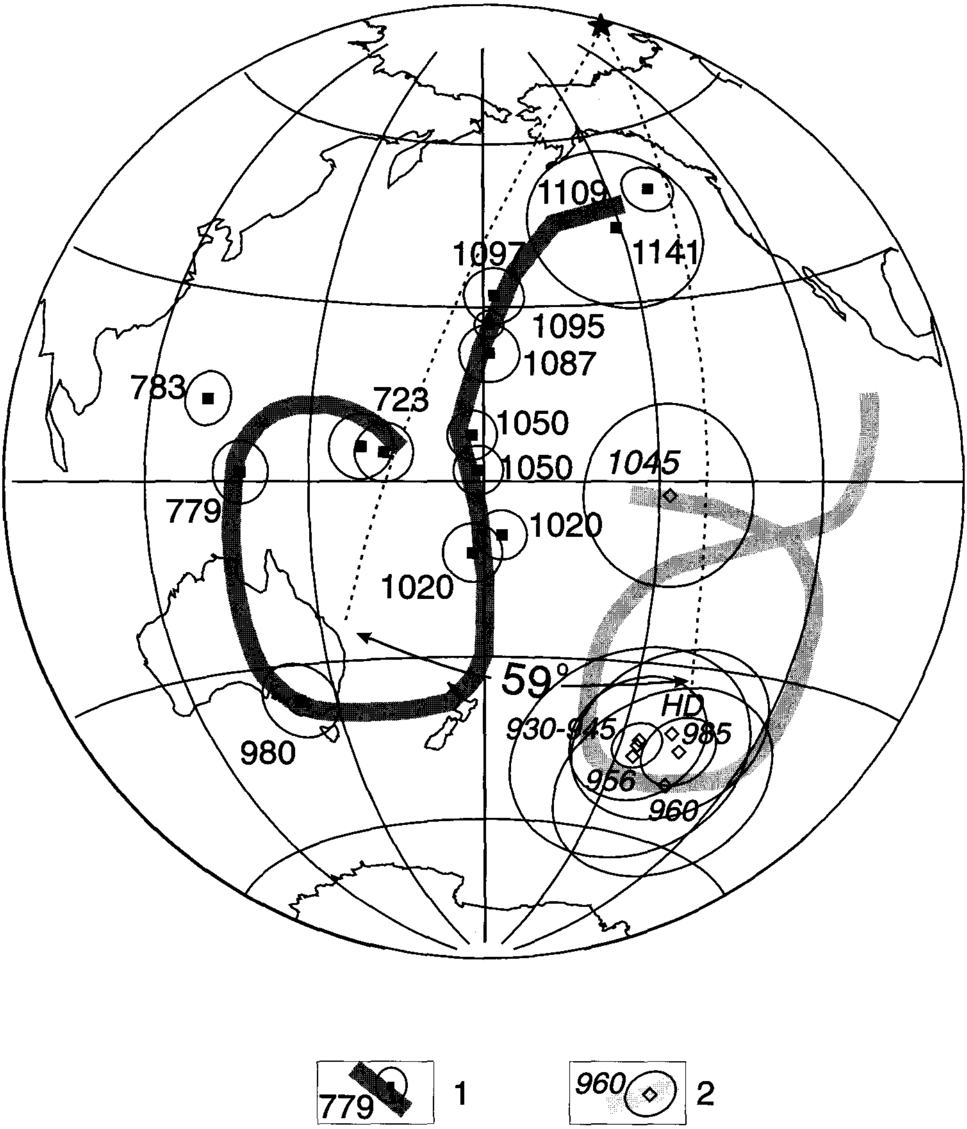


Fig. 1. Apparent polar wander paths for Laurentia and Baltica. 1, Laurentian palaeopoles and path; 2, Baltican palaeopoles and path. Star represents a Euler pole of a 59° rotation which provides a best fit for two paths. HD, Hunnedalen Dykes pole.

of northwestern Scandinavia that removes 400–500 km of Caledonian shortening (e.g. Park *et al.* 1994). Because *c.* 1050 Ma palaeopoles from the two cratons are incompatible according to the present reconstruction (Table 1; Fig. 1), it is proposed that their Rodinian fit was achieved via an oblique and substantially rotational collision between 1050 and 1000 Ma. Similar kinematics characterize the tectonic models of Park (1992) and Starmer (1996).

The proposed position of Baltica (Fig. 2) also permits juxtaposition of East Greenland and fragments of a possible Barentsia plate (East Svalbard), which may explain striking similarities between the Palaeoproterozoic and Neoproterozoic–Early Palaeozoic strata of these two areas (e.g. Gee *et al.* 1994; Fairchild & Hambrey 1995; Higgins *et al.* 2001 and refs cited therein). The results of recent studies by Higgins & Leslie (2000) and Higgins *et al.* (2001), which show that the pre-Caledonian margin of East Greenland restores 500–700 km to the east of the present coastline, have been incorporated into the

Fig. 2. Southern Rodinia at 990 Ma. Am, Amazonia; B, Barentsia; Ba, Baltica; Ch, Chortis; Gr, Greenland; La, Laurentia; O, Oaxaquia; P, Pampean terrane; R, Rockall; RP, Rio de la Plata; WA, West Africa. Grey regions, palinspastically restored pre-Caledonian margins of East Greenland and Baltica.

present model. The eastern (Uralian) edge of Baltica was probably a long-lived passive margin from the Late Mesoproterozoic to the Vendian (e.g. Willner *et al.* 2001).

Laurentia–Baltica and Amazonia

In the majority of Rodinia reconstructions, Amazonia is juxtaposed against eastern Laurentia and Baltica. According to this interpretation, the Rondonia–Sunsas Belt in southwestern Amazonia resulted from continental collision with Laurentia between 1080 and 970 Ma (e.g. Sadowski & Bettencourt 1996; Tassinari *et al.* 2000 and refs cited therein). There is little evidence for a Grenville-age collision in the northern part of autochthonous Amazonia, apart from the poorly understood 'Nickerian' Event at *c.* 1200 Ma (Gibbs & Barron 1993). Keppie & Ramos (1999) proposed that two Central American terranes – Oaxaquia (Mexico) and Chortis (Honduras and Guatemala) – were situated along the northern boundary of South America in their reconstruction for the Vendian–Cambrian boundary. Keppie & Ortega-Gutierrez (1999) suggested that these blocks originated as arcs in a Grenvillian ocean between Laurentia, Baltica and Amazonia, and were caught between the colliding cratons. Alternatively, Oaxaquia and Chortis could represent part of a continental arc formed on the present northern margin of Amazonia. In both scenarios, these blocks have experienced high-grade, collisional-style tectonometamorphism during the terminal collisions among Amazonia, Laurentia and Baltica.

In the present model, the Oaxaquia and Chortis blocks are placed along the northern margin of Amazonia, within the zone of its collision with Baltica at *c.* 1000 Ma (Fig. 2); the model is also constrained by palaeomagnetic data from Oaxaquia (Ballard *et al.* 1989) – see Table 1. Recent preliminary palaeomagnetic results of D'Agrella-Filho *et al.* (2001) from the Rondonia–Sunsas Province generally support a model of Amazonia–Laurentia collision after *c.* 1100 Ma.

Amazonia, West Africa and Rio de la Plata

Trompette (1994, 1997) proposed the existence of a single West Africa–Amazonia–Rio de la Plata megacraton in the Mesoproterozoic and Neoproterozoic. However, he did not exclude the possibility of minor relative movements between its components. For example, Onstott & Hargraves (1981) suggested that *c.* 1500 km of dextral shearing occurred between West Africa and Amazonia, based on comparison of Palaeoproterozoic–Mesoproterozoic palaeomagnetic data from these two blocks. The data are rather scattered and the conclusion is not very convincing, so for the purpose of this paper the Gondwanaland Amazonia– West Africa fit (Fig. 2) has been used, although it is acknowledged that such shearing was possible. Neoproterozoic palaeomagnetic data from West Africa are few and contradictory (Perrin & Prevot 1988), and therefore have not been taken into account in the present model.

Rio de la Plata is a poorly known craton, with no reliable palaeomagnetic data available for 1000–700 Ma; its Precambrian boundaries are similarly uncertain. The Rio de la Plata Block, depicted by Dalziel (1997) and Weil *et al.* (1998), for example, included parts of the Pampean Terrane as well as the southern extremity of the Guapore Block. In contrast, Ramos (1988) envisaged a Pampean–Rio de la Plata collision at 600–570 Ma and Trompette (1994) considered the possibility of an Amazonian affinity for the southern Guapore cratonic extension. Pimentel *et al.* (1999) suggested a collision between the São Francisco Craton and the Paraná Block between 790 and 750 Ma. Alkmim *et al.* (2001) considered the Paraná Block as part of Rio de la Plata, although supporting evidence is lacking (e.g. Trompette 1994; Cordani *et al.* 2000). Ramos (1988) depicted a shear zone between Rio de la Plata and the western Alto Paraguay Terrane, now covered by the Palaeozoic–Mesozoic Paraná Basin. Depending on its total displacement, this shear zone may allow the Rio de la Plata and Paraná Blocks to be considered as separate palaeogeographic entities in Early Neoproterozoic time (Ramos 1988).

In the present reconstructions, three separate blocks are proposed: (1) Rio de la Plata *sensu stricto,* which includes basement NE and SW of Buenos Aires (Cingolani & Dalla Salda 2000), and does not include the Luis Alves Block and the southern extremity of the Guapore Block; (2) the Pampean Terrane; and (3) the Paraná Block. Generally, the tectonic model of Ramos (1998) has been followed for the Rio de la Plata and Pampean Blocks, keeping them in the vicinity of Laurentia, and that of Pimentel *et al.* (1999) for the Paraná–Saõ Francisco collision.

Laurentia and Australia

The western margin of Laurentia, from northern Canada to southern USA, contains a rift–passive margin succession initiated at *c.* 750 Ma (e.g. Moores 1991; Ross *et al.* 1995 and refs cited therein). Moores (1991) proposed that Australia–East Antarctica rifted from Laurentia at that time [SW US–East Antarctic (SWEAT) hypothesis]. This configuration was used by Hoffman (1991), Dalziel (1997) and Weil *et al.* (1998) in their reconstructions of Rodinia. The SWEAT hypothesis suggested that the Grenville Belt of Laurentia continued around Antarctica, and into India and Australia. Li *et al.* (1995), using tectonostratigraphic analysis, modified the SWEAT configuration slightly by placing the South China Craton between Australia and northwestern Laurentia. Brookfield (1993), Karlstrom *et al.* (1999) and Burrett & Berry (2000) proposed an alternative Australia–Laurentia fit (AUSWUS) based on comparison of Precambrian terranes on both cratons. Until recently, Australian Late Mesoproterozoic–Neoproterozoic palaeomagnetic data were inadequate to discriminate between these hypotheses. However, a new palaeomagnetic result from the 1070 Ma Bangemall Sills, Western Australia (Wingate *et al.* 2002), supports neither of these models. According to this result, Australia at 1070 Ma was situated at lower palaeolatitudes than would be permitted by the SWEAT or AUSWUS models, placing the Cape River Province of NE Australia at a similar latitude to the southwestern end of the 1250–980 Ma Grenville Province of Laurentia (Rivers 1997; Mosher 1998). High-grade metamorphic and magmatic rocks in the Cape River Province contain 1240, 1145 and 1105 Ma zircon-age components, and may correlate to the west with Grenvillian-age rocks in the Musgrave and Albany–Fraser Orogens (Blewett *et al.* 1998). If the proposed AUSMEX reconstuction (Fig. 3) is correct, the Grenville Province may have continued through Australia. A recent palaeomagnetic study of the deep drillhole Empress 1A in the Officer Basin (Pisarevsky *et al.* 2001) indicated low palaeolatitudes for Australia between *c.* 810 and 750 Ma, also supporting this fit. While maintaining most of the geological comparisons argued in favour of AUSWUS and some of those in favour of SWEAT, the AUSMEX fit also helps to resolve some additional problems. For example, the Wyoming Craton is a more suitable source for 2.78 Ga detrital zircons in Papua New Guinea (Baldwin & Ireland, 1995) than the smaller and possibly displaced Nova Terrane proposed by Burrett & Berry (2000) in their AUSWUS fit. The AUSMEX reconstruction, however, requires conjugate passive margins for western Laurentia and eastern Australia to be identified. In the present reconstruction (Fig. 3) the latter is supposed to be in the poorly known Rio de la Plata Craton and the former in South China (see below).

Australia, Antarctica and India

A feature common to most Rodinia reconstructions (e.g. Powell *et al.* 1993, Dalziel 1997; Weil *et al.* 1998) is the assumption that East Gondwanaland (Australia, India, Madagascar and East Antarctica in their Gondwanaland configuration) has been a single tectonic entity since the end of the Mesoproterozoic. The assumption has been based mainly on the apparent continuity of a Grenville-age metamorphic belt along the India–East Antarctica Margin, and its extension into the Late Mesoproterozoic Albany–Fraser Mobile Belt of Australia, and a supposed absence of Neoproterozoic or younger sutures between the continental blocks. Late Neoproterozoic high-grade gneisses occur in the Darling Mobile Belt of Western Australia (Wilde & Murphy 1990; Harris 1994) and in the correlative Prydz–Denman Zone in East Antarctica (Fitzsimons 2000), but direct evidence for oceanic subduction is lacking and subsequent metamorphism has generally been regarded as intracontinental reactivation of

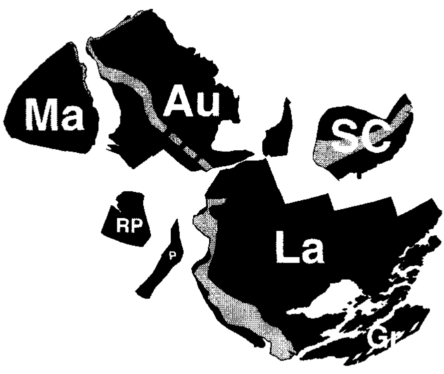


Fig. 3. Northern Rodinia at 990 Ma. Au, Australia; Ma, Mawson Craton; SC, South China. Other abbreviations as in Figure 2.

old crustal weaknesses during the Late Neoproterozoic collision of East and West Gondwanaland farther to the west.

Fitzsimons (2000) disproved the hypothesis of a single continuous Late Mesoproterozoic orogenic belt along the margin of East Antarctica. Three separate Late Mesoproterozoic–earliest Neoproterozoic orogenic belts, with different ages of metamorphism and plutonism, exist along the margins of East Antarctica. Importantly, Fitzsimons (2000) highlighted two Late Neoproterozoic orogenic zones in Antarctica, across which there are unknown amounts of displacement in Pan-African time. In a Gondwanaland reconstruction, one zone is the southern extension of the East African Orogen to the west of India, and the other is the Prydz–Denman–Darling Orogen between India and Australia–Wilkes Land (Antarctica) in East Gondwanaland.

Palaeomagnetic data for India (Table 1) also contradict the integrity of East Gondwanaland. In an East Gondwanaland fit the *c.* 1080 Ma pole for the Wajrakarur Kimberlites in central India (Miller & Hargraves 1994) does not coincide with the 1070 Ma Bangemall Pole for Australia (Wingate *et al.* 2002). Additionally, India was at high palaeolatitudes at *c.* 810 Ma, whereas Australia was at low palaeolatitudes at that time (Pisarevsky *et al.* 2001).

Combining palaeomagnetic geochronological and geological data, Powell & Pisarevsky (2002) proposed a new model for the Neoproterozoic tectonic history of East Gondwanaland, in which India (together with the Rayner Block of Antarctica) was not a part of Rodinia, but collided obliquely with the rest of East Gondwanaland (West Australia and the Mawson Craton of Australia–Antarctica) between 680 and 610 Ma [or later, as discussed by Fitzsimons (2002)]. Boger *et al.* (2001) presented a slightly different model, but with a similar conclusion that large sections of East Antarctica and India were not parts of East Gondwanaland or Rodinia.

Kalahari and Australia

A comparison of Late Mesoproterozoic palaeopoles from the Kalahari Craton and the correlative Grunehogna fragment in East Antarctica indicates that, in Rodinia, the Kalahari–Grunehogna Craton (e.g. Jacobs *et al.* 1993) could have lain to the SW of Laurentia with the Namaqua–Natal orogenic belt facing outboard and away from the Laurentian Craton (Powell *et al.* 2001). Powell *et al.* (2001) also showed, by comparing palaeopoles from coeval Umkondo and Keweenawan igneous Provinces, that Kalahari could not be the ‘southern continent’ that indented the Grenvillian Llano Orogen between 1150 and 1100 Ma (Mosher 1998; Dalziel *et al.* 2000). Available geochronological data from the Namaqua Belt are similarly incompatible with those from the southwestern Grenville Belt (Powell *et al.* 2001). However, Kalahari could have lain off the western margin of Australia until 800–750 Ma, when breakup associated with the 755 Ma Mundine Well Mafic Dyke Swarm (Wingate & Giddings 2000) caused Kalahari to rotate anticlockwise away from the western margin of Australia. Bruguier *et al.* (1999) suggested that India collided with the western margin of Australia along the Darling Mobile Belt *c.* 1080 Ma but as discussed above, India did not achieve this position until the Late Neoproterozoic. Jacobs *et al.* (1998) identified *c.* 1080 Ma syntectonic granite sheets and plutons in Dronning Maud Land, at the same time as the Namaqua–Natal Belt was undergoing transpressional shearing. Following Fitzsimons (2002), it is proposed that here the Kalahari–Dronning Maud Land Craton joined the Australia–Mawson Craton during oblique collision between 1100 and 1000 Ma (Fig. 4a). Metamorphism in both Dronning Maud Land and the Darling Mobile Belt occurred at 1080–1050 Ma (Jacobs *et al.* 1998; Bruguier *et al.* 1999), and metasediments in both belts have indistinguishable detrital zircon populations (Fitzsimons 2002). Consistent with this model, palaeopoles from Kalahari converge with the Laurentian APWP between 1065 and 1000 Ma (Table 1; Fig. 4a).

Western Laurentia and South China

Dismissal of the SWEAT and AUSWUS hypotheses reopens the question of the conjugate to the west Laurentian Neoproterozoic passive margin. Li *et al.* (1995, 1999) proposed that the Cathaysia Block of South China was part of a 1.9–1.4 Ga continental strip adjoining western Laurentia prior to collision with the Yangtze Block along the Sibao Orogen by *c.* 1000 Ma (Li *et al.* 2002). The suggestion is based mainly on similarities between Neoproterozoic sedimentary successions in South China and western Canada. The Cathaysia Block could have been the source of the Mesoproterozoic detrital zircons in the Belt Supergroup in northwestern USA (Ross *et al.* 1992; Li *et al.* 1995). In the present model, South China is kept juxtaposed with western Laurentia (Fig. 3), but Australia is placed further to the south than suggested by Li *et al.* (1995, 1999, 2002). The Sibao Orogen may also be considered as a source of Grenville-age detrital zircons in the Mackenzie Mountains and the Amundsen Basin (Rainbird *et al.* 1997), and could have produced the few enigmatic 1070–1244 Ma zircons in the Buffalo Hump Formation in Washington State (Ross *et al.* 1992).

South China is not of sufficient size to cover the entire West Laurentian passive margin (Fig. 3),

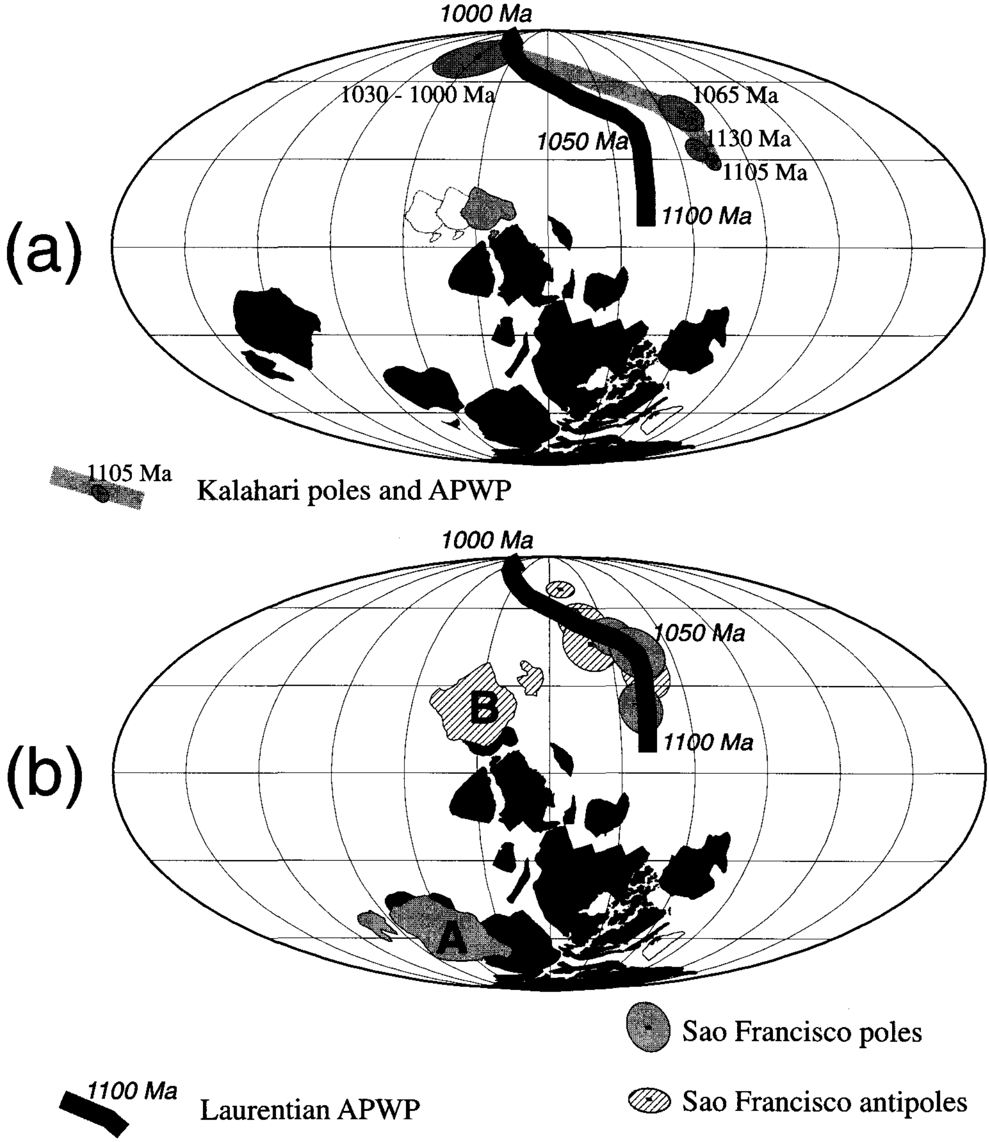


Fig. 4. (**a**) Proposed position of Kalahari and palaeomagnetic constraints; (**b**) alternative palaeopositions of Congo–São Francisco according to the two polarity options of its apparent polar wander paths (APWP) (see text).

hence other continental blocks are likely to have been attached to northwestern Laurentia in the Mesoproterozoic and Neoproterozoic – Northern Alaska, northern blocks of eastern Siberia and the Kara Plate are all possible candidates. There have been suggestions that these blocks constituted a large Precambrian craton, Arctida (Zonenshain *et al.* 1990). However, the tectonic history of these blocks is relatively well understood only back to Early Palaeozoic time (e.g. Natal'in *et al.* 1999), hence the shape, constitution and reconstruction of Arctida within Rodinia remain highly uncertain (question mark in Fig. 6). The position of the Tarim Block (Fig. 6) is in accordance with the reconstruction of Li *et al.* (1996), which is based predominantly on tectonostratigraphic comparisons.

Laurentia and Siberia

Sears & Price (1978, 2000) proposed the Siberian Craton as an alternative counterpart to western

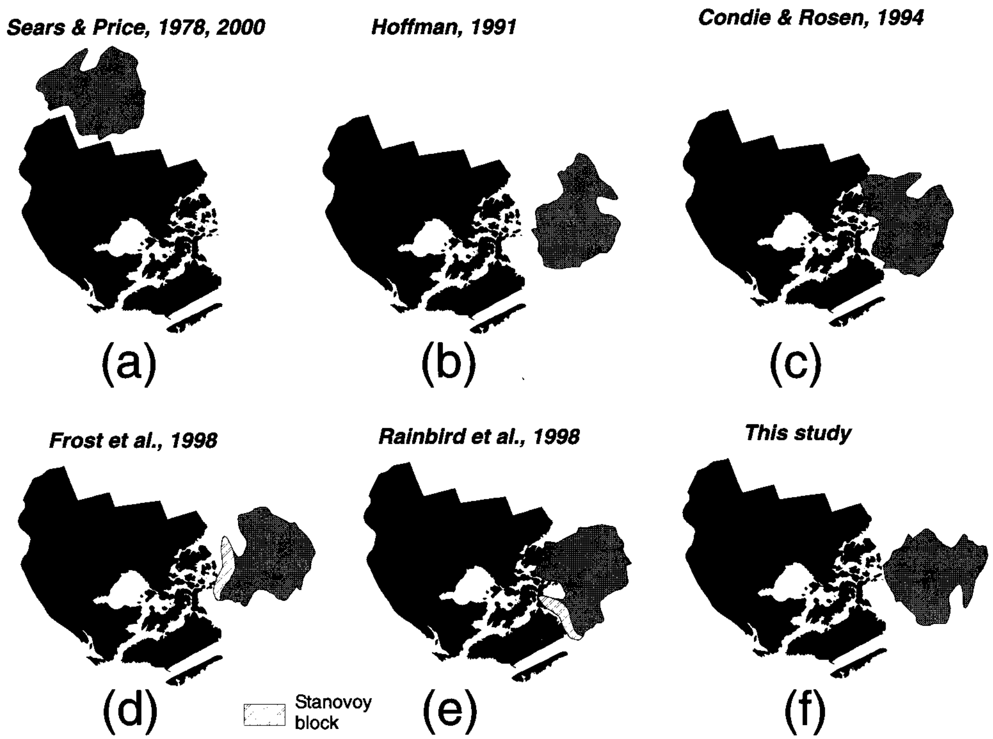


Fig. 5. Proposed palaeopositions of Siberia with respect to Laurentia.

Laurentia instead of Australia and Antarctica (Fig. 5a). Such a configuration raises several problems.

There is a mismatch of crustal age domains. Southwestern North America is dominated by juvenile, Early Proterozoic belts, whereas the Aldan Shield of Siberia is Archaean (e.g. Condie & Rosen 1994). Sears & Price (2000), citing Nd isotopic data from Ramo & Calzia (1998), argued for the presence of a substantial Archaean source component in the Death Valley area of Mojavia. However, Ramo & Calzia (1998) concluded that this Archaean component was introduced as sedimentary detritus, and was probably subducted and mixed with juvenile material at a convergent zone, either at the present western margin of the Wyoming Craton or elsewhere. Sears & Price (2000) also correlated a 1740 Ma U–Pb zircon crystallization age from the Okhotsk Massif in Siberia with similar-aged magmatic events from the Mojave, Yavapai and Mazatzal Provinces (Van Schmus & Bickford 1993). The original source of this 1740 Ma age date from the Okhotsk Massif (Kuzmin *et al.* 1995, table 1; see also Khudoley *et al.* 2001), and is the youngest in a series of 21 age determinations ranging from 3350 to 1830 Ma, all of which are systematically older than those in the Mojave, Yavapai and Mazatzal Provinces (Van Schmus & Bickford 1993).

Sears & Price (2000) juxtaposed the Palaeoproterozoic (maximum 2.4–2.5 Ga; Rosen *et al.* 2000), Birekte Block of Siberia [or Olenek blocks, following the determination of Condie & Rosen (1994)] against the Archaean Hearne Province/Medicine Hat Block (Hoffman 1989). Sears & Price (2000) attempted to correlate the North Alberta Palaeoproterozoic continental and oceanic-arc terranes with the predominantly metasedimentary Hapshan Orogenic Belt which underwent granulite–facies metamorphism at 2080–1970 Ma (Rosen *et al.* 2000). The North Alberta arcs experienced granulite–facies metamorphsim during accretion to the Hearne Province, *c.* 200 Ma later, at *c.* 1850–1800 Ma (Ross *et al.* 2000).

For these reasons, the model of Sears & Price (1978, 2000) is not followed and Siberia is positioned against northern Laurentia. Within this general configuration, almost every conceivable permutation has been explored (Fig. 5b–f). These Siberia–northern Laurentia fits are based primarily on the comparison of Archaean and Palaeoproterozoic terranes that are assumed to have maintained their integrity since Late Palaeoproterozoic assembly (Hoffman 1991; Condie & Rosen 1994; Frost *et al.* 1998; Rainbird *et al.* 1998). The fit (Fig. 5b) proposed by Hoffman (1991) has additional constraints based on stratigraphic and palaeontological similarities between northern Siberian and northern Laurentian successions in the Early Cambrian (Pelechaty 1996 and refs cited therein).

Frost *et al.* (1998) juxtaposed southern Siberia with northern Laurentia (Fig. 5d). Their fit is based on comparison of the Thelon Magmatic Belt with the Aldan Terrane of the Aldan Shield. The main problem with this fit is the presence of the Stanovoy Province, which contains structures that are generally perpendicular to those of the Aldan Block (highlighted in Fig. 5d and e). A chain of Early Proterozoic gabbro–anorthosite plutons along the northern margin of Stanovoy Block (Gusev & Khain 1996), and other collision-related magmatic and metamorphic events, provide evidence for collision of the Stanovoy and Aldan Blocks at 1.8–2.0 Ga (Rosen *et al.* 1994 and refs cited therein). The model of Rainbird *et al.* (1998), in which southern Siberia is juxtaposed with northern Greenland (Fig. 5e), faces the same problem. Evidence for 1000–800 Ma island arcs along the southern boundary of Siberia (Rytsk *et al.* 1999; Kuzmichev *et al.* 2001) is also not supportive of these two models. Two new palaeopoles of Gallet *et al.* (2000) are not precisely dated and cannot give unequivocal support to any of the proposed fits. They also do not exclude the possibility that Siberia was not a part of Rodinia. New Late Mesoproterozoic–Early Neoproterozoic geochronological data (Rainbird *et al.* 1998) necessitated a revision of younger Neoproterozoic Siberian palaeomagnetic data, summarized by Smethurst *et al.* (1998). If Siberia was not connected to Laurentia, the identity of the conjugate to the passive margin of northern Laurentia (Frisch & Trettin 1991) is unknown.

In the present reconstruction, a N–N fit of Siberia and Laurentia is proposed (Fig. 5f), which is not contradicted by the palaeomagnetic data of Gallet *et al.* (2000) if an age of *c.* 1000 Ma is assumed for those sediments. Subsequent minor extensions and rotations could have led to the configurations of Hoffman (1991) and Pelechaty (1996), prior to final separation in the Early Cambrian (Pelechaty 1996).

Congo–São Francisco

This craton is traditionally treated as a single entity, owing to the similarity of Archaean and Palaeoproterozoic–Mesoproterozoic rocks and bounding Late Neoproterozoic mobile belts (e.g. Teixeira *et al.* 2000; Trompette 1994). The Irumide and Mozambique Belts of east-central Africa (south and SE margins of Congo) comprise a collage of sedimentary and island-arc-related intrusive rocks with U–Pb zircon crystallization ages of between *c.* 1400 and 1000 Ma (Pinna *et al.* 1993; Kröner *et al.* 1997, 2001; Oliver *et al.* 1998; Johnson & Oliver, 2000). This region is best interpreted as facing an open ocean undergoing passive arc accretion during the Mesoproterozoic until *c.* 1000 Ma (Kröner *et al.* 1997, 2001; Johnson & Oliver 2000). The Neoproterozoic East African Orogen (east margin of Congo Craton) consists mainly of reworked Neoarchaean and Palaeoproterozoic crust, and, as yet, no Mesoproterozoic ages have been identified, so it is difficult to determine whether this margin faced an ocean or other continental blocks in Rodinia time.

The northern margin of the Congo Craton is very poorly known. A northward-deepening sedimentary succession in northern Congo and the Central African Republic (Lindian and Bangui Basins) contains putative glacial deposits, indicating a likely Neoproterozoic age (Evans 2000 and refs cited therein). This succession is deformed within the Oubanguide Belt at *c.* 620 Ma (Penaye *et al.* 1993), which may represent either a continent–continent collision (Trompette 1994) or an intracratonic Pan-African remobilization.

The *c.* 1000–910 Ma West Congolian Belt, of lower Congo and Angola, is a series of rift-related sediments and volcanics, overlain by a passive-margin succession (Tack *et al.* 2001). Owing to the palaeogeographic position of the São Francisco Craton with respect to Congo, it is possible that the West Congolian orogenic cycle, as well as its Brazilian counterpart in the Aracuaí Belt (Pedrosol-Soares *et al.* 2001), represents mainly intracratonic tectonic events. In contrast, there is evidence for the existence of ocean basins west and south of the São Francisco Craton in the early Neoproterozoic until its collision with the Paraná Block at 750–790 Ma (e.g. Pimentel *et al.* 1999).

Collectively, these data provide evidence against a long-term connection between the Congo–São Francisco Craton and any other large continental block along any of its margins, with the possible exception of the present northern and eastern margins.

Four palaeopoles from the São Francisco Craton (Table 1) generate a slightly curved APWP that is anchored at its ends by hornblende Ar–Ar dates of 1078 ± 18 and 1011 ± 24 Ma for the Olivenca and Ilheus Dykes, respectively (Renne *et al.* 1990). The similarity of this track to the Laurentian 'Keweenawan' APWP track suggests common motion of Congo–São Francisco and Laurentia during this time interval, and the possibility of restoring their relative positions by superimposing their APWP.

The low curvatures of the two APWPs' segments permit using both polarity options (Fig. 4b). If one polarity option is accepted (position A in Fig. 4b), Congo–São Francisco lies directly on top of West

Africa and Amazonia. In this case, arguments for the position of those cratons in Rodinia would need to be revised (see above). The other polarity option (position B in Fig. 4b) shows a connection (or proximity) between the Congo northern margin and Western Australia. As noted above, very little is known about this margin of Congo, so such a possibility cannot be excluded. However, this fit causes an overlap of Congo with Kalahari, and, in this case, the proposed attachment of Kalahari to Australia (Fig. 4a) would be incorrect. A third possibility is that the apparent similarity between Laurentian and São Franciscan poles is coincidental, and that these cratons moved independently. A less reliable palaeomagnetic pole from the *c.* 950 Ma Nyabikere Massif (Meert *et al.* 1994) contradicts position A in Fig 4b, but may agree with position B after minor modification. However, the palaeopole from the Gagwe Lavas (Table 1) does not permit such a juxtaposition for *c.* 800 Ma. Therefore, if position B of Congo at 1000 Ma is accepted, its breakup from Australia probably occurred prior to the onset of breakup in other sectors of Rodinia (see below).

There is insufficient information to prove or disprove option B, in which Congo–São Francisco is positioned close to Western Australia and correspondingly forms a part of Rodinia, so this option is left open for further investigation. However, it is recognized that the configuration preferred for the present model (Fig. 4a), with Kalahari attached to Western Australia and Congo–São Francisco as an independent plate, is also poorly constrained.

Configuration of Rodinia

The proposed reconstruction of Rodinia at *c.* 990 Ma is shown in Fig. 6; the corresponding rotation parameters for each block are listed in Table 2. The main differences with previous reconstructions are: (1) the position of Australia, which is juxtaposed against Laurentia in the AUSMEX fit; (2) East Antarctica was not a single block; (3) Congo–São Francisco and India–Rayner Cratons were not parts of Rodinia; (4) Siberia was situated close to northern Laurentia, but in a position different from all proposed previously; (5) Kalahari–Dronning Maud Land was attached to Western Australia.

Breakup of Rodinia

Many scientists have suggested that the breakup of Rodinia started along the western boundary of Laurentia between 820 and 720 Ma (e.g. Hoffman 1991; Powell *et al.* 1994; Li *et al.* 1999; Wingate & Giddings 2000). Rifting along the eastern margin of Laurentia started significantly later, *c.* 620–550 Ma (e.g. Bingen *et al.* 1998; Cawood *et al.* 2001). Wingate & Giddings (2000) concluded that if the SWEAT fit (Moores 1991) is correct, then breakup between Australia and western Laurentia occurred prior to 755 Ma, although a similar conclusion can be drawn for either the AUSWUS (Brookfield 1993; Karlstrom *et al.* 1999; Burrett & Berry 2000) or AUSMEX (Wingate *et al.* 2002) configurations.

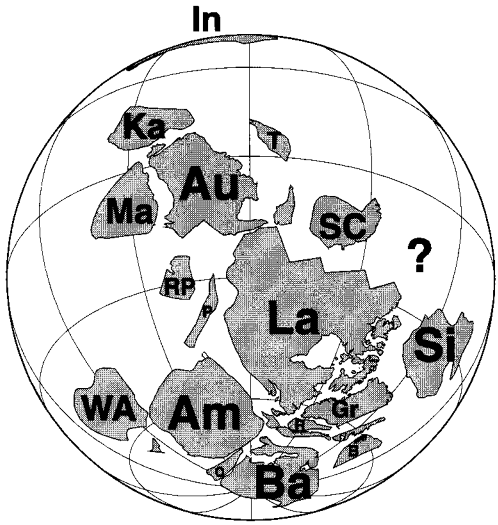


Fig. 6. The shape of Rodinia at 990 Ma. In, India; Ka, Kalahari; Si, Siberia; T, Tarim. See also notes to Figures 2 & 3. The position of Congo–São Francisco is outside the shown projection – for its proposed location see Figure 4a.

Extensive mafic magmatism related to rifting is recognized in western Laurentia (Ross *et al.* 1995), SE Australia (Wingate *et al.* 1998) and South China (Li *et al.* 1999), although it occurred at 730 –780 Ma in western Laurentia, and at 820–830 Ma in SE Australia and South China. This mismatch is difficult to explain in the context of the SWEAT or AUSWUS hypotheses. The AUSMEX configuration, however, can provide a plausible explanation. It is suggested that, initially, breakup started *c.* 830 Ma between South China–Laurentia–Rio de la Plata in the east, and Australia–Mawson Craton in the west (Fig. 7a). Initiation of rifting was probably related to the 827 Ma Gairdner Dyke Swarm (Wingate *et al.* 1998) and coeval South China dykes (Li *et al.* 1999). At *c.* 780 Ma, this spreading stopped and a new rifting event began (Fig. 7b), the evidence for which includes three 780 Ma mafic intrusive suites in western Laurentia (Park *et al.* 1995). A possible analogy for such a set of events is the opening of the North Atlantic Ocean (Fig. 7b, inset). Impingement of a mantle plume may have accompanied Rodinia breakup (Wingate *et al.* 1998; Li *et al.* 1999), in the

Table 2. *Euler rotation parameters*

Craton/block/terrane	Age (Ma)	Pole (°N)	Pole (°E)	Angle (°)
Laurentia to absolute framework	990	13.9	−144.1	−134.7
	800–790	31.8	−149.0	−87.0
	780–770	20.6	−148.5	−93.7
	760–750	18.0	−140.2	−95.2
Baltica to Laurentia	990–750	75.8	−95.8	−59.2
Greenland to Laurentia	990–750	67.5	−118.5	−13.8
Amazonia to Laurentia	990–750	12.0	−47.0	−110.7
West Africa to Amazonia	990–750	53.0	−35.0	−51.0
Rio de la Plata to Laurentia	990–750	9.9	−47.4	−93.7
Pampean to Rio de la Plata	990–750	70.9	−10.8	−3.8
Rockall to Laurentia	990–750	75.3	159.6	−23.5
Oaxaquia to Amazonia	990–750	12.1	81.7	53.4
Chortis to Amazonia	990–750	5.7	−78.5	139.8
Siberia to Laurentia	990	65.0	159.3	−69.6
	800–750	3.5	13.1	23.2
South China to absolute framework	990	66.4	−107.9	127.9
	800–790	65.1	176.0	143.0
	780–770	61.0	172.6	150.9
	760–750	50.4	166.9	172.7
Australia to absolute framework	990	42.6	−5.2	115.8
	800–790	56.6	51.1	72.7
	780–770	55.4	53.0	71.9
	760–750	50.8	71.3	70.8
Mawson to Australia	990–750	1.3	37.7	30.3
Kalahari to Australia	990–750	79.8	97.1	73.4
Dronning Maud Land to Kalahari	990–750	9.7	148.7	−56.3
Tarim to Australia	990–750	13.5	98.3	−153.4
India to absolute framework	990	58.6	−3.9	86.3
	800–790	32.9	6.5	59.2
	780–770	40.7	6.2	53.7
	760–750	68.7	4.3	44.9
Sri Lanka to India	990–750	9.8	82.9	−24.3
Rayner to India	990–750	4.9	−163.4	−93.2
Congo to absolute framework	990	45.6	83.8	68.3
	800–790	55.8	57.1	130.1
	780–770	46.5	65.9	129.6
	760–750	20.0	79.1	135.4
São Francisco to Congo	990–750	53.0	−35.0	51.0

same manner as Iceland in the North Atlantic (Lawer and Müller 1994).

Figure 7c shows several reliable palaeopoles with ages *c.* 760–750 Ma. The low-latitude position of Australia between 800 and 750 Ma is also constrained by the palaeomagnetic study of a deep drill-hole in Western Australia (Pisarevsky *et al.* 2001). The 755 Ma Mundine Well mafic dykes in Western Australia may indicate a rifting event, possibly involving a detachment of the Kalahari Craton (Fig.

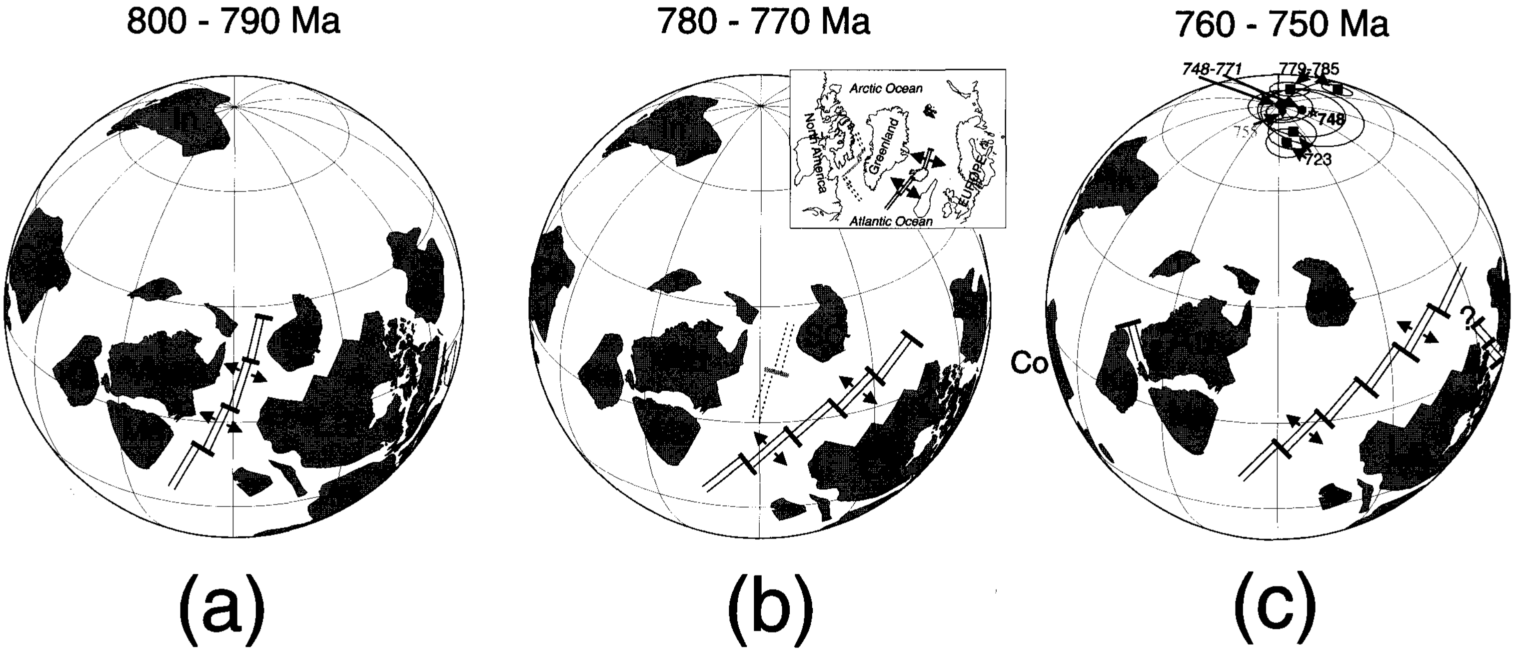


Fig. 7. Sequential breakup of Rodinia. Palaeomagnetic poles: ■, Laurentian; ●, Indian; ◆, Australian; ☆, South China. Abbreviations as in previous figures; for details, see text and Table 1.

7c). Figure 7c also shows the possible initiation of rifting between northern Laurentia and Siberia that may be represented by the 723 Ma Franklin Dykes (e.g. Heaman *et al.* 1992). However, this may have been an aborted rift, with final separation between Laurentia and Siberia delayed until the Early Cambrian (e.g. Pelechaty 1996).

Although India is not regarded as part of Rodinia, two sets of palaeomagnetic data can be used to position this block during the period associated with Rodinia breakup. The Harohalli Dykes of southern India, dated at 823–810 Ma (Radhakrishna & Matthew 1996), place India at high palaeolatitudes (Fig. 7a). Two high-quality poles, from the Seychelles at 755–748 Ma (Torsvik *et al.* 2001*a*), and the Malani Igneous Suite (MIS) of northwestern India at 771–751 Ma (Torsvik *et al.* 2001*b*), can be matched in a tight reconstruction at intermediate, northerly latitudes, tracing India's motion from polar to moderate latitudes (Fig. 7b and c). Traditionally, Madagascar is positioned with the Seychelles and the MIS, based on the correlation of contemporaneous, bimodal igneous intrusive rocks, interpreted as a 450 km long continental arc (Handke *et al.* 1999; Torsvik *et al.* 2001*a,b*; Tucker *et al.* 2001; Collins *et al.* 2002). However, identification of a significant Pan-African suture zone in eastern Madagascar (the Betsimisraka Fault; Kröner *et al.* 2000; Collins *et al.* 2002), which divides a thin eastern region of Indian or Karnataka Craton affinity from the main, central block of Neoarchaean and Palaeoproterozoic age, indicates that most of Madagascar was never connected to India prior to Neoproterozoic time. This raises two alternative palaeogeographic scenarios. The first is that the correlation between central Madagascar, the Seychelles and the MIS is incorrect (Collins *et al.* 2002), and that central Madagascar was not part of the Seychelles–MIS–Greater India block. The second preserves the Madagascar–Seychelles–MIS connection but extends the Betsimisraka Suture Zone through the Aravalli Belt of northwestern India, thereby separating the Seychelles and the MIS from Greater India until Neoproterozoic time (Torsvik *et al.* 2001*b*, fig. 7a). If the second scenario is correct, then there is only one reliable palaeopole for India (Harohalli Dykes; Table 1) and two poles for this separate block (Malani and Mahe; Table 1) during the 1000–550 Ma period. In this case, India would still be excluded from Rodinia and its position in Figure 7a is probably correct. Less certain would be the location of India in Figure 7b and c, but India's depicted southerly motion is consistent with eventual collision with Australia at *c.* 640 Ma (Powell & Pisarevsky 2002). In the present reconstructions, only the easternmost rocks of Madagascar, in their original position adjacent to India, are shown; central Madagascar is of uncertain position and is thus not shown.

The positions of Congo–São Francisco in Figure 7a and c are constrained by the Gagwe and Mbozi Poles, respectively (Table 1). The longitudes of the India and Congo–São Francisco Cratons in Figure 7 are unconstrained, as only individual poles, not APWP, are being compared. Tectonics of the Congo–São Francisco Craton during this interval of Rodinia fragmentation is intriguing: collision of the São Francisco Craton and Paraná Block had probably occurred by 790–750 Ma (Pimentel *et al.* 1999), and thus the onset of Gondwanaland's assembly may have overlapped in time with the final stages of Rodinia's demise.

Conclusions

A new configuration of Rodinia is proposed in this study, based on available geological data and reliable palaeopoles. Rodinia was finally assembled *c.* 1000 Ma, as manifest in the series of orogenic belts of 'Grenvillian' age. However, Grenvillian orogenesis was probably multistaged, as was shown for East Antarctica by Fitzsimons (2000). New palaeomagnetic data from Australia (Wingate *et al.* 2002) contradict the popular SWEAT and AUSWUS hypotheses, and a new AUSMEX fit is suggested. The proposed composition of Rodinia does not include India or the Congo–São Francisco Cratons; a new position of Kalahari against Western Australia is suggested.

The breakup of Rodinia probably started at *c.* 820–800 Ma by rifting between Australia–Mawson–Kalahari and South China–Laurentia–Rio de la Plata. At 780–770 Ma, the spreading centre jumped to a position between Laurentia and South China, and the initial branch was aborted. Kalahari detached from Australia at 760–750 Ma and the Rodinia fragments began the slow journey toward their reassembly in Gondwanaland, and, ultimately, Pangaea.

This research was supported by the Australian Research Council (ARC) through its Research Centres program. S. A. Pisarevsky acknowledges a University of Western Australia Gledden Senior Fellowship. Reconstructions were made using PLATES software from the University of Texas at Austin, and GMT software of Wessel and Smith. We are very grateful to M. W. McElhinny and T. Raub for their helpful reviews. This is Tectonics Special Research Centre publication no. 180 and a contribution to International Geological Correlation Project 440.

References

ALKMIM, F. F., MARSHAK, S. & FONSECA, M. A. 2001. Assembling West Gondwana in the Neoproterozoic: clues from the São Francisco craton region, Brazil. *Geology*, **29**, 319–322.

ALVAREZ, V. C. & DUNLOP, D. J. 1998. A regional paleomagnetic study of lithotectonic domains in the Central Gneiss Belt, Grenville Province, Ontario. *Earth and Planetary Science Letters*, **157**, 89–103.

BALDWIN, S. & IRELAND, T. A. 1995. Tale of two eras: Pliocene–Pleistocene unroofing of Cenozoic andesite Archean zircons from active metamorphic core complexes, Solomon Sea, Papua New Guinea. *Geology*, **23**, 1023–1026.

BALLARD, M. M., VAN DER VOO, R. & URRUTIA-FUCUGAUCHI, J. 1989. Paleomagnetic results from Grenvillian-aged rocks from Oaxaca, Mexico: evidence for a displaced terrane. *Precambrian Research*, **42**, 343–352.

BERGER, G. W. & YORK, D., 1981. Geochronometry from $^{40}Ar/^{39}Ar$ dating experiments. *Geochimica Cosmochimia Acta*, **45**, 795–811.

BINGEN, B., DEMAIFFE, D. & VAN BREEMEN, O. 1998. The 616 Ma old Egersund basaltic dike swarm, SW Norway, and Late Neoproterozoic opening of the Iapetus Ocean. *Journal of Geology*, **106**, 565–574.

BLEWETT, R. S., BLACK, L. P., SUN, S-S., KNUTSON, J., HUTTON, L. J. & BAIN, J. H. C. 1998. U–Pb zircon and Sm–Nd geochronology of the Mesoproterozoic of North Queensland: implications for a Rodinian connection with the Belt supergroup of North America. *Precambrian Research*, **89**, 101–127.

BOND, G. C., NICKESON, P. A. & KOMINZ, M. A. 1984. Breakup of a supercontinent between 625 Ma and 555 Ma: new evidence and implications for continental histories. *Earth and Planetary Science Letters*, **70**, 325–345.

BOGER, S. D., WILSON, C. J. L. & FANNING, C. M. 2001. Early Paleozoic tectonism with the East Antarctic craton: the final suture between east and west Gondwana. *Geology*, **29**, 463–466.

BRIDEN, J. C., DUFF, B. A. & KRÖNER, A. 1979. Palaeomagnetism of the Koras Group, Northern Cape Province, South Africa. *Precambrian Research*, **10**, 43–57.

BROOKFIELD, M. E. 1993. Neoproterozoic Laurentia–Australia fit. *Geology*, **21**, 683–686.

BRUGUIER, O., BOSCH, D., PIDGEON, R. T., BYRNE, D. I. & HARRIS, L. B., 1999. U–Pb chronology of the Northampton Complex, Western Australia – Evidence for Grenvillian sedimentation, metamorphism and deformation and geodynamic implications. *Contributions to Mineralogy and Petrology*, **136**, 258–267.

BUCHAN, K. L. & DUNLOP, D. J. 1976. Paleomagnetism of the Haliburton Intrusions: superimposed magnetisations, metamorphism, and tectonics in the late Precambrian. *Journal of Geophysical Research*, **81**, 2951–2966.

BURRETT, C. & BERRY, R. 2000. Proterozoic Australia–Western United States (AUSWUS) fit between Laurentia and Australia. *Geology*, **28**, 103–106.

BYLUND, G. 1985. Palaeomagnetism of middle Proterozoic basic intrusives in central Sweden and the Fennoscandian apparent polar wander path. *Precambrian Research*, **28**, 283–310.

BYLUND, G. 1992. Palaeomagnetism, mafic dykes and the Protogine Zone, southern Sweden. *Tectonophysics*, **201**, 49–63.

BYLUND, G. & PISAREVSKY, S. A. 2002. Palaeomagnetism of Mesoproterozoic dykes from the Protogine Zone and the enigmatic Sveconorwegian Loop. *Geologiska Föreningen i Stockholm Förhandlingar*, **124**, 11–18.

CAWOOD, P. A., MCCAUSLAND, P. J. A. & DUNNING, G. R. 2001. Opening Iapetus: constraints from the Laurentian margin in Newfoundland. *Geological Society of America Bulletin*, **113**, 443–453.

CINGOLANI, C. & DALLA SADA, L. 2000. Buenos Aires cratonic region. *In:* CORDIANI, U. G., MILANI, E. J., THOMAZ FILHO, A. & CAMPOS, D. A. (eds) *Tectonic Evolution of South America*, 31st International Geological Congress, Rio de Janeiro. 139–150.

COLLINS, A. S., FITZSIMONS, I. C. W., H, B. & RAZAKAMANANA, T. 2002. Structure of the eastern margin of the East African Orogen in Central Madagascar. *Precambrian Research*, in press.

CONDIE, K. C. & ROSEN, O. M. 1994. Laurentia–Siberia connection revisited. *Geology*, **22**, 168–170.

CORDANI, U. G., SATO, K., TEIXEIRA, W., TASSINARI, C. G. & BASEI, M. A. S. 2000. Crustal evolution of the South American Platform. *In:* CORDIANI, U. G., MILANI, E. J., THOMAZ FILHO, A. & CAMPOS, D. A. (eds) *Tectonic Evolution of South America*, 31st International Geological Congress, Rio de Janeiro. 19–40.

D'AGRELLA-FILHO, M. S., CORDANI, U. G., DE BRITO NEVES, B. B., TRINIDADE, R. I. F. & PACCA, I. G. 2001. Evidence from South America on the formation and disruption of Rodinia. *Geological Society of Australia, Abstracts*, **65**, 27.

D'AGRELLA-FILHO, PACCA, I. G., RENNE, P. R., ONSTOTT, T. C. & TEIXEIRA, W. 1990. Paleomagnetism of Middle Proterozoic (1.01 to 1.08 Ga) mafic dykes in southeastern Bahia State–Sao Francisco Craton, Brazil. *Earth and Planetary Science Letters*, **101**, 332–348.

DALRYMPLE, G. B. 1979. Critical tables for conversion of K–Ar ages from old to new constants. *Geology*, **7**, 558–560.

DALY, J. S, FITZGERALD, R. C., BREWER, T. S., MENUGE, J. F., HEAMAN, L. M. & MORTON, A. C. 1994. Persistent geometry of Palaeoproterozoic juvenile crust on the southern margin of Laurentia–Baltica: evidence from Ireland and Rockall Bank. *Terra Abstracts*, 2, **6**, 15.

DALZIEL, I. W. D. 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation. *Geological Society of America Bulletin*, **109**, 16–42.

DALZIEL, I. W. D., MOSHER, S. & GAHAGAN, L. M. 2000. Laurentia–Kalahari collision and the assembly of Rodinia. *Journal of Geology*, **108**, 499–513.

DAVIS, D. W. & GREEN, J. C. 1997. Geochronology of the North American Midcontinent rift in western Lake Superior and implications for its geodynamic evolution. *Canadian Journal of Earth Sciences*, **34**, 476–488.

DAVIS, D. W. & PACES, J. B. 1990. Time resolution of geologic events on the Keweenaw Peninsula and applications for development of the Midcontinent Rift system. *Earth and Planetary Science Letters*, **97**, 54–64.

DAVIS, D. W. & SUTCLIFFE, R. H. 1985. U–Pb ages from the Nipigon plate and northern Lake Superior. *Geological Society of America Bulletin*, **96**, 1572–1579.

DEBLOND, A., PUNZALAN, L. E., BOWEN, A. & TACK, L.

2001. The Malagarazi Supergroup of SE Burundi and its correlative Bukoba Supergroup of NW Tanzania: Neo- and Mesoproterozoic chronostratigraphic constraints from Ar–Ar ages on mafic intrusive rocks. *Journal of African Earth Sciences*, **32**.

DIEHL, J. F. & HAIG, T. D. 1994. A paleomagnetic study of the lava flows within the Copper Harbour Conglomerate, Michigan: new results and implications. *Canadian Journal of Earth Sciences*, **31**, 369–380.

ELMING, S.-Å., PESONEN, L. J., LEINO, M. A. H. *ET AL.* 1993. The drift of the Fennoscandian and Ukrainian shields during the Precambrian: a palaeomagnetic analysis. *Tectonophysics*, **223**, 177–198.

ERNST, R. E. & BUCHAN, K. L. 1993. Paleomagnetism of the Abitibi dike swarm, southern Superior Province, and implications for the Logan Loop. *Canadian Journal of Earth Sciences*, **30**, 1886–1897.

EVANS, D. A. D. 2000. Stratigraphic, geochronological, and paleomagnetic constraints upon the Neoproterozoic climatic paradox. *American Journal of Science*, **300**, 347–433.

EVANS, D. A. D., LI, Z. X., KIRSCHVINK, J. L. & WINGATE, M. T. D. 2000. A high-quality mid-Neoproterozoic paleomagnetic pole from South China, with implications for ice ages and the breakup configuration of Rodinia. *Precambrian Research*, **100**, 313–334.

FAIRCHILD, I. J. & HAMBREY, M. J. 1995. Vendian basin evolution in East Greenland and NE Svalbard. *Precambrian Research*, **73**, 217–233.

FITZSIMONS, I. C. W. 2000. Grenville-age basement provinces in East Antarctica: evidence for three separate collisional orogens. *Geology*, **28**, 879–882.

FITZSIMONS, I. C. W. 2002. Comparison of detrital zircon ages in the Pinjarra orogen (WA) and Maud province (Antarctica): evidence for collision of western Australia with southern Africa at 1100 Ma. *Geological Society of Australia*, in press.

FRISCH, T. & TRETTIN, H. P. 1991. Precambrian successions in the northernmost part of the Canadian Shield. *In*: TRETTIN, H. P. (ed.) *Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland.* Geological Survey of Canada, Geology of Canada, **3**, 103–108.

FROST, B. R., AVCHENKO, O. V., CHAMBERLAIN, K. R. & FROST, C. D. 1998. Evidence for extensive Proterozoic remobilization of the Aldan Shield and implications for Proterozoic plate tectonic reconstructions of Siberia and Laurentia. *Precambrian Research*, **89**, 1–23.

GALLET, Y., PAVLOV, V. E., SEMIKHATOV, M. A. & PETROV, P. YU. 2000. Late Mesoproterozoic magnetostratigraphic results from Siberia: paleogeographic implications and magnetic field behaviour. *Journal of Geophysical Research*, **105**, 16481–16499.

GEE, D. G., BJÖRKLUND, L. & STØLEN, L.-K. 1994. Early Proterozoic basement in Ny Friesland – implications for the Caledonian tectonics of Svalbard. *Tectonophysics*, **231**, 171–182.

GIBBS, A. K. & BARRON, C. N. 1993. *The Geology of the Guiana Shield.* Oxford Monographs on Geology and Geophysics, **22**.

GORBATSCHEV, R. & BOGDANOVA, S. 1993. Frontiers in the Baltic Shield. *Precambrian Research*, **64**, 3–21.

GUSEV, G. S. & KHAIN, V. YE. 1996. On relations between the Baikal–Vitim, Aldan–Stanovoy, and Mongol–Okhotsk terranes (south of mid-Siberia). *Geotectonics*, **29**, 422–436.

HALLS, H. C. & PESONEN, L. J. 1982. Paleomagnetism of Keweenawan rocks. *Geological Society of America, Memoirs*, **156**, 173–201.

HANDKE, M. J., TUCKER, R. D. & ASHWAL, L. D. 1999. Neoproterozoic continental arc magmatism in west-central Madacascar. *Geology*, **27**, 351–354.

HARLAN, S. S., GEISSMAN, J. W. & SNEE, L. W. 1997. *Paleomagnetic and $^{40}Ar/^{39}Ar$ geochronologic data from late Proterozoic mafic dykes and sills, Montana and Wyoming*. USGS Professional Paper 1580.

HARRIS, L. B. 1994. Neoproterozoic sinistral displacement along the Darling Mobile Belt, Western Australia, during Gondwanaland assembly. *Journal of the Geological Society, London*, **151**, 901–904.

HEAMAN, L. M., LECHEMINANT, A. N. & RAINBIRD, R. H. 1992. Nature and timing of Franklin igneous event, Canada: implications for a Late Proterozoic mantle plume and the break-up of Laurentia. *Earth and Planetary Science Letters*, **109**, 117–131.

HENRY, S. G., MAUK, F. J. & VAN DER VOO, R. 1977. Paleomagnetism of the upper Keweenawan sediments: the Nonesuch Shale and Freda Sandstone. *Canadian Journal of Earth Sciences*, **14**, 1128–1138.

HIGGINS, A. K. & LESLIE, A. G. 2000. Restoring thrusting in the East Greenland Caledonides. *Geology*, **28**, 1019–1022.

HIGGINS, A. K., SMITH, M. P., SOPER, N. J., LESLIE, A. G., RASMUSSEN, J. A. & SØNDERHOLM, M. 2001. The Neoproterozoic Hekla Sund Basin, eastern North Greenland: a pre-Iapetian extensional sequence thrust across its rift shoulders during the Caledonian orogeny. *Journal of the Geological Society, London*, **158**, 487–499.

HOFFMAN, P. F. 1989. Precambrian geology and tectonic history of North America. *In:* BALLY, A. W. & PALMER, A. R. (eds) *The Geology of North America – An Overview.* Geological Society of America, The Geology of North America, **A**, 447–512.

HOFFMAN, P. F. 1991. Did the breakout of Laurentia turn Gondwana inside out? *Science*, **252**, 1409–1412.

HYODO, H. & DUNLOP, D. J. 1993. Effect of anisotropy on the paleomagnetic contact test for a Grenvillian dike. *Journal of Geophysical Research*, **98**, 7997–8017.

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 Maud Land. *Journal of Geology*, **106**, 385–406.

JACOBS, J, THOMAS, R. J. & WEBER, K. 1993. Accretion and indentation tectonics at the southern edge of the Kaapvaal craton during the Kibaran (Grenville) orogeny. *Geology*, **21**, 203–206.

JOHNSON, S. P. & OLIVER, G. J. H. 2000. Mesoproterozoic oceanic subduction, island-arc formation and the initiation of back-arc spreading in the Kibaran Belt of central, southern Africa: evidence from the Ophiolite Terrane, Chewore Inliers, northern Zimbabwe. *Precambrian Research*, **103**, 125–146.

KALSBEEK, F., THRANE, K., NUTMAN, A. P. & JEPSEN, H. F. 2000. Late Mesoproterozoic to early Neoproterozoic history of the East Greenland Caledonides: evidence for Grenvillian orogenesis? *Journal of the Geological Society, London*, **157**, 1215–1225.

KARLSTROM, K. E., HARLAN, S. S., WILLIAMS, M. L., MCLELLAND, J., GEISSMAN, J. W & ÅHALL, K.-I. 1999. Refining Rodinia: geologic evidence for the Australia–Western U.S. connection in the Proterozoic. *GSA Today*, **9**, 1–7.

KEPPIE, J. D. & ORTEGA-GUTIERREZ, F. O. 1999. Middle American Precambrian basement: a missing piece of the reconstructed 1–Ga orogen. *Geological Society of America, Special Paper*, **336**, 199–210.

KEPPIE, J. D. & RAMOS, V. A. 1999. Odyssey of terranes in the Iapetus and Rheic oceans during the Paleozoic. *Geological Society of America, Special Paper*, **336**, 267–276.

KHUDOLEY, A. K., RAINBIRD, R. H., STERN, R. A. *ET AL.* 2001. Sedimentary evolution of the Riphean – Vendian basin of southeastern Siberia. *Precambrian Research*, **111**, 129–163.

KRÖNER, A., HEGNER, E., COLLINS, A. S., WINDLEY, B. F., BREWER, T. S., RAZAKAMANANA, T. & PIDGEON, R. T. 2000. Age and magmatic history of the Antanarivo Block, central Madagsacar, as derived from zircon geochronology and Nd isotopic systematics. *American Journal of Science*, **300**, 251–288.

KRÖNER, A., SACCHI, R., JAECKEL, P. & COSTA, M. 1997. Kibaran magmatism and Pan-African granulite metamorphism in northern Mozambique: single zircon ages and regional implications. *Journal of African Earth Sciences*, **25**, 467–484.

KRÖNER, A., WILLNER, A. P., HEGNER, E., JAECKEL, P. & NEMCHIN, A. 2001. Single zircon ages, PT evolution and Nd isotopic systematics of high-grade gneisses in southern Malawi and their bearing on the evolution of the Mozambique Belt in southeastern Africa. *Precambrian Research*, **190**, 257–291.

KUZMICHEV, A. B., BIBIKOVA, E. V. & ZHURAVLEV, D. Z. 2001. Neoproterozoic (~800 Ma) orogeny in the Tuva–Mongolia Massif (Siberia): island arc-continent collision at the northeast Rodinia margin. *Precambrian Research*, **110**, 109–126.

KUZMIN, V. V., CHUCHONIN, A. P. & SHULEZHKO, I. K. 1995. Stages of metamorphic evolution of rocks of crystalline basement of the Kukhtui Uplift (Okhotsk Massif). *Reports of Russian Academy of Sciences*, **342**, 789–791 [in Russian].

LARSON, S.-Å. & BERGLUND, J. 1992. A chronological subdivision of the Transscandinavian Igneous Belt – three magmatic episodes? *Geologiska Föreningen i Stockholm Förhandlingar*, **114**, 459–461.

LAWER, L. A. & MÜLLER, R. D. 1994. Iceland hotspot track. *Geology*, **22**, 311–314.

LECHEMINANT, A. N. & HEAMAN, L. M. 1994. 779 Ma mafic magmatism in the northwestern Canadian Shield and northern Cordillera: a new regional time-marker. *Proceedings of the 8th International Conference. Geochronology, Cosmochronology and Isotope Geology, Program Abstracts*, **1107**, 197.

LI, Z. X. & POWELL, C. MCA. 1999. Palaeomagnetic study of Neoproterozoic glacial rocks of the Yangzi Block: palaeolatitude and configuration of South China in the late Proterozoic Supercontinent. *Precambrian Research*, **94**, 1–5.

LI, Z. X., LI., X. H., KINNY, P. D. & WANG, J. 1999. The breakup of Rodinia: did it start with a mantle plume beneath South China? *Earth and Planetary Science Letters*, **173**, 171–181.

LI, Z. X., LI, X. H., ZHOU, H. & KINNY, P. D. 2002. Grenville-aged continental collision in South China: new SHRIMP U–Pb zircon results and implications for Rodinia configuration. *Geology*, **30**, 163–166.

LI, Z. X., ZHANG, L. & POWELL, C. MCA. 1995. South China in Rodinia: part of the missing link between Australia–East Antarctica and Laurentia? *Geology*, **23**, 407–410.

LI, Z. X., ZHANG, L. & POWELL, C. MCA. 1996. Positions of the East Asian cratons in the Neoproterozoic supercontinent Rodinia. *Australian Journal of Earth Sciences*, **43**, 593–604.

MCCABE, C. & VAN DER VOO, R. 1983. Paleomagnetic results from the upper Keweenawan Chequamegon Sandstone: implications for red bed diagenesis and Late Precambrian apparent polar wander of North America. *Canadian Journal of Earth Sciences*, **20**, 105–112.

MCELHINNY, M. W. & MCFADDEN, P. L. 2000. *Paleomagnetism: Continents and Oceans.* Academic Press, San Diego.

MCMENAMIN, M. A. S. & MCMENAMIN, D. L. 1990. *The Emergence of Animals; The Cambrian Breakthrough.* Columbia University Press, New York.

MEERT, J. G. & POWELL, C. MCA. 2001. Assembly and break-up of Rodinia: introduction to the special volume. *Precambrian Research*, **110**, 1–8.

MEERT, J. G., HARGRAVES, R. B., VAN DER VOO, R., HALL, C. H. & HALLIDAY, A. N. 1994. Paleomagnetism and $^{40}Ar/^{39}Ar$ studies of Late Kibaran intrusives in Burundi, East Africa: implications for Late Proterozoic supercontinents. *Journal of Geology*, **102**, 621–637.

MEERT, J. G., VAN DER VOO, R. & AYUB, S. 1995. Paleomagnetic investigation of the Late Proterozoic Gagwe lavas and Mbozi complex, Tanzania and the assembly of Gondwana. *Precambrian Research*, **69**, 113–131.

MERTANEN, S., PESONEN, L. J. & HUHMA, H. 1996. Palaeomagnetism and Sm–Nd ages of the Neoproterozoic diabase dykes in Laanila and Kautokeino, northern Fennoscandia. *In*: BREWER, T. S. (ed.) *Precambrian Crustal Evolution in the North Atlantic Region.* Geological Society of London, Special Publication, **112**, 331–358.

MILLER, J. A., MATTHEWS, D. H. & ROBERTS, D. G. 1973. Rock of Grenville age from Rockall Bank. *Nature Physical Science*, **246**, 61.

MILLER, K. C. & HARGRAVES, R. B. 1994. Paleomagnetism of some Indian kimberlites and lamproites. *Precambrian Research*, **69**, 259–267.

MOORES, E. M. 1991. Southwest US–East Antarctic (SWEAT) connection: a hypothesis. *Geology*, **19**, 425–428.

MORTON, A. C. & TAYLOR, P. N. 1991. Geochemical and isotopic constraints on the nature and age of basement rocks from Rockall Bank, NE Atlantic. *Journal of the Geological Society, London*, **148**, 631–634.

MOSHER, S. 1998. Tectonic evolution of the southern Laurentian Grenville orogenic belt. *Geological Society of America Bulletin*, **110**, 1357–1375.

MÖLLER, C. & SÖDERLUND, U. 1997. Age constraints on the deformation within the Eastern Segment SW Sweden: Late Sveconorwegian granite dyke intrusion and metamorphic–deformational relations. *Geologiska Föreningen i Stockholm Förhandlingar*, **119**, 1–12.

NATAL'IN, B. A., AMATO, J. M., TORO, J. & WRIGHT, J. E. 1999. Paleozoic rocks of northern Chukotka Peninsula, Russian Far East: implications for the tectonics of the Arctic region. *Tectonics*, **18**, 977–1003.

OLIVER, G. J. H., JOHNSON, S. P., WILLIAMS, I. S. & HERD, D. A. 1998. Relict 1.4 Ga oceanic crust in the Zambezi Valley, northern Zimbabwe: evidence for Mesoproterozoic supercontinental fragmentation. *Geology*, **26**, 571–573.

ONSTOTT, T. C. & HARGRAVES, R. B. 1981. Proterozoic transcurrent tectonics: palaeomagnetic evidence from Venezuela and Africa. *Nature*, **289**, 131–136.

ONSTOTT, T. C., T. C., HARGRAVES, R. B. & JOUBERT, P. 1986. Constraints on the evolution of the Namaqua Province II: Reconnaissance palaeomagnetic and $^{40}Ar/^{39}Ar$ results from the Namaqua Province and the Kheis Belt. *Transactions of the Geological Society of South Africa*, **89**, 143–170.

PALMER, H. C., BARAGAR, W. R. A., FORTIER, M. & FOSTER, J. H. 1983. Paleomagnetism of Late Proterozoic rocks, Victoria Island, Northwest Territories, Canada. *Canadian Journal of Earth Sciences*, **20**, 1456–1469.

PARK, J. K. 1994. Palaeomagnetic constraints on the position of Laurentia from middle Neoproterozoic to Early Cambrian times. *Precambrian Research*, **69**, 95–112.

PARK, J. K., J. K. & AITKEN, J. D. 1986. Paleomagnetism of the Katherine Group in the Mackenzie Mountains: implications for post-Grenville (Hadrynian) apparent polar wander. *Canadian Journal of Earth Sciences*, **23**, 308–323.

PARK, J. K., J. K., BUCHAN, K. L. & HARLAN, S. S. 1995. A proposed giant radiating dyke swarm fragmented by separation of Laurentia and Australia based on paleomagnetism of ca. 780 Ma mafic intrusions in western North America. *Earth and Planetary Science Letters*, **132**, 129–139.

PARK, J. K., J. K., NORRIS, D. K. & LAROCHELLE, A. 1989. Paleomagnetism and the origin of the Mackenzie Arc of northwestern Canada. *Canadian Journal of Earth Sciences*, **26**, 2194–2203.

PARK, J. K., R. G. 1992. Plate kinematic history of Baltica during the Middle to Late Proterozoic: a model. *Geology*, **20**, 725–728.

PARK, J. K., R. G., CLIFF, R. A., FETTES, D. J. & STEWARD. A. D. 1994. Precambrian rocks in northwest Scotland west of the Moine Thrust: the Lewisian Complex and the Torridonian. *In*: GIBBONS, W. & HARRIS, A. L. (eds) *A Revised Correlation of Precambrian Rocks in the British Isles*. Geological Society, London, Special Report, **22**, 6–22.

PEDROSA-SOARES, A. C., NOCE, C. M., WIEDEMANN, C. M. & PINTO, C. P. 2001. The Araçoaí–West-Congo Orogen in Brazil: an overview of a confined orogen formed during Gondwanaland assembly. *Precambrian Research*, **110**, 307–323.

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

PENAYE, J., TOTEU, S. F., VAN SCHMUS, W. R. & NZENTI, J.-P. 1993. U–Pb and Sm–Nd preliminary geochronologic data on the Yaounde series, Cameroon: re-interpretation of the granulitic rocks as the suture of a collision in the 'Centrafrican' belt. *Comptes Rendus de l'Académie des Sciences Paris, Série II*, **317**, 789–794.

PERRIN, M. & PREVOT, M. 1988. Uncertainities about the Proterozoic and Paleozoic polar wander path of the West African craton and Gonwana: evidence for successive remagnetization events. *Earth and Planetary Science Letters*, **88**, 337–347.

PIMENTEL, M. M., FUCK, R. A. & BOTELHO, N. F. 1999. Granites and the geodynamic history of the Neoproterozoic Brazilia belt, Central Brazil: a review. *Lithos*, **46**, 463–483.

PINNA, P., JOURDE, G., CALVEZ, J. Y., MROZ, J. P. & MARQUES, J. M. 1993. The Mozambique Belt in northern Mozambique: Neoproterozoic (1100–850 Ma) crustal growth and tectogenesis, and superimposed Pan-African (800–550 Ma) tectonism. *Precambrian Research*, **62**, 1–59.

PIPER, J. D. A. 1987. *Palaeomagnetism and the Continental Crust*. Open University Press, Milton Keynes.

PIPER, J. D. A., J. D. A. 2000. The Neoproterozoic Supercontinent: Rodinia or Palaeopangaea? *Earth and Planetary Science Letters*, **176**, 131–146.

PISAREVSKY, S. A. & BYLUND, G. 1998. Palaeomagnetism of a key section of the Protogine Zone, southern Sweden. *Geophysical Journal International*, **133**, 185–200.

PISAREVSKY, S. A., S. A., LI, Z. X., GREY, K. & STEVENS, M. K. 2001. A palaeomagnetic study of Empress 1A, a stratigraphic drillhole in the Officer Basin: new evidence for the low-latitude position of Australia in the Neoproterozoic. *Precambrian Research*, **110**, 93–108.

POWELL, C.MCA. & PISAREVSKY, S.A. 2002. Late Neoproterozoic assembly of East Gondwanaland. *Geology*, **30**, 3–6.

POWELL, C. MCA., JONES, D. L, PISAREVSKY, S. A. & WINGATE, M. T .D. 2001. Paleomagnetic constraints on the position of the Kalahari craton in Rodinia. *Precambrian Research*, **110**, 33–46.

POWELL, C. MCA., LI, Z. X., MCELHINNY, M. W., 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., PREISS, W. V., GATEHOUSE, C. G., KRAPEZ, B. & LI, Z. X. 1994. South Australian record of a Rodinian epicontinental basin and its mid-Neoproterozoic breakup (~700 Ma) to form the Palaeo-Pacific Ocean. *Tectonophysics*, **237**, 113–140.

RADHAKRISHNA, T. & MATHEW, J. 1996. Late Precambrian (850–800 Ma) palaeomagnetic pole for the south Indian shield from the Harohalli alkaline dykes: geotectonic implications for Gondwana reconstructions. *Precambrian Research*, **80**, 77–87.

RAINBIRD, R. H., Hamilton, M. A. & Young, G. M. 2001. Detrital zircon geochronology and provenance of the

Torridonian, NW Scotland. *Journal of the Geological Society, London*, **158**, 15–27.

RAINBIRD, R. H., MCNICOLL, V. J., THERIAULT, R. J., HEAMAN, L. M., ABBOT, J. G., LONG, J. G. & THORKELSON, D. J. 1997. Pan-continental river system draining Grenville orogen recorded by U–Pb and Sm–Nd geochronology of Neoproterozoic quartzites and mudrocks, northwestern Canada. *Journal of Geology*, **105**, 1–17.

RAINBIRD, R. H., STERN, R. A., KHUDOLEY, A. K., KROPACHEV, A. P., HEAMAN, 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 and Planetary Science Letters*, **164**, 409–420.

RAMO, O. T. & CALZIA, J. P. 1998. Nd isotopic composition of cratonic rocks in the southern Death Valley region: evidence for a substantial Archean source component in Mojavia. *Geology*, **26**, 891–894.

RAMOS, V. A. 1988. Late Proterozoic–Early Paleozoic of South America – a collisional history. *Episodes*, **11**, 168–174.

RENNE, P. R., ONSTOTT, T. C., D'AGRELLA-FILHO, M. S., PACCA, I. G. & TEIXEIRA, W. 1990. $^{40}Ar/^{39}Ar$ dating of 1.0–1.1 Ga magnetizations from the São Francisco and Kalahari cratons: tectonic implications for Pan-African and Brasiliano mobile belts. *Earth and Planetary Science Letters*, **101**, 349–366.

RIVERS, T. 1997. Lithotectonic elements of the Grenville province: review and tectonic implications. *Precambrian Research*, **86**, 117–154.

ROBB, L. J., ARMSTRONG, R. A. & WATRES, D. J. 1999. The history of granulite-facies metamorphism and crustal growth from single zircon U–Pb geochronology: Namaqualand, South Africa. *Journal of Petrology*, **40**, 1747–1770.

ROSEN, O. M., CONDIE, K. C, NATAPOV, L. M. & NOZHKIN, A. D. 1994. Archean and Early Proterozoic evolution of the Siberian craton: a preliminary assessment. *In*: CONDIE, K. C. (ed.) *Archean Crustal Evolution*. Elsevier, Amsterdam, 411–459.

ROSEN, O. M., ZHURAVLEV, D. Z., SUKHANOV, M. K. BIBIKOVA, E. B. & ZLOBIN, V. L. 2000. Early Proterozoic terranes, collosion zones, and associated anorthosites in the northeast of the Siberian craton: isotope geochemistry and age characteristics. *Geology and Geophysics*, **41**, 163–180 [in Russian].

ROSS, G. M., BLOCH, J. D. & KROUSE, H. R. 1995. Neoproterozoic strata of the southern Canadian Cordillera and the isotopic evolution of seawater sulfate. *Precambrian Research*, **73**, 71–99.

ROSS, G. M., EATON, D. W., BOERNER, D. E. & MILES, W. 2000. Tectonic entrapment and its role in the evolution of continental lithosphere: an example from the Precambrian of western Canada. *Tectonics*, **19**, 116–134.

ROSS, G. M., PARRISH, R. R. & WINSTON, D. 1992. Provenance and U–Pb geochronology of the Mesoproterozoic Belt Supergroup (northwestern United States): implications for age of deposition and pre-Panthalassa plate reconstructions. *Earth and Planetary Science Letters*, **113**, 57–76.

ROY, J. L. & ROBERTSON, W. A. 1978. Paleomagnetism of the Jacobsville Formation and the apparent polar path for the interval ~1100 to ~670 m.y. for North America. *Journal of Geophysical Research*, **83**, 1289–1304.

RYTSK, E. YU., AMELIN, YU. V., KRYMSKY, R. SH., RIZVANOVA, N. G. & SHALAEV, V. S. 1999. Baikal–Muya belt: age evolution of crust forming. *Proceeding of the Materials of the XXXII Tectonic Meeting*. Geos Press, Moscow, **2**, 93–95 [in Russian].

SADOWSKI, G. R. & BETTENCOURT, J. S. 1996. Mesoproterozoic tectonic correlations between eastern Laurentia and the western border of the Amazon Craton. *Precambrian Research*, **76**, 213–227.

SEARS, J. W. & PRICE, R. A. 1978. The Siberian connection: a case for Precambrian separation of the North American and Siberian cratons. *Geology*, **6**, 267–270.

SEARS, J. W. & PRICE, R. A. 2000. New look at the Siberian connection: no SWEAT. *Geology*, **28**, 423–426.

SMETHURST, M. A., KHRAMOV, A. N. & TORSVIK, T. H. 1998. The Neoproterozoic and Palaeozoic palaeomagnetic data for the Siberian Platform: from Rodinia to Pangea. *Earth-Science Reviews*, **43**, 1–24.

STARMER, I. C., 1996. Accretion, rifting and collision in the North Atlantic supercontinent, 1700–950 Ma. *In*: BREWER, T. S. (ed.) *Precambrian Crustal Evolution in the North Atlantic Region*. Geological Society of London, Special Publication, **112**, 219–248.

STEARN, J. E. F. & Piper, J. D. A. 1984. Palaeomagnetism of the Sveconorwegian mobile belt of the Fennoscandian Shield. *Precambrian Research*, **23**, 201–246.

TACK, L., WINGATE, M. T. D., LIÉGEOUS, J.–P., FERNANDEZ-ALONSO, M. & DEBLOND, A. 2001. Early Neoproterozoic magmatism (1000–910 Ma) of the Zadinian and Mayumbian Groups (Bas-Congo): onset of Rodinia rifting at the western edge of the Congo Craton. *Precambrian Research*, **110**, 277–306.

TASSINARI, C. C. G., BETTENCOURT, J. S., GERALDES, M. C., MACAMBIRA, M. J. B. & LAFON, J. M. 2000. The Amazonian craton. *In*: CORDIANI, U. G., MILANI, E. J., THOMAZ FILHO, A. & CAMPOS, D. A. (eds) *Tectonic Evolution of South America*, 31st International Geological Congress, Rio de Janeiro. 41–95.

TEIXEIRA, W., SABATE, P., BARBOSA, J., NOCE, C. M. & CARNEIRO, M. A. 2000. Archean and Paleoproterozoic tectonic evolution of the São Francisco craton, Brazil. *In*: CORDIANI, U. G., MILANI, E. J., THOMAZ FILHO, A. & CAMPOS, D. A. (eds) *Tectonic Evolution of South America*, 31st International Geological Congress, Rio de Janeiro. 101–137.

TORSVIK, T. H. & EIDE, E. 1997. Database of Norwegian Geochronology. NGU Report 98–003.

TORSVIK, T. H., ASHWAL, L. D., TUCKER, R. D. & EIDE, E. A. 2001*a*. Neoproterozoic geochronology and palaeogeography of the Seychelles microcontinent: the India link. *Precambrian Research*, **110**, 47–59.

TORSVIK, T. H., CARTER, L. M., ASHWAL, L. D., BHUSHAN, S. K., PANDIT, M. K. & JAMTVEIT, B. 2001*b*. Rodinia refined or obscured: palaeomagnetism of the Malani igneous suite (NW India). *Precambrian Research*, **108**, 319–333.

TORSVIK, T. H., SMETHURST, M. A., NEERT, J. G. *ET AL*. 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic – a tale of Baltica and Laurentia. *Earth-Science Reviews*, **40**, 229–258.

TROMPETTE, R. 1994. *Geology of Western Gondwana (2000–500 Ma)*. A. A. Balkema, Rotterdam.

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

TUCKER, R. D., ASHWAL, L. D., & TORSVIK, T. H., 2001. U–Pb geochronology of Seychelles granitoids: a Neoproterozoic continental arc fragment. *Earth and Planetary Science Letters*, **187**, 27–38.

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 Research*, **53**, 149–163.

VAN SCHMUS, W. R. & BICKFORD, M. E. 1993. Transcontinental Proterozoic provinces. *In*: REED, J. C., BICKFORD, M. E. & HOUSTON, R. S. ET AL. *(eds) Precambrian: Continental US.* Geological Society of America, Geology of North America, **C-2**, 171–334.

WALDERHAUG, H. J., TORSVIK, T. H., EIDE, E. A., SUNDVOLL, E. A. & BINGEN, B. 1999. Geochronology and palaeomagnetism of the Hunnedalen dykes, SW Norway: implications for the Sveconorwegian apparent polar wander loop. *Earth and Planetary Science Letters*, 169, 71–83.

WANG, X. D. & LINDH, A. 1996. Temperature–pressure investigation of the southern part of the southwest Swedish Granulite region. *European Journal of Mineralogy*, **8**, 51–67.

WANG, X. D., PAGE, L.M. & LINDH, A. 1996. $^{40}Ar/^{39}Ar$ geochronological constraints from the southeasternmost part of the eastern segment of the Sveconorwegian orogen: implications for timing of granulite facies metamorphism. *Geologiska Föreningen i Stockholm Förhandlingar*, **118**, 1–8.

WEIL, A. B., VAN DER VOO, R., MAC NIOCAILL, C & MEERT, J. G. 1998. The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstruction for 1100 to 800 Ma. *Earth and Planetary Science Letters*, **154**, 13–24.

WILDE, S. A., & MURPHY, D. M. K. 1990. The nature and origin of Late Proterozoic high-grade gneisses of the Leeuwin Block, Western Australia. *Precambrian Research*, **47**, 251–270.

WILLNER, A. P., ERMOLAEVA, T., STROINK, L. ET AL. 2001. Contrasting provenance signals in Riphean and Vendian sandstones in the SW Urals (Russia): constraints for a change from passive to active continental margin conditions in the Neoproterozoic. *Precambrian Research*, **110**, 215–239.

WINGATE, M. T. D. 2001. SHRIMP baddeleyite and zircon ages for an Umkondo dolerite sill, Nyanga Mountains, eastern Zimbabwe. *South African Journal of Geology*, **104**, 13–22.

WINGATE, M. T. D. & GIDDINGS, J. W. 2000. Age and palaeomagnetism of the Mundine Well dyke swarm, Western Australia: implications for an Australia–Laurentia connection at 755 Ma. *Precambrian Research*, **100**, 335–357.

WINGATE, M. T. D., CAMPBELL, I. H., COMPSTON, W. & GIBSON, G. M. 1998. Ion microprobe U–Pb ages for Neoproterozoic basaltic magmatism in south-central Australia and implications for the breakup of Rodinia. *Precambrian Research*, **87**, 135–159.

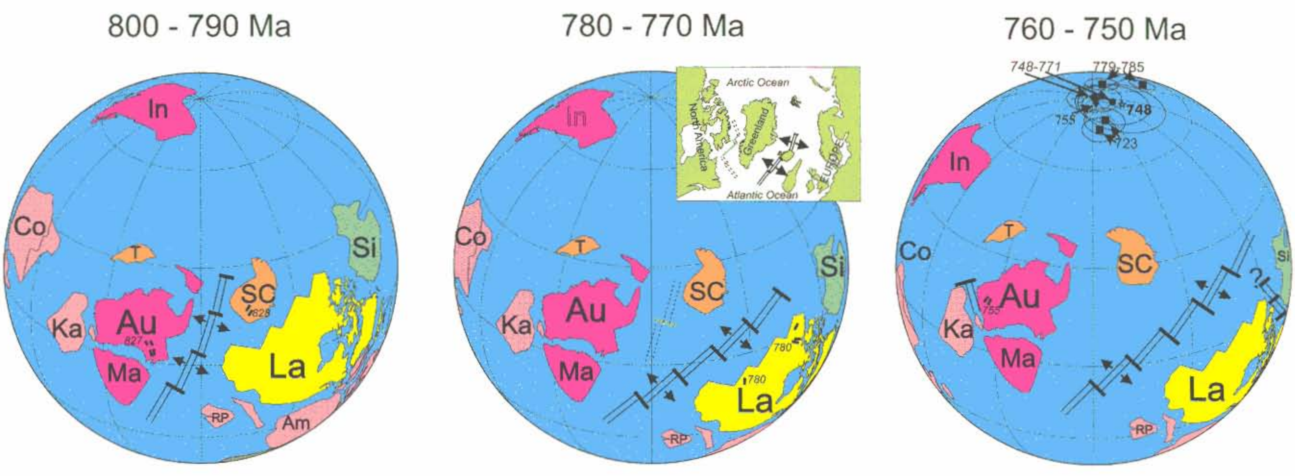
WINGATE, M. T. D., PISAREVSKY, S. A. & EVANS, D. A. D. 2002. A revised Rodinia supercontinent: no SWEAT, no AUSWUS. *Terra Nova*, **14**, 121–128.

ZONENSHAIN, L. P., KUZMIN, M. I. & NATAPOV, L. M. 1990. *Geology of the USSR: A Plate-Tectonic Synthesis*. Geodynamics Series, **21**.

Proterozoic East Gondwana: Supercontinent Assembly and Breakup

edited by M. Yoshida, B. F. Windley & S. Dasgupta

Geological Society Special Publication No. 206



Published by The Geological Society