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Rodinia refined or obscured: palaeomagnetism of the Malani igneous suite (NW India)

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Abstract

New palaeomagnetic data from the Neoproterozoic felsic volcanic rocks of the Malani igneous suite (MIS) in NW India, combined with data from an earlier study, yield a palaeomagnetic pole with latitude = 74.5°N, longitude = 71.2°E (dp/dm = 7.4/9.7°). A statistically positive fold test and remanences carried by typical high-temperature oxidation (deuteric) minerals support a primary magnetic signature. U/Pb ages from MIS (771–751 Ma) overlap with those for granitoids and dolerite dykes from the Seychelles microcontinent (mainly 748–755 Ma), and palaeomagnetic data for both entities can be matched with a tight reconstruction fit (Seychelles → India: Euler latitude = 25.8°N, longitude = 330°E, rotation angle = 28°). In this Neoproterozoic time interval, MIS and the Seychelles must have been located at intermediate northerly latitudes along the western margin of Rodinia, with magmatism that probably originated in a continental arc.

The most reliable, dated palaeomagnetic data ($\pm$756 Ma) from MIS, Seychelles and Australia require a crucial reappraisal of the timing and plate dynamics of Rodinia break-up and Gondwana assemblage. These new data necessitate an entirely different fit of East Gondwana elements than previously proposed, and also call to question the validity of the Southwest US–East Antarctic and Australia–Southwest US models. The palaeomagnetic data mandate that Greater India was located west of Australia rather than forming a conjugate margin with East Antarctica in the Mid-Neoptroterozoic. Break-up of Rodinia along western Laurentia may therefore have taken place along two major Neoproterozoic rifts; one leading to separation of Laurentia and Australia–East Antarctica, and the second between Australia and India.

Keywords: Rodinia; Neoproterozoic; Malani igneous suite; India; Palaeomagnetism; Palaeogeography

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1. Introduction

The Malani igneous suite (MIS) in Rajasthan, NW India (Fig. 1) is the third largest felsic magmatic province in the world (Pareek, 1981) and consists of subequal volumes of contemporaneous felsic volcanics and granitoids. The MIS rocks overlie and intrude the Early–Middle Proterozoic Aravalli/Delhi metasediments (Pareek, 1984), erinpura granites and trondhjemite/granodiorites (Pandit et al., 1999). The contact relationship between the MIS and the basement is poorly exposed due to extensive sand cover, but in some places, the rocks of the lowermost MIS are marked with a basal conglomerate (Bhushan, 2000). The polyphase magmatism of MIS commenced with an initial extrusion of predominantly felsic volcanics (in places with associated basalts), having more than 3 km of cumulative thickness, and was immediately followed by emplacement of granitic plutons (Bhushan, 1985). The granites are crosscut by a host of dyke swarms (mainly rhyolitic) that mark the end of the magmatic cycle. Two distinct geochemical types of silicic magmatic rocks have been identified (Eby and Kochhar, 1990) and include peraluminous (Jalore-type) and peralkaline (Siwana-type) varieties. The MIS rocks are unmetamorphosed, gently tilted and folded (Mukherjee, 1966) and are unconformably overlain by sedimentary sequences of supposed Early Cambrian age (red beds and evaporites). The age of local tilting is not known, but predates Cambrian sedimentation.

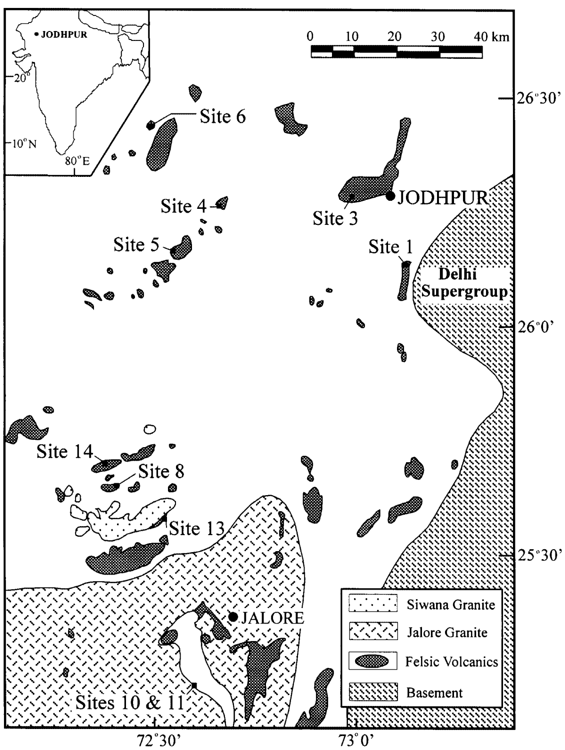

Fig. 1. Simplified map of the MIS showing outcrops of felsic volcanics and sampling sites. Inset map of India shows the location of Jodhpur.

Until recently, the cited age of MIS was based solely on Rb/Sr whole rock isochrons. Crawford and Compston (1970), for example, dated rhyolites to 730 ± 10 Ma (recalculated using the new Rb–Sr decay constant of $\lambda = 1.42 \times 10^{-11}$ yr^{-1}, Steiger and Jäger (1977)). Dhar et al. (1996) argued for a single magmatic event at 725 ± 7 Ma (rhyolites and granites), whilst Rathore et al. (1996, 1999) suggested a more protracted magmatic history (779 ± 10 to 681 ± 20 Ma) for the rhyolites. These latter authors also argued for a Pan-African resetting (500–550 Ma), based on whole-rock $^{40}Ar/^{39}Ar$ age spectra, but the latter were of poor quality with no statistically valid plateau. New U/Pb ages for Malani rhyolites range between 771 ± 2 and 751 ± 3 Ma (Tucker et al., pers. comm.), and support the timing range suggested by some of the older Rb/Sr data.

The MIS was studied palaeomagnetically by Athavale et al. (1963) and Klootwijk (1975). Both studies yielded similar palaeomagnetic results, but statistically significant fold tests were not obtained and thus could not constrain the relative magnetisation age (pre- or post-fold). We report here new palaeomagnetic data of the MIS that yield a statistically positive fold test, and that have significant bearing on the Rodinia Supercontinent configuration during the Mid-Neoproterozoic (≈ 750 Ma).

2. Sampling details and palaeomagnetic experiments

Ten sites in the vicinity of Jodhpur and Jalore, western Rajasthan (Fig. 1) were studied. All sites appear fresh and non-weathered in outcrop, except site 11, the only sampled basalt flow. Samples were drilled in the field, and orientated with both sun and magnetic compasses. Paleomagnetic sites 3 and 4 (Malani rhyolites; Fig. 1) were sampled for U–Pb zircon geochronology, and dated to 751 ± 3 and 771 ± 2 Ma, respectively (Tucker et al., pers. comm.).

The natural remanent magnetisation (NRM) was measured with JR5A and 2G Squid magnetometers. NRM stability was tested by thermal (MMTD60 furnace) and, to a lesser extent, by alternating field (AF) demagnetisation (two-axis tumbler). Characteristic remanence components were calculated with least-square regression methods.

Samples from most sites yield extremely well-defined single-component magnetisations; within-site grouping is good (low α_{95} and high k; Table 1), and mainly with northwesterly or northerly declinations and steep positive inclinations (denoted as component A, Fig. 2(a) and (b)). A few sites show minor low unblocking components that are typically demagnetised below 200–300°C (Fig. 2(c)). In situ low unblocking components (denoted as component C) plot close to the axial dipole field; they probably represent a present-day/recent viscous overprint, and hence are not considered further.

Single-component A magnetisations (Fig. 2(b)), or an interplay of components A and C (Fig. 2(c)), characterise samples from nine of the ten studied sites (Table 1). Site 11 samples differ from this pattern-they show low unblocking C-components (Fig. 2(d)), but high unblocking components (denoted as component B) with southerly declinations and negative inclinations (reverse polarity). Due to the dominance of high-coercivity mineral phases, the maximum AF demagnetisation field of 160 mT proved insufficient to demagnetise the samples, and samples were therefore further demagnetised thermally (Fig. 2(d)).

3. Magnetomineralogy

Unblocking temperatures up to 670–680°C (Fig. 2(b)–(d)), the resistance to AF demagnetisation, and Curie temperatures at around 670–680°C (Fig. 3(a)) show that hematite is a remanence carrier in all samples. Hematite is notably important in rhyolitic rocks, but subordinate amounts of titanomagnetite (TM) are indicated for many samples (Curie temperatures at ≈ 560–580°C; Fig. 3(a) and (c)). TM commonly oxidises to hematite at high temperatures (>600°C), and results in lowered saturation magnetisation after cooling (Fig. 3(a)). This probably indicates that TM grains in our samples are very fine in size. The importance of hematite in the MIS rhyolite samples is clearly reflected in isothermal remanent magnetisation (IRM) curves that are not saturated in the maximum available field of 1200 mT (Fig. 3(b)). Trachyte samples (sites 8, 13–14; Table 1) show a larger proportion of lower coercivity phases (<4–500 mT), but once again hematite is important due to the lack of saturation (Fig. 3(b)).

Microscopic examination of the rhyolitic rocks shows that primary TM and ilmenite were highly oxidised at high temperatures (deuteric, $>$ 600°C). Most samples contain irregular to euhedral grains (<0.5 mm) with almost complete pseudomorphic oxidation, mainly or entirely of original TM. The most common textures are irregular, composite intergrowths of titanohematite + rutile, or of titanohematite + pseudobrookite (oxidation stages C5–C7 of Haggerty, 1991). Extremely fine-grained hematite (main remanence carrier) is disseminated throughout all of the rhyolitic rocks, and gives rise to the characteristic brick-red coloration visible in hand specimens and outcrops. Original low-titanium TM grains (oxyexsolved) are difficult to identify, and are probably mostly present with grain size below optical resolvability.

A few samples show a 'kink' at ≈ 170°C (Fig. 3(c)), then inversion at ≈ 350°C, followed by Curie temperatures at both ≈ 580°C (TM) and 680°C (hematite). This kink is a typical low-temperature TM (maghemitisation) phenomenon (Ade-Hall et al., 1971; Torsvik et al., 1998). This

Table 1
Site-mean directions (components A and B) from the MIS (mean sampling location: 25.9°N, 72.6°E)[a]

Site	Rock type	Bedding	Lat.	Long.	Comp.	Dec.	Inc.	α_{95}	k	N	BDec.	BInc.	α_{95}	k	Palaeomagnetic pole
1	Rhyolite	215/15	26.0	73.0	A	073.5	64.9	5.6	188.9	5	038.6	70.6			
3	Rhyolite 751 ± 3 Ma[b]	0/0	26.3	73.0	A	017.2	51.8	1.6	678.2	13	017.2	51.8			
4	Rhyolite 771 ± 2 Ma[b]	356/11	26.3	72.6	A	295.8	63.6	5.8	51.7	13	312.8	72.3			
5	Rhyolite	0/0	26.2	72.5	A	356.2	64.1	3.0	511.1	6	356.2	64.1			
6	Rhyolite	003/18	26.4	72.5	A	004.5	50.4	3.4	178.9	11	024.7	46.7			
8	Trachyte	088/10	25.7	72.4	A	354.9	49.4	2.1	322.0	16	354.0	59.4			
10	Dacite	285/9	25.2	72.6	A	325.3	70.7	12.9	51.6	4	339.9	64.0			
11	Basalt	285/9	25.2	72.6	B	200.0	−25.6	7.7	99.5	5	199.6	−16.6			
13	Trachyte	268/42	25.6	72.5	A	154.2	53.9	7.3	109.0	5	057.5	74.0			
14	Trachyte	042/30	25.7	72.4	A	344.5	40.6	4.3	200.5	7	012.7	62.1			
Site means															
771–751 Ma					A	000.3	67.3	19.0	8.3	9	008.7	65.1	9.7	29.4	Pole: 67.7°N, 088.3°E, dp/dm = 12.7/15.7°
					A[c]	356.8	61.4	9.6	13.8	18	359.5	60.4	6.4	29.9	Pole: 74.5°N, 071.2°E, dp/dm = 7.4/9.7° (both bedding corrected)
					B[d]	207.9	−27.3	10.5	138.0	3	190.0	−20.4	21.5	33.9	Pole: 61.5°N, 180.8°E, dp/dm = 6.2/11.4° (in situ)

[a] Lat./Long. = sampling latitude (north)/longitude(east); Comp. = Component classification A–B (low-unblocking components C not listed); Dec./Inc. = mean declination/ inclination; α_{95} = 95% confidence circle; k = precision parameter; N = number of samples; Bdec./BInc. = Bedding corrected Dec./Inc.; dp/dm = semi-axes of the cone of 95% confidence about the pole.
[b] U/Pb zircon ages (Tucker et al., pers. comm.).
[c] Combined with RI-2–5, RI-7–8, RI-10–12 site-means of Klootwijk (1975).
[d] Combined with RI-15 and RI-16 site-means of Klootwijk (1975), Table 1).

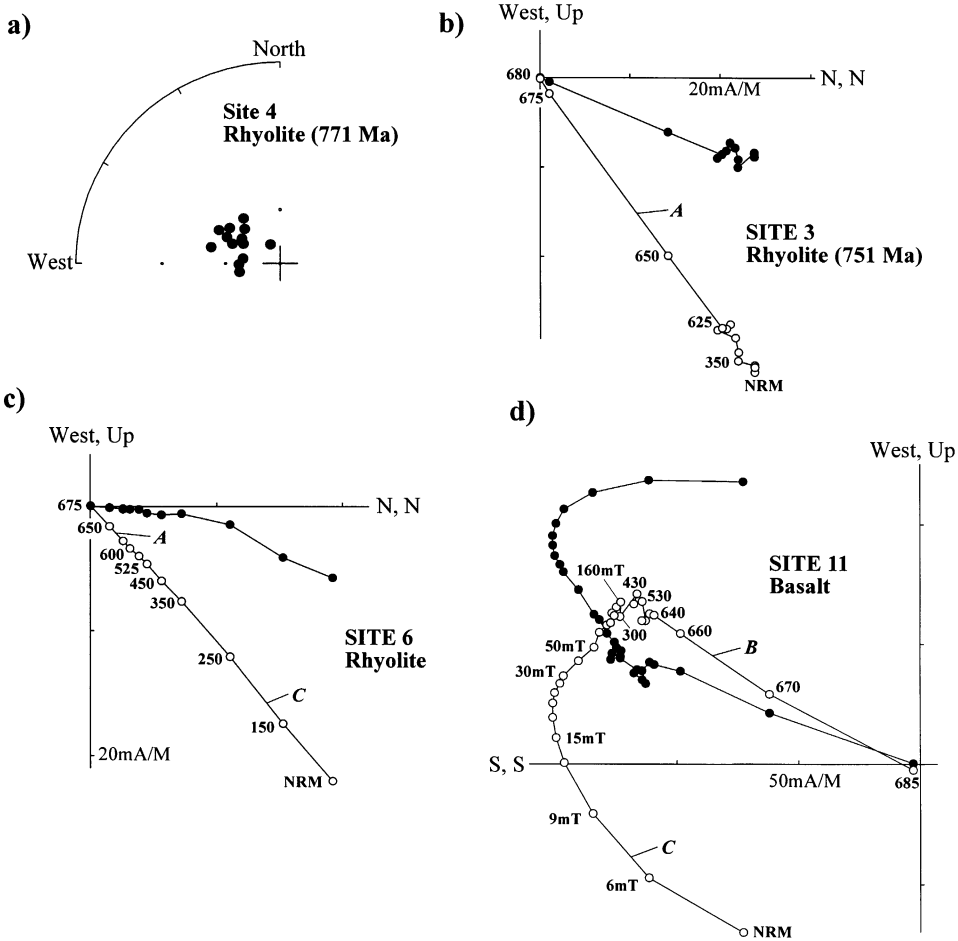

Fig. 2. (a) Example of in situ distribution of magnetisation components from site 4 (rhyolite). (b–d) Examples of thermal and AF demagnetisation of MIS samples (in situ co-ordinates). A, B and C denote components A–C discussed in the text. In orthogonal vector plots, solid (open) symbols represent points in the horizontal (vertical) plane. Characteristic remanence components are labelled A, B and C. In stereoplots, closed (open) symbols represent positive (negative) inclinations. Ages in (a, b) are U/Pb zircon ages (Tucker et al., pers. comm.)

phenomenon is rare in our sample suite (observed only from sites 11 and 13).

4. Interpretation of palaeomagnetic data

4.1. Component A

Component A is of normal polarity (Fig. 4(a)), and stepwise unfolding yields uniform increases in the statistical precision parameter k. The 100% unfolded state (Fig. 4(b)) is statistically better than the in situ distribution at the 95% confidence level (Table 1). Component A is therefore pre-fold. Most of Klootwijk (1975) MIS sites are also of normal polarity and resemble our component A. Our normal polarity sites, combined with those of Klootwijk (1975), also yield a statistically positive fold test (Table 1). Component A is carried by high-temperature oxidation minerals (hematite and variable amounts of pseudo-single domain TM) that formed during initial extrusion of the rhyolites. This deuteric mineral assemblage is ideal for preserving a primary magnetisation

(Walderhaug et al., 1991), and temperatures needed to reset this magnetisation would normally exceed closure temperatures for whole rock or standard minerals used in either Rb/Sr or $^{40}Ar/^{39}Ar$ geochronology (e.g. $^{40}Ar/^{39}Ar$ closure temperatures for a range of minerals are commonly indicated to span a range of $\approx 500°C$ for hornblende to $\approx 250°C$ for plagioclase; McDougall and Harrison, 1999). We argue, therefore, that component A is primary and acquired between 751 ± 3 and 771 ± 2 Ma (U/P zircon ages from sites 3 and 4; Tucker et al., pers. comm.).

4.2. Component B

Component B is of reverse magnetic polarity (Fig. 4(c)), and Klootwijk (1975) combined normal and reverse polarity data to calculate a mean direction for MIS. We do not think that normal and reverse components (corresponding to our A and B components) can be averaged in this way, because (1) components A and B are not antipodal, (2) component B has significantly shallower inclinations (Fig. 4), and (Fig. 3) a stepwise unfolding test, combining site 11 and the two reverse polarity site means of Klootwijk (1975), indicates that component B is post-folding (marginally failing a statistically significant negative fold test at the 95% confidence level; Fig. 4(d)). Furthermore, site 11 (basaltic flow) shows clear signs of hydrothermal alteration as compared with rocks from other sites with pristine magmatic characters (rhyolite, trachyte and dacite). Thus, component B can be attributed to a secondary origin. Site 11 is overlain by a dacite flow (site 10) that show typical A components (Table 1).

5. Neoproterozoic–Early Cambrian APW path for India

Neoproterozoic to early Palaeozoic palaeomagnetic poles from India (see references in Table 2) come from the Harohalli alkaline dykes in southern India (823 ± 15–810 ± 25 Ma: Rb/Sr and K/Ar whole rock ages), MIS (this study and references cited above), and the Early Cambrian Bhander and Rewa series in northern India (ages

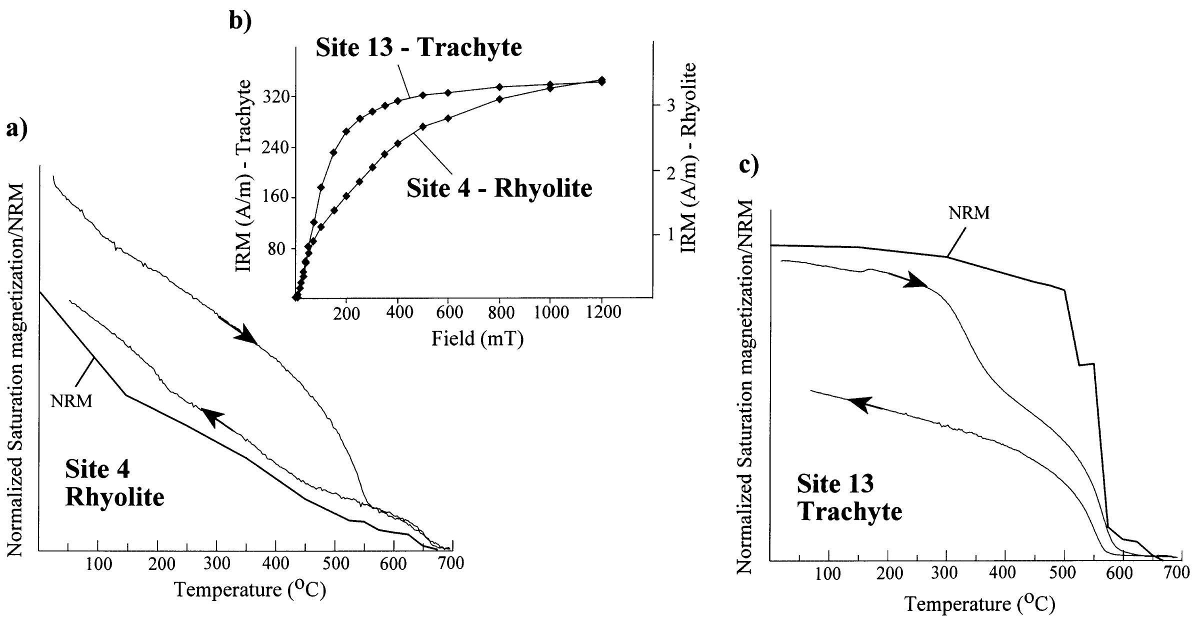

Fig. 3. (a) Thermomagnetic analysis (TMA) and NRM thermal demagnetisation spectra for a rhyolite sample. (b) IRM curve for a rhyolite (site 4) and trachyte (site 13) sample. (c) TMA and NRM thermal demagnetisation spectra for a site 13 sample (trachyte).

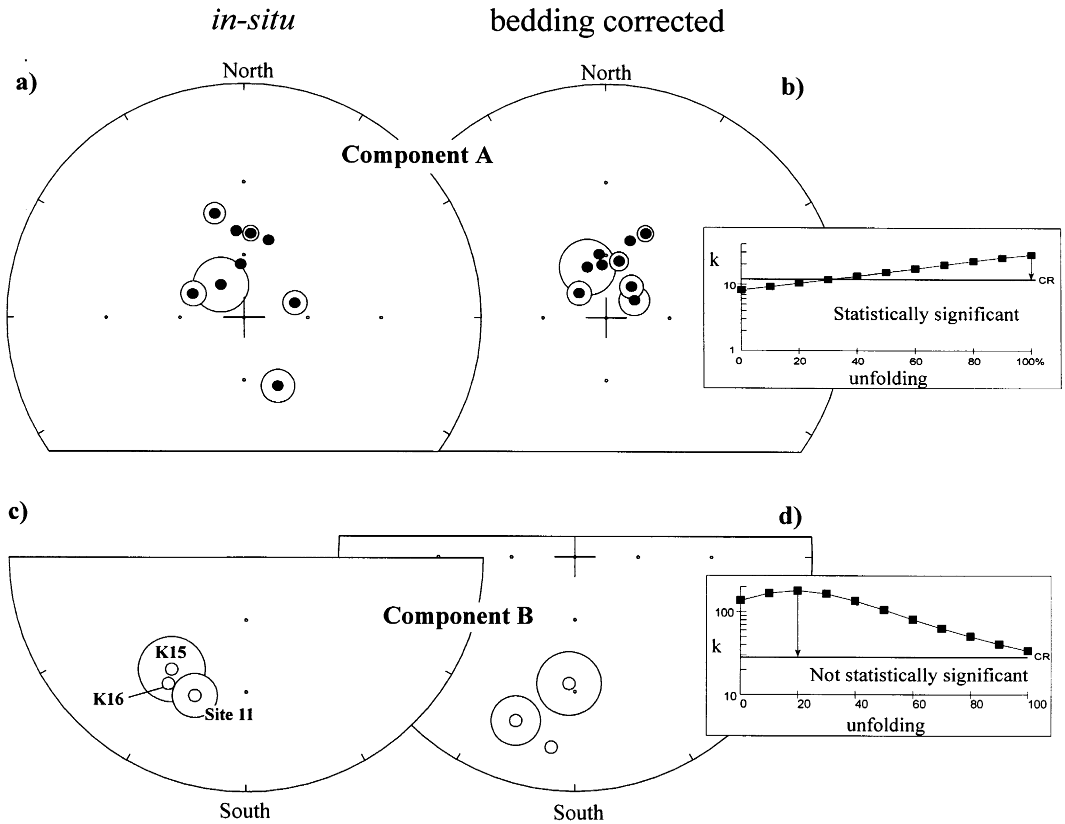

Fig. 4. Site mean directions for components A and B. Site means are plotted with α_{95} confidence circles, and shown in both in situ (left-hand stereoplots) and bedding corrected co-ordinates. Right-hand inset diagrams show variation in precision parameter k as a function of stepwise unfolding. The line marked CR is the 'critical ratio-line' to cross for a statistically significant fold test at the 95% level. Site means K15 and K16 from Klootwijk (1975).

not well constrained). Cambrian poles also exist from Pakistan (Klootwijk, 1996). These latter poles plot near the Bhander and Rewa poles, but structural corrections due to oroclinal bending (Himalayas) make these poles less reliable. Harohalli, MIS and the Early Cambrian sandstones (poorest palaeomagnetic quality and age control) were each studied by several independent palaeomagnetic groups; results are broadly similar for each rock unit (Table 2).

The Harohalli mean pole (823–810 Ma) plots in northern India (Fig. 5(a)). The Indian APW path then tracks via Siberia/Barents sea (MIS: 771–751 Ma), and finally ends up in the pacific ocean by Early Cambrian times. The MIS B-component pole plots between MIS A-component and the Early Cambrian poles (Fig. 5(a)). MIS B-pole could therefore be a Late Precambrian magnetic overprint, but we stress that only one site shows this magnetisation component, whilst Klootwijk (1975) found two sites with similar reverse polarity magnetisation.

6. Rodinia

The Rodinia Supercontinent is thought to have formed at ≈ 1100 Ma, with initial break-up commencing at 750–725 Ma (Dalziel, 1991; Hoffman, 1991; Dalziel, 1992; Powell et al., 1993; Torsvik et al., 1996; Weil et al., 1998). Fig. 6 shows a 'subtropical' section of Western Rodinia at ≈ 750 Ma (modified from Torsvik et al., 2001), with reconstruction fits from Dalziel (1992), and we also

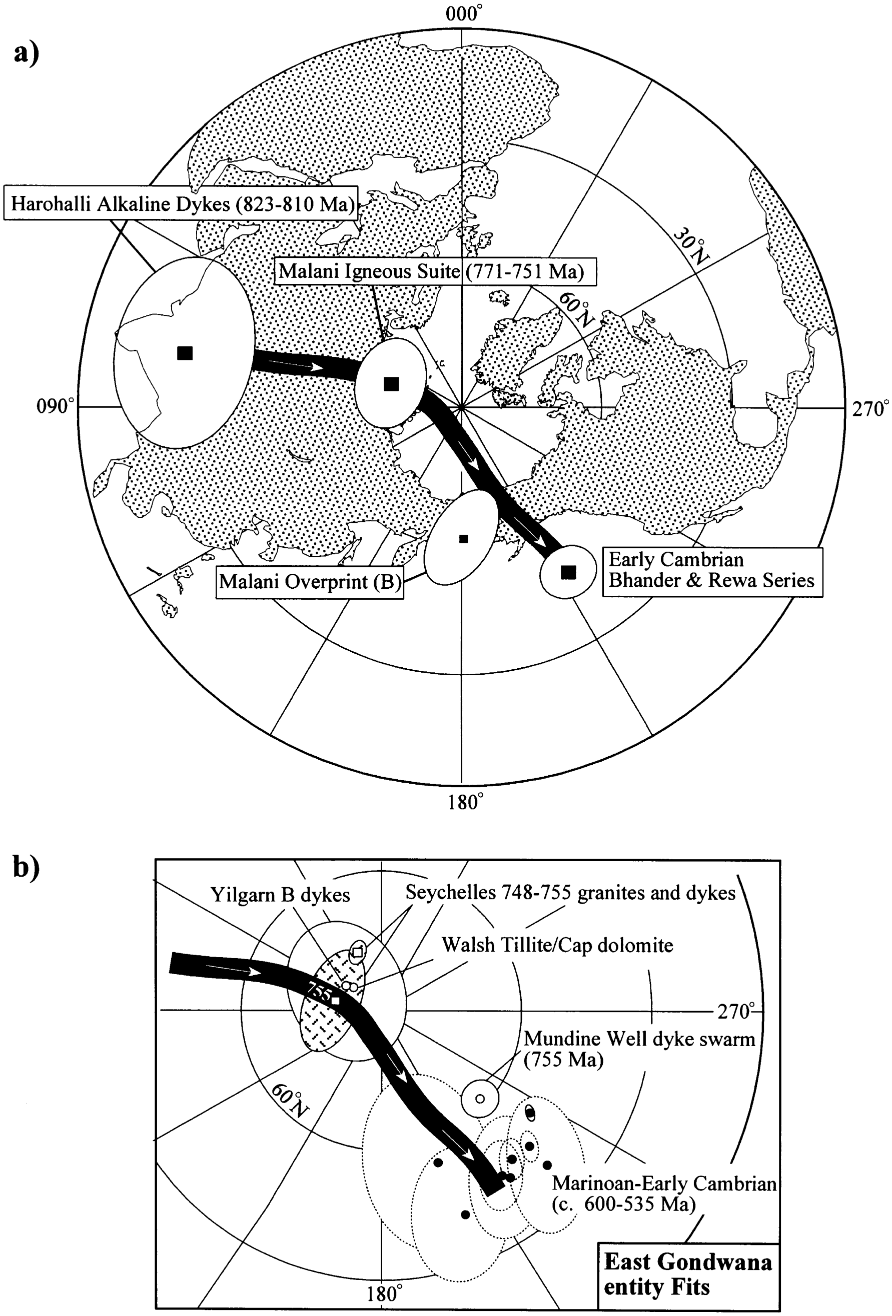

Fig. 5. (a) Palaeomagnetic mean poles from India (Table 2) plotted with dp/dm confidence ovals, except Bhander and Rewa Series (A95). Neoproterozoic–Early Cambrian India APW path indicated as thick black line with white arrows. (b) Indian APW path (as in (a)) compared with palaeomagnetic poles from Australia and the Seychelles (Table 3). Fits as in Fig. 6 (Table 3). Mundine Well dyke pole plotted with A95; other poles plotted with dp/dm ellipses. Yilgarn B pole is shown without dp/dm for clarity (large errors – Table 3). Australian Marinoan (Late Precambrian) and Early Cambrian poles are plotted as solid circles and stippled dp/dm ellipses.

include the Seychelles microcontinent. Rodinia reconstructions are to a large extent based on an attempt to link the Kibaran–Grenvillian–Sveconorwegian orogenic belts ($\approx$1100–1300 Ma); thus, the Kibaran–Grenville belts in East Antarctica have been attached to those in eastern India and southern Australia (Fig. 6). We discuss the background of published Rodinia fits below and present the argument as to why our new data necessitate that parts of these earlier models must be re-evaluated.

6.1. SWEAT

An intrinsic component of many Rodinia Supercontinent reconstructions is that the western margin of North America (Laurentia) should and can be matched with East Antarctica and Australia (SWEAT hypothesis; Dalziel, 1991; Hoffman, 1991; Moores, 1991). In addition, the East Gondwanan elements Australia–East Antarctica–India (Fig. 6) are predicted essentially to have maintained the same relative positions during Neoproterozoic to Early Mesozoic times (referred to later as the East Gondwana entity). In the model, East Gondwana supposedly rifted off the western margin of Laurentia (Powell et al., 1993), and later collided with West Gondwana blocks to form Gondwana at $\approx$550 Ma (Meert and Van der Voo, 1997). The SWEAT hypothesis and the East Gondwana entity at $\approx$750 Ma are supported by palaeomagnetic poles from Australia, MIS (India) and the Seychelles (Torsvik et al., 2001). These poles (Fig. 5(b)), along with Laurentian poles (Torsvik et al., 1996), are compatible with the reconstruction as in Fig. 6. However, the age of the Australian poles (Yilgarn B dykes: Giddings, 1976; Walsh Tillite-Cap dolomite: Li, 2000) are neither isotopically nor stratigraphically constrained (ages quoted in the literature for these poles range between 770 and 700 Ma) (Table 3).

6.2. No SWEAT

A palaeomagnetic pole obtained from the 755 Ma Mundine Well dyke swarm (MDS) in western Australia (Wingate and Giddings, 2000) casts serious doubt on the East Gondwana reconstruction in Fig. 6. The MDS pole does not match with contemporaneous poles from MIS and Seychelles (with continental 'SWEAT' fits as those in Fig. 6), but plots nearer to Marinoan and Early Cambrian poles from Australia (Fig. 5(b)), and implies a considerably lower palaeolatitude for Australia relative to Laurentia (Fig. 7(a)). If MDS, MIS and the Seychelles poles are reliable, and have approximately the same age [756 $\pm$ 17 Ma-simple mean age of palaeomagnetic dated sites from MIS (751, 771 Ma), Seychelles (750, 755 Ma) and MDS (755 Ma)], this has some important implica-

Table 2
Neoproterozoic–Early Cambrian north poles from India[a]

Formation	GLat.	GLon.	PLat.	PLon.	α_{95}	Age (Ma)	Reference
Harohalli Alkaline Dykes	12.7	77.5	24.7	084.1	5.7	823–810	Dawson and Hargraves (1994)
Harohalli Alkaline Dykes combined	12.6	77.5	27.3	078.9	9.2	823–810	Radhakrishna and Mathew (1996)
MIS (A)	25.9	72.6	67.7	088.3	9.7	771–751	Table 1
MIS	26.0	73.0	80.5	043.5	8.0	771–751	Klootwijk (1975)
MIS	26.0	73.0	78.0	045.0	10.0	771–751	Athavale et al. (1963)
Malani Combined (A)	25.9	72.6	74.5	071.2	6.4	771–751	Table 1
Rewa Sandstone	23.8	78.9	35.0	222.0	13.7	Early Cambrian?	Athavale et al. (1972)
Bhander and Rewa series	27.0	77.5	51.0	217.8	8.1	Early Cambrian?	McElhinny et al. (1978)
Upper Bhander Sandstone	26.6	77.7	48.5	213.5	5.5	Early Cambrian?	Klootwijk (1973)
Upper Bhander Sandstone	23.7	79.6	31.5	199.0	5.7	Early Cambrian?	Athavale et al. (1972)
Bhander and Rewa combined	–	–	47.3	212.7	5.8[b]	Early Cambrian?	McElhinny et al. (1978)

[a] GLat./GLon. = Geographic latitude/longitude; PLat./PLon. = Pole latitude/longitude.
[b] A95.

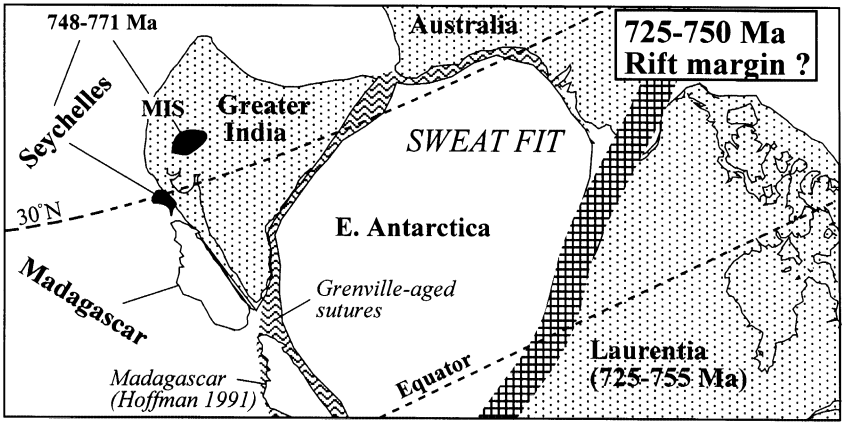

Fig. 6. 750–755 Ma 'sub-tropical' section of Western Rodinia showing Madagascar, Seychelles, Greater India, East Antarctica, Australia, and Laurentia (after Torsvik et al., 2001). Madagascar–India–Antarctica–Australia–Laurentia fits after Dalziel (1992). Seychelles–India after Torsvik et al. (2001). Continents reconstructed from palaeomagnetic data are shaded (see text). Equal area projection.

tions: (1) the SWEAT hypothesis is not valid or Rodinia break-up had already taken place at $\pm$ 756 Ma as suggested by Wingate and Giddings (2000), (2) East Gondwana was not a coherent entity throughout the Neoproterozoic (as suggested by Meert and Van der Voo, 1997), and (3) the age and origin of the Walsh Tillite Cap and the Yilgarn B dykes remanences are dubious (quoted ages are 770–700 Ma).

6.3. Rodinia refined ($\pm$ 756 Ma)

Palaeomagnetic data from Baltica–Laurentia (Torsvik et al., 1996, 2001) and the South China block (Evans et al., 2000) are consistent with the reconstruction in Fig. 7(a)) at $\pm$ 756 Ma. No palaeomagnetic data exist for Amazonia, East Antarctica, Madagascar or Siberia at this time period, but plausible configurations include: Amazonia attached to eastern Laurentia, East Antarctica attached to southern Australia, and Siberia (geographically upside-down) located north of Laurentia. Siberia is of notable interest, since Central Taimyr (attached to Siberia since Vendian times) comprises an accreted terrane with island arc units and ophiolites with associated 740 ± 38 Ma (U/Pb zircon) plagiogranites (Vernikovsky, 1997). These ophiolites are important as they demonstrate sea-floor spreading, probably along the NE margin of Rodinia (Fig. 7(a)), and suggest that at least some fragmentation of Rodinia must have taken place by $\pm$ 756 Ma.

India, Seychelles and Madagascar formed a tectonic trio at least since the assembly of Gondwana ($\approx$ 550 Ma), but the their pre-Gondwanan history is less constrained. Palaeomagnetic data from the Seychelles and MIS yield local palaeolatitudes of 30°N and 41°N (Fig. 7(a)), and a new MIS–Seychelles fit (Torsvik et al., 2001) places the Seychelles only 600 km apart from MIS during the Mid-Neoproterozoic.

The location of Madagascar is more enigmatic: Hoffman (1991) placed Madagascar next to the Kibaran–Grenville belts in East Antarctica, but Madagascar did not play an important role in Rodinia amalgamation as evidence for Kibaran–Grenvillian magmatism or metamorphism in Madagascar is scarce as of yet (see review of U/Pb ages in Kröner et al., 2000). On the other hand, Dalziel (1992), Torsvik et al. (1996), Torsvik et al. (2001) and Handke et al. (1999) favoured a position of Madagascar next to western India (Fig. 6). These models invariably must rely upon the fact that the extensive Neoproterozoic magmatism in MIS (771–751 Ma), the Seychelles (703–809 Ma, but vast majority between

748–755 Ma; Tucker et al., pers. comm.) and central-northern Madagascar (824–720 Ma; Kröner et al., 2000) may have constituted a single Andean-type arc, formed on the western margin of Rodinia (Fig. 7(a)).

The latitudinal position of MIS–Seychelles (Fig. 7(a)) relative to Australia (using the MDS pole) differs radically from traditional Neoproterozoic reconstructions (Fig. 6). If MIS–Seychelles depict the general palaeoposition for Greater India (tectonic coherence), then India was a conjugate margin to Western Australia, and not East Antarctica as in traditional Mid-Neoproterozoic models (Fig. 6). Break-up of Rodinia along western Laurentia must therefore have taken place along two major Neoproterozoic rifts; one leading to separation of Laurentia and Australia–East Antarctica, and the second between Australia–India. Eastward subduction and magmatism in India–Seychelles and Madagascar preceded, but also overlapped in age with the MDS in western Australia. The voluminous MDS dykes have a strike length of more than 900 km, and Wingate and Giddings (2000) speculated that this dyke swarm represents a major extensional event that may have led to separation of Western Australia from an unknown continent. This unknown 'continent' may have been India–Seychelles and possibly also Madagascar (Fig. 7(a)). Palaeolongitude is not determined from the palaeomagnetic data, hence the tight fit between India–Australia (or Australia–Laurentia) is therefore uncertain at ± 756 Ma. India separating from Australia–Antarctica during the Neoproterozoic is not an entirely new idea: Meert and Van der Voo (1997) suggested that East

Table 3
Neoproterozoic–Early Cambrian north poles from the Seychelles and Australia. Listed as original poles and in Indian co-ordinates[a]

India co-ordinates Formation/rock type	Continent	PLat.	PLon.	Plat.	Plon.	α_{95}	Age	Reference
Mahe dykes	Seychelles	54.8	057.6	79.8	78.6	11.2	752	Torsvik et al. (2001)
Mahe granites	Seychelles	54.0	038.2	76.6	23.0	2.0	755–748	Suwa et al. (1994)
Mundine Well dyke swarm	Australia	45.3	135.4	51.0	237.1	4.0[b]	755	Wingate and Giddings (2000)
Walsh Tillite, Cap dolomite	Australia	21.5	102.4	78.5	169.4	9.8	Sturtian?	Li (2000)(? 770–750 Ma)
Yilgarn B dykes	Australia	19.9	102	77.9	162.0	28.1	Unknown	Giddings (1976)(? 750–700 Ma)
Angepena formation	Australia	33	164	28.4	222.5	13	Marinoan	McWilliams and McElhinny (1980)
Elatina formation	Australia	50.9	157.1	36.1	242.6	3.4	Marinoan	Embleton and Williams (1986)
Elatina formation	Australia	54.3	146.9	41.9	247.7	1.8	Marinoan	Schmidt et al. (1991)
Brachina formation	Australia	33	148	41.5	219.0	16	Marinoan	McWilliams and McElhinny (1980)
Elatina formation	Australia	51.5	166.6	30.2	243.8	15.2	Marinoan	Schmidt and Williams (1995)
Arumbera –Pertataka Frm.	Australia	44.3	161.9	32.3	234.9	12	Marinoan	Kirschvink (1978)
Upper Arumbera Sandstone	Australia	46.6	157.3	35.8	237.3	4.1	Marinoan	Kirschvink (1978)
Todd River Dolomite	Australia	43.2	159.9	33.6	233.4	6.7	Early Cambrian	Kirschvink (1978)

[a] Seychelles–India fit:25.8°N, 330°E, 28° Torsvik et al. (2001); Australia–India fit: 13.1°N, 189.7°E, −64.5° (recalculated from Dalziel (1992)).
[b] A95.

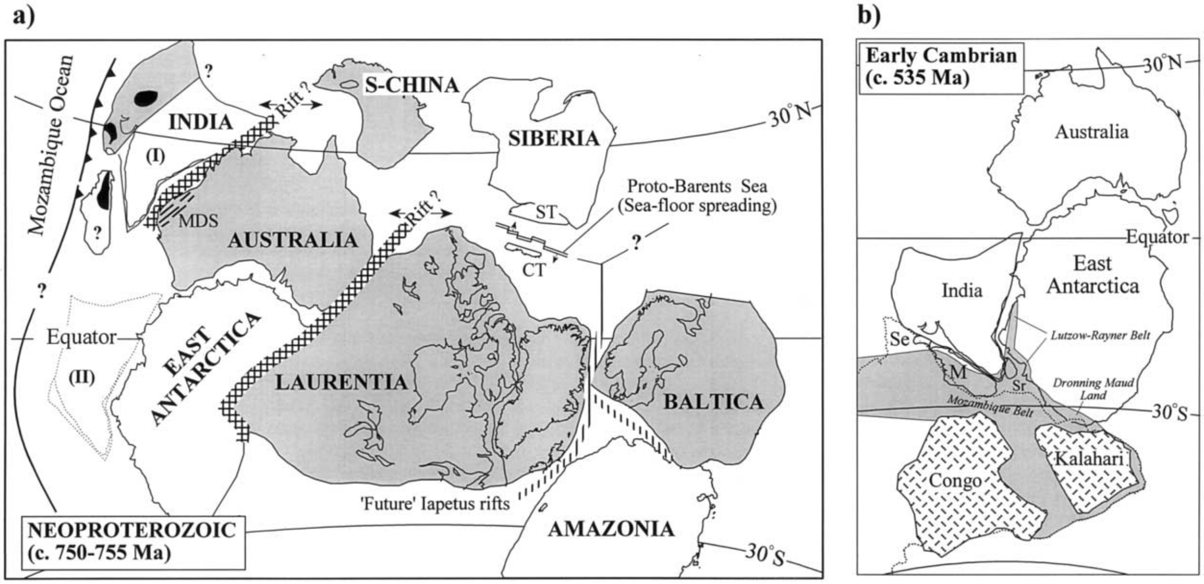

Fig. 7. (a) Neoproterozoic reconstruction of some Rodinian elements at c. 750–755 Ma (modified from Torsvik et al. (2001)). Location of Laurentia as in Fig. 6. Australia–East Antarctica and South China Block according to Wingate and Giddings (2000) and Evans et al. (2000), respectively. Location of Mid-Neoproterozoic magmatic rocks in Northern Madagascar, Seychelles and MIS indicated as black patches; possibly formed above an eastward-dipping subduction zone. Madagascar is not constrained palaeomagnetically, but a position near MIS–Seychelles is indicated. Parts of Greater India are shown in two possible positions. (I) If MIS is representative for India (i.e. not a separate terrane) then India was located at latitudes comparable with those of western Australia. (II) If MIS–Seychelles–North Madagascar (see text) was a separate terrane and separated from remaining India then it is possible to keep Eastern India (stippled outlines) as a conjugate margin with East Antarctica. CT = Central Taimyr; ST = South Taimyr (part of Siberian plate). Sea-floor spreading probably occurred between CT and ST (see text). (b) Early Cambrian (≈ 535 Ma) reconstruction of parts of Gondwana after final assemblage (≈ 550 Ma). Palaeomagnetic reconstruction pole: Late Precambrian–Early Cambrian Todd River dolomite (Table 3). Many continental fits have been published for Gondwana (essentially Mesozoic fits), but they are grossly similar, and we have employed the Lawver and Scotese (1987) reconstruction. 'Pan-African' (≈ 550 Ma) belts are shaded. Se = Seychelles, M = Madagascar, Sr = Sri Lanka.

Gondwana was not a coherent unit in the Neoproterozoic, and advocated that India–Madagascar–Sri Lanka rifted off Australia–Antarctica (> 650 Ma).

The dispersal history of Rodinia is not very well constrained due to gaps in the palaeomagnetic record and uncertainties about the Rodinian continental fits. Laurentia and Baltica had clearly drifted into high southerly latitudes by the end of the Precambrian (Torsvik et al., 1996), and these two continental units separated before 600 Ma (Iapetus rifts-Fig. 7(a)). Australia–East Antarctica essentially straddled the equator and their Gondwana location was not much different from their Mid-Neoproterozoic Rodinia position (compare Fig. 7(a) and (b)). India–Seychelles and Madagascar had a more tortuous history: having rifted off Australia, India–Seychelles at some stage drifted southward, and during Late Precambrian times, India collided with Madagascar/East Africa and East Antarctica (Fig. 7(b)). A ≈ 550 Ma metamorphic event is common to Madagascar, East Africa, southernmost India, Sri Lanka and East Antarctica (Kröner et al., 2000). This reflects final Gondwana assembly, probably caused by collisional events between proto-Africa (including Congo and Kalahari cratons), India–Seychelles, Madagascar and Antarctica–Australia.

7. A note of caution

As stated earlier, Laurentia poles and two undated, but presumed $\approx$770–700 Ma Neoproterozoic Australian poles, support the SWEAT hypothesis (Fig. 5(b) and Fig. 6). However, the new and well-dated 755 Ma MDS pole from Australia implies a lower palaeolatitude than the SWEAT hypothesis would require, but not as low as that predicted from the more recent Australia–Southwest US (AUSWUS) reconstruction (Karlstrom et al., 1999). U/Pb zircon ages from MIS–Seychelles and MDS overlap at $\pm$756 Ma. Remanence acquisition could be younger than the U/Pb ages, but in contrast to the MDS pole, the MIS (component A) and the perhaps less reliable Seychelles (no stability tests) poles do not fall on the expected younger part of the Indian path (Fig. 5(a)). A prerequisite for successful plate reconstructions is the acquisition of precise and primary magnetisation data. The MDS pole plots near Vendian and Early Cambrian poles from Australia, and implies insignificant APW for more than 200 million years (755–535 Ma; Fig. 5(b)). The positive contact test claimed for the MDS is not overwhelmingly strong, but we cannot point to any conclusive arguments that this pole should represent a younger remagnetisation. As yet, this pole is therefore the only well-dated Mid-Neoproterozoic pole from Australia, and cannot be overlooked.

The palaeogeographic reconstruction that we favour at $\pm$756 Ma (Fig. 7(a)), placing India as a conjugate margin to western Australia, perhaps suffers from extensively known Kibaran–Grenvillian belts in western Australia, but Bruguier et al. (1999) have recently identified Grenvillian metamorphism and deformation in south–western Australia. Tucker et al. (1999) suggested that MIS–Seychelles along with the endmost northern parts of Madagascar may have comprised a separate terrane in the Neoproterozoic. One advantage of this latter model is that the Kibaran–Grenvillian belts of remaining India (negative evidence-no palaeomagnetic data) can be placed next to East Antarctica as with conventional models (stippled continental outlines in Fig. 7(a)), but it requires that an as yet unidentified suture runs through mainland India. This model also suffers from lack of known Late Precambrian deformation in the Seychelles and MIS (Fig. 7(b)) that would be expected with subsequent collisions with both India and Madagascar.

8. Conclusions

Palaeomagnetic data from MIS are of excellent quality and the predominant magnetisation (component A-normal polarity) resembles previous palaeomagnetic results. Component A is a pre-folding and primary magnetisation that is carried by high-temperature oxidised (deuteric) mineral assemblages. The study area is free from any deformation or tectonic rotations. The high-stability magnetisation (771–751 Ma) yields a local palaeolatitude of 41°N ($^{+8}/_{-7}$) when combined with normal polarity sites of Klootwijk (1975). U/Pb zircon ages from MIS and the Seychelles microcontinent (mainly 748–755 Ma) overlap, and palaeomagnetic data for both entities (both of normal polarity) can be matched with a tight India–Seychelles fit (Torsvik et al., 2001). MIS and the Seychelles microcontinent formed the western margin of the Rodinia Supercontinent at 750–755.

Laurentia, Baltica, India, Seychelles and the South China block best define Rodinia or the possible remnants at $\approx$750 Ma, whereas other continental blocks remain enigmatic. Rodinia break-up has traditionally been estimated to have occurred after 750–725 Ma, but palaeomagnetic data are not conclusive with respect to the timing of Rodinia break-up, since its break-up configuration is not fully understood. At least some fragmentation and sea-floor spreading, however, must have taken place in northeast Rodinia due to the identification of Mid-Neoproterozoic island arc units and ophiolites in Arctic Siberia.

The new Australian MDS pole is contemporaneous with the MIS and Seychelles poles, and requires a radical new fit between Australia and MIS–Seychelles. The concept of an East Gondwana entity during the Neoproterozoic is, therefore, called into question, and the Late Precambrian formation of Gondwana must be much more complex than previously anticipated (see also Meert and Van der Voo, 1997). Taken at face value, the best available palaeomagnetic poles from Australia–India–Seychelles imply no SWEAT, AUSWUS, or East Gondwana entities. A new and radical tectonic history for both Rodinia break-up and Gondwana assembly is required, and in this framework the eastern margin of India rifted off Western Australia during the Mid-Neoproterozoic whilst the same margin collided later with East Antarctica (≈ 550 Ma).

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