Growing Gondwana and Rethinking Rodinia: A Paleomagnetic Perspective

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Abstract: The formation of Gondwana during the latest Neoproterozoic to earliest Cambrian times (550-530 Ma) was traditionally viewed as the welding of two, more or less contiguous, Proterozoic continental masses called East and West Gondwana. The notion of a united West Gondwana is no longer tenable as a wealth of geochronologic and structural data indicate major orogenesis amongst its constituent cratons during the final stages of greater Gondwana assembly. The idea that East Gondwana may also have formed through the amalgamation of a collage of cratonic nuclei during the Cambrian is controversial. Recent paleomagnetic, geochronologic and structural data from elements of East Gondwana indicate that its formation may have extended well into Cambrian time. Thus, the terms 'East' and 'West' Gondwana may be relegated to convenient geographical terms rather than any connotation of tectonic coherence during the Proterozoic. In addition, the paleomagnetic data also challenge the conventional views of the Neoproterozoic supercontinent Rodinia and the SWEAT fit. Alternative variants including Protopangea and AUSWUS are not supported by paleomagnetic data during the interval 800-700 Ma.

Keywords: Gondwana, Rodinia, paleomagnetism, Neoproterozoic

Introduction

Professor Masaru Yoshida has long been interested in both the assembly and break-up of Gondwana (see for example Yoshida et al., 1992; Yoshida, 1995). He co-founded the research journal 'Gondwana Research' and has been instrumental as leader and participant of numerous IGCP projects related to issues of Gondwana assembly and dispersal. It is with great honor that I present an updated view of Gondwana assembly based on the extant paleomagnetic database in celebration of Prof. Yoshida's superannuation from the Department of Geosciences, Osaka City University.

It is generally agreed that greater Gondwana was assembled following the breakup of an earlier supercontinent called Rodinia (Fig 1, Stern, 1994; Meert and Van der Voo, 1996; Dalziel, 1997; Meert, 1999; Hoffman, 1999) although there is significant debate regarding both the makeup of Rodinia and the timing of its breakup (Torsvik et al., in press; Wingate et al., 2000; Meert, 1999; Sears and Price, 2000). Similarly, there is growing debate regarding the unity of the East Gondwana craton although Professor Yoshida views East Gondwana a coherent cratonic unit from Mesoproterozoic time with reactivation of orogenic belts in the Pan-African (Yoshida, 1995).

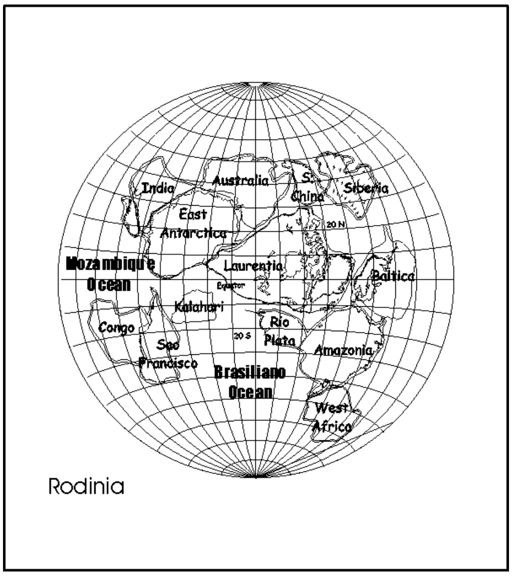

Figure 1: Reconstruction of Rodinia prior to its breakup (c. 750 Ma) modified from the fits of Dalziel (1992) and Weil et al. (1998). All cratonic blocks are rotated to Laurentia and then positioned according to paleomagnetic data in Torsvik et al. (1996).

Paleomagnetic studies can potentially provide important constraints on the dynamics of Gondwana formation, but the extant database is hampered by a paucity of high-quality paleomagnetic data (see Van der Voo & Meert, 1991; Meert et al., in press). Nevertheless, a number of recent studies provide some important constraints on the breakup of the earlier supercontinent and the formation of Gondwana. This paper presents a review of these data along with a tentative hypothesis for Gondwana formation.

Paleomagnetic Database 550-500 Ma

Paleomagnetic data from Gondwana were recently summarized by Meert (1999) and Meert et al. (in press). The purpose of this paper is to update these compilations, briefly review these data and reiterate that the data support that Gondwana assembly was largely completed by 550-530 Ma. The interpretation of these data does not preclude small-scale motions between individual cratonic nuclei, the collision of smaller terranes with Gondwana or continued collision between nuclei—only that these motions cannot be resolved by the extant database.

Paleomagnetic data are now available from all the larger cratonic nuclei or orogenic margins of these nuclei for the interval from 550-500 Ma (Table 1 and Figure 2a). The data compilation in Table 1 is not meant to be exhaustive. There are a number of other poles from Gondwana blocks for this same time interval (for example see Van der Voo and Meert, 1991; Grunow and Encarnacion, 2000a) but many have extremely poor age resolution and are not relevant to this discussion. In addition, both Grunow and Encarnacion (2000b) and Meert et al. (in press) point out that the younger end (510-490 Ma) of the Gondwana path may contain considerably more motion than shown in Figure 2b, but it does not alter the conclusion that greater Gondwana assembly had already taken place. Therefore these 'outlier' poles are not included in this discussion or Table 1.

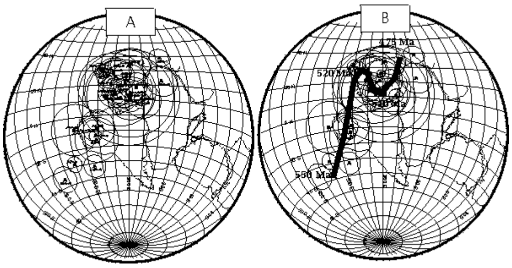

Figure 2: (a) Paleomagnetic poles from Gondwana for the interval 560-500 Ma as given in Table 1 (Africa fixed) and (b) revised apparent polar wander path as in Meert et al. (in press).

Figure 2a shows these data rotated to the Gondwana fit of Lawver and Scotese (1987) and Figure 2b shows the proposed apparent polar wander path (APWP) for Gondwana during this interval (Meert et al., in press). This path is similar to that proposed by Meert and Van der Voo (1997) in its general trend from the 550 Ma Sinyai dike pole (Meert and Van der Voo, 1996) towards the mean Ordovician pole (475 Ma) of Grunow (1995). This path indicates a period of rapid drift between 540 Ma to 520 Ma of 1.94°/Ma and a slightly lower rate of motion between 520 and 510 Ma of 1.48°/Ma. The APWP is in reasonable agreement with the paleolatitudinal indicators including the occurrence of tillites of 540-520 Ma in the Toaudeni Basin of Mauritania (Bertrand-Sarfati et al., 1995). New paleomagnetic data from South America (Bettuci and Rapalini, 1997 and D'Agrella-Filho et al., 2000; Table 1) support the APWP trend noted by Meert et al (in press) and illustrated in Figure 2b.

Table 1. Selected Paleomagnetic Poles 560-500 Ma for Gondwana

Pole #	Name	α_{95}	Plat	Plong	Age (S,I)[a]	Reconstr.	Reference
African Poles							
AF-1	**Sinyai Dolerite**	5.0°	28.4 S	319.1 E	547.0 (I)	Fixed	Meert & Van der Voo, 1996
AF-2	**Mirbat SS (Oman)**	7.2°	31.9 S	333.9 E	550.0 (S,I)	ANS-AFR	Kempf et al., 2000
AF-3	**Ntonya Ring Structure**	1.9°	27.5 N	355.2 E	522.0 (I)	Fixed	Briden et al., 1993
Antarctic Poles							
AN-1	**Sor Rondane**	4.5°	10.6 N	008.3 E	515.0 (I)	ANT-AFR	Zijderveld, 1968
An-2	**Mt. Loke/Killer Ridge**	8.0°	34.0 N	001.6 E	499.0 (S,I)	ANT-AFR	Grunow & Encarnacion, 2000
Australian Poles							
AU-1	**Lower Arumbera SS**	12°	8.2 S	338.8 E	550.0 (S)	AUS-AFR	Kirschvink, 1978
AU-2	**Brachina Fm**	16°	7.4 S	323.5 E	550.0 (S)	AUS-AFR	McWilliams and McElhinny, 1980
AU-3	**Bunyeroo Fm**	10.7°	28.2 N	349.7 E	550.0 (S)	AUS-AFR	McWilliams and McElhinny, 1980
AU-4	**U. Arumbera SS**	4.1°	12.6 S	337.6 E	535.0 (S)	AUS-AFR	Kirschvink, 1978
AU-5	**Todd River Dolomite**	6.7°	9.0 S	336.5 E	532.0 (S)	AUS-AFR	Kirschvink, 1978
AU-6	**Hawker Gp. A**	11.4°	25.5 N	351.2 E	525.0 (S)	AUS-AFR	Klootwijk, 1980
AU-7	**Hawker Gp. B**	21.2°	21.2 N	348.3 E	525.0 (S)	AUS-AFR	Klootwijk, 1980
AU-8	**Aroona-Wirealpa-A**	14.4°	11.1 N	001.0 E	510.0 (S)	AUS-AFR	Klootwijk, 1980
AU-9	**Aroona-Wirealpa-B**	22.6°	15.2 N	354.4 E	510.0 (S)	AUS-AFR	Klootwijk, 1980
AU-10	**Tempe Fm**	5.0°	11.1 N	355.0 E	510.0 (S)	AUS-AFR	Klootwijk, 1980
AU-11	**Hudson Fm**	14.0°	21.0 N	357.6 E	508.0 (S)	AUS-AFR	Luck, 1972
AU-12	**Lake Frome-A**	10.1°	18.2 N	005.1 E	505.0 (S)	AUS-AFR	Klootwijk, 1980
AU-13	**Lake Frome-B**	27.7°	13.0 N	001.0 E	505.0 (S)	AUS-AFR	Klootwijk, 1980
AU-14	**Giles Creek Dol. L.**	32.6°	12.7 N	000.2 E	505.0 (S)	AUS-AFR	Klootwijk, 1980
AU-15	**Giles Creek Dol U.**	11.7°	9.6 N	009.1 E	505.0 (S)	AUS-AFR	Klootwijk, 1980
AU-16	**Illara SS**	10.8°	15.8 N	351.1 E	505.0 (S)	AUS-AFR	Klootwijk, 1980
AU-17	**Deception Fm**	6.5°	13.6 N	351.7 E	500.0 (S)	AUS-AFR	Klootwijk, 1980
Indian Poles							
IN-1	**Bhander-Rewa Mean**	11°	23.0 S	333.0 E	550.0 (S)	IND-AFR	McElhinny et al., 1978
Madagascan Poles							
MA-1	**Carion Granite**	11°	12.7 N	359.7 E	508.0 (I)	MAD-AFR	Meert et al., in press
South American Poles							
SA-1	**Sierra de las Animas-2**	8°	35.3 S	307.0 E	560 (I)	SAM-AFR	Bettucci & Rapalini, 1997
SA-2	**Sierra de las Animas-1**	9°	33.2 N	359.8 E	520 (I)	SAM-AFR	Bettucci & Rapalini, 1997
SA-3	**Bambui Group B**	2.5°	25.7 N	358.5 E	515 (I,S)	SAM-AFR	D'Agrella-Filho et al., 2000
SA-4	**Bambui Group C**	3.8°	31.6 N	339.1 E	515 (I,S)	SAM-AFR	D'Agrella-Filho et al., 2000
SA-5	**Salitre Fm**	4.9°	29.5 N	341.8 E	515 (I,S)	SAM-AFR	D'Agrella-Filho et al., 2000
SA-6	**Piquete Fm**	10.2°	23.0 N	022.0 E	515 (I,S)	SAM-AFR	D'Agrella-Filho et al., 2000
Sri Lanka Poles							
SR-1	**Tonigala Granite**	6.2°	39.0 N	23.2 E	500 (I)	SRI-AFR	Yoshida et al., 1992

[a] S=stratigraphic age, I= isotopic age, SI=both stratigraphic and isotopic age. Rotation parameters: ANS-AFR; 26.5° N, 21.5° E, -7.6°: ANT-AFR; -7.78° N, -31.42 E, +58°: AUS-AFR; 25.1° N, 110.1° E, -56.7°: IND-AFR; 27.9°, 43.64°, -64.4°: MAD-AFR; -3.41 N, -81.7 E, +19.7°: SAM-AFR; 45.5° N, -32.2° E, +58.2°: SRI-AFR; 17.3° N, 52.5° E, -89.8°.

The paleomagnetic data are also supported by a wealth of geologic and geochronologic data throughout Gondwana indicating major orogenesis during this same interval of time (Hoffman, 1999; Meert, 1999; Dalziel, 1997; Stern, 1994).

Rodinia Breakup and Gondwana Assembly

Although most authors agree that Gondwana assembly occurred in the interval from 550-530 Ma, there is a diversity of opinion regarding the pre-550 Ma history of the elements of East and West Gondwana. This difference of opinion arises, at least in part, because of a lack of high-quality paleomagnetic data from elements of East and West Gondwana. Despite these disagreements, there is general consensus that the elements of West Gondwana were dispersed prior to 550 Ma (Hoffman, 1999; Dalziel, 1997). In general, East Gondwana is treated as a coherent entity from 1300 Ma until its Mesozoic breakup (Yoshida et al., 1992; Dalziel, 1997). In a recent review paper, Fitzsimons (2000) noted that the idea of a coherent East Gondwana oversimplifies previous interpretations on the geologic history of East Antarctica. Specifically, Fitzsimons (2000) proposes that at least two 'Pan-African' orogenic belts cut across the East Antarctic shield and offset three Grenville-age crustal segments. These three segments were subsequently juxtaposed during Cambrian times. Support for this idea comes primarily from isotopic age and structural studies in the Lützow Holm and Prydz belts suggesting that both developed during final closure of the Mozambique Ocean through the coalescence of different blocks in East Antarctica (Wilson et al., 1997; Meert, 1999). If the East Antarctic craton does indeed represent a collage of independent blocks, then ideas regarding the makeup and breakup of the Rodinia supercontinent will require revision. Indeed, recent paleomagnetic data from India and Australia highlight this controversial idea.

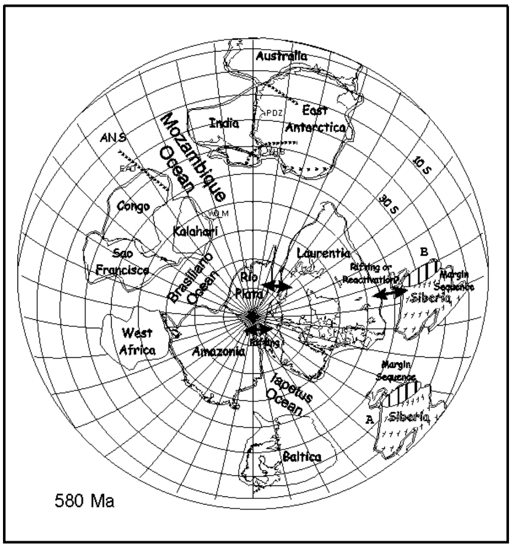

Figure 3: Paleoreconstruction at 580 Ma based on paleomagnetic data given in Meert (1999a,b), Torsvik et al. (1996), Smethurst et al. (1998) and Table 2. Siberia is shown in two alternative positions A & B. Position A indicates the tightest allowable fit of Siberia against northern Laurentia (Rodinia fit) and position B indicates the tightest allowable fit of Siberia against western Laurentia (Sears and Price, 2000). The Cambrian passive margin sequences on Siberia are denoted by hatched lines. Since the rift-drift transition off present-day eastern Laurentia is younger than 580 Ma, the west Gondwana elements (Rio Plata, Amazonia, W. Africa) are positioned using the traditional Rodinia fit (Dalziel, 1992). The Congo-Kalahari, Sao Francisco and Arabian-Nubian shield (ANS) are placed between 'East Gondwana' and the other West Gondwana blocks in order to minimize drift necessary to fully assemble Gondwana by 550-530 Ma. East Gondwana is positioned according to paleomagnetic data from Australia given in Table 2. Possible suture zones within East Gondwana are denoted by dashed lines. EAO= East Africa Orogen (Stern, 1994), WDM=Western Dronning Maud Land, LHB= Lutzöw-Holm Block and PDZ= Prydz bay.

Figures 3 and 4 show possible global paleoreconstructions for 580 and 550 Ma. In this reconstruction, the final vestiges of Rodinia are breaking apart as elements of West Gondwana rift from eastern Laurentia. The paleoposition of Siberia remains controversial and Figure 3 shows two possible positions for this continental block, but note that if Siberia is placed alongside western Laurentia (position B in Figure 3) it does not match the geologic interpretation of Sears and Price (2000). Figure 3 maintains the connection between the East Gondwana elements, but possible terranes within East Gondwana are delineated. Figure 4 (550 Ma) shows Gondwana fully assembled with the South American cratons near the south pole and the Iapetus ocean opened between Laurentia and Gondwana. Dalziel (1997) suggested that rifting of Gondwana from Laurentia did not begin until ca. 550 Ma and therefore maintains a linkage between Gondwana and Laurentia. This configuration is at odds with limited paleomagnetic data from Laurentia as discussed in Meert (1999).

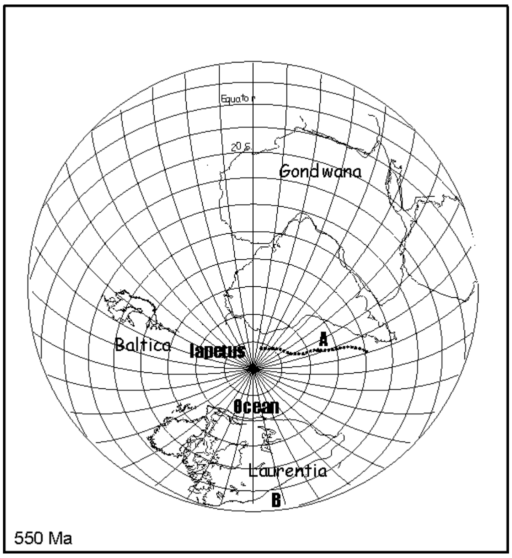

Figure 4: Relationship of the fully assembled Gondwana to Laurentia and Baltica during the opening of the Iapetus ocean (c. 550 Ma). Positions of the continents are based on paleomagnetic data in Table 1 and Meert (1999a,b). Paleomagnetic data from Laurentia are controversial and position A indicates the preference of Dalziel (1997) based on stratigraphic evidence for the rift to drift transition and position B is based on paleomagnetic data.

600-800 Ma Paleomagnetic Data from Gondwana Continents

Interpretation of the 600-800 Ma drift history of the Gondwana continents presents a challenge to global reconstructions due to the paucity of high-quality data. Table 2 lists paleomagnetic available from the Gondwana blocks. There are several important notes regarding these data. The age of the Gagwe lavas pole is based on a number of K-Ar ages (see Meert et al., 1995); however, recent unpublished ^{40}Ar-^{39}Ar studies on these same rocks suggest a younger age for the Bukoban sequence (L. Tack, personal communication 2000). The Malani igneous suite (India) has been redated using the U-Pb method and the new age for this suite is 758 Ma. Paleomagnetic data and new geochronologic constraints for the Seychelles microcontinent now indicate the best age for the pole is 750 Ma (formerly thought to be 683 Ma—see Meert, 1999). Figure 5a shows these paleomagnetic poles rotated into Rodinia coordinates (Laurentia fixed) and in figure 5b the poles are rotated into Gondwana coordinates.

Although there are currently too few paleomagnetic data to support any rigorous conlcusions regarding the makeup of Gondwana elements for this time period, several preliminary hypotheses can be discussed. The first is that the elements of Gondwana appear to be dispersed during the interval from 800-600 Ma. Spot paleomagnetic readings at 750 Ma also suggest that neither India nor Australia can be joined in either a traditional East Gondwana or Rodinia fit (Fig 5a,b; Table 2). Taken at face value these data present problems for both the notion of Rodinia and the idea of a

Table 2. Selected Paleomagnetic Poles 800-600 Ma for Gondwana

Pole #	Name	α_{95}	Plat	Plong	Age (S,I)[a]	Rodinia[b]	Gondwana[c]	Reference
African Poles								
AF-1	**Gagwe Lavas[1]**	10°	25.0 S	273.0 E	813.0 (I)		fixed	Meert et al., 1995
AF-2	**Mbozi Complex**	9°	46.0 N	325.0 E	743.0 (I)	40 S, 324 E	fixed	Meert et al., 1995
Australian Poles								
AU-1	**Mundine Dykes**	4°	46.0 N	135.0 E	755.0 (I)	21 S, 288 E	20 S, 321 E	Wingate & Giddings, 2000
AU-2	**Yaltipena Fm**	11°	44.2 N	172.7 E	600.0 (S)		01 S, 339 E	Sohl et al., 2000
AU-3	**Elatina Fm**	6.2°	39.7 N	181.9 E	600.0 (S)		07 N, 343 E	Sohl et al., 2000
AU-4	**Bunyeroo Fm (Impact)**	10.7°	18.1 S	16.3 E	590.0 (S,I)		57 N, 335 E	Williams and Schmidt, 1996
Indian Poles								
IN-1	**Harohalli Dikes Combined**	9.2°	27.3 N	78.9 E	823.0 (I)	22 S, 024 E	01 N, 060 E	Radhakrisha & Joseph, 1998
IN-2	**Malani Igneous Suite[2]**	6.4°	74.5 N	71.2 E	758.0 (I)	18 S, 334 E	29 S, 279 E	Torsvik et al., in press
Madagascan Poles								
MA-1	**Stratoid Granites**	12°	8.3 S	349.0 E	611.0 (I)		11 N, 348 E	Meert et al., 1999
Seychelles Poles								
SE-1	**Mahe Island Rocks**	11.2°	54.8 N	57.6 E	750.0 (I)	18 S, 327 E	36 S, 279 E	Torsvik et al., in press
South American Poles								
SA-1	**La Tinta Fm**	5°	80.0 S	301.0 E	709 (S)	14 S, 073 E	51 S, 063 E	Valencio et al., 1980
Laurentia Reference Pole								
LA-1	**Mean Pole**	15°	25.0 N	328.0 E	810.0 (I,S)	Fixed	N/A	Torsvik et al., 1996
LA-2	**Mean Pole**	6°	02.0 N	319.0 E	780.0 (I,S)	Fixed	N/A	Torsvik et al., 1996
LA-3	**Mean Pole**	15°	06.0 S	336.0 E	725.0 (I,S)	Fixed	N/A	Torsvik et al., 1996

[a] S=stratigraphic age, I= isotopic age, SI=both stratigraphic and isotopic age.

[b] Rotation parameters of Dalziel (1992); Seychelles to Rodinia 51.3 N, 122.5 E, 161.7°

[c] Rotation as in Table 1

[1] Age of the Gagwe now considered c. 710 Ma based on unpublished $^{40}Ar/^{39}Ar$ data (Andre Deblond personal communication, 2000)

[2] Combined result with that of Klootwijk, 1975 new ages are U- Pb zircon ages (Torsvik, personal communication 2000)

coherent East Gondwana. For example, the Mundine dykes pole (Wingate and Giddings, 2000) falls some 30° away from the reference 810-723 Ma Laurentian path leading Wingate and Giddings (2000) to suggest that breakup along the western Laurentian margin had commenced prior to 755 Ma. That conclusion is in direct conflict with paleomagnetic data from the Seychelles and India (Torsvik et al., in press) for the same time interval that support a Rodinia link to the Laurentian reference path (figure 5a).

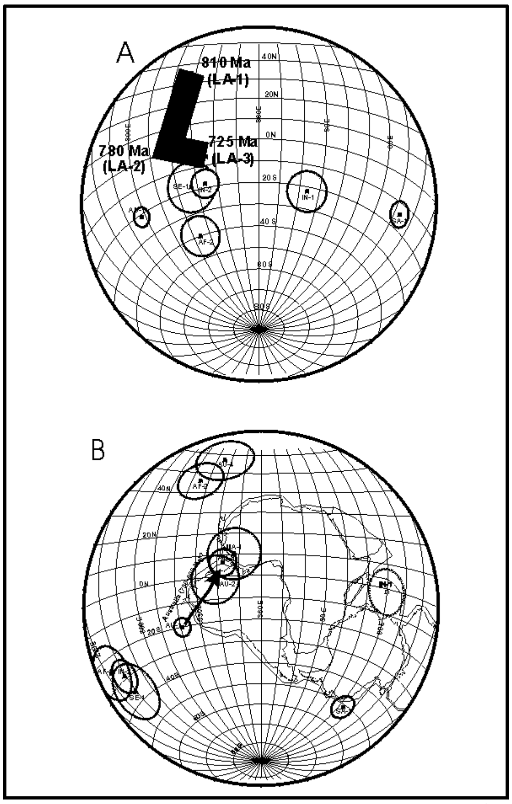

Figure 5: (a) Apparent polar wander path for Laurentia (solid black swathe 15° error envelope) from 810 to 725 Ma according to data in Table 2. Selected paleomagnetic data from Table 2 are rotated to Laurentian coordinates according to the traditional Rodinia fit of Dalziel (1992). Note that pole AU-1 (Mundine dykes) falls some 20-30 degrees from the Laurentian APWP whilst the India-Seychelles poles fall close to the APWP and (b) paleomagnetic poles from Table 2 rotated to Gondwana coordinates (Africa fixed). Pole IN-1 is shown as an anti-pole.

Although paleomagnetic data from India-Seychelles support a traditional Rodinia-East Gondwana link at 750 Ma, the length of the apparent polar wander path for Laurentia during the 810-750 Ma interval is slightly less than the length of the India path (25° vs. 47°). If India-Seychelles were drifting with Laurentia, the APWP lengths should be equal. Therefore, it is possible that these data collectively challenge the notions of a coherent East Gondwana and the traditional Rodinia fit (SWEAT, Dalziel, 1997). Additionally, these well-dated poles also negate the Protopangea fit of Piper (2000) as both the Malani and Mundine dyke poles fall well away from the Laurentian path when rotated using the fits outlined in Piper (2000).

Any attempt to test the coherence of East Gondwana prior to 600 Ma must be viewed with caution because the data are too few to rigourously test this idea. Coeval data from Seychelles-India and Australia are incompatible with traditional East Gondwana fits (Figures 5a, 5b). Although it is possible to rotate the paleomagnetic poles from both continents so that they overlap, the resultant reconstruction places India to the N-NW of Australia, a position for which there is little geologic support (Figure 6a).

The SWEAT hypothesis (Moores, 1991) has come under fire recently (Sears and Price, 2000; Piper, 2000; Karlstrom et al., 1999). Karlstrom et al. (1999) maintain East Gondwana coherence, but propose a more southerly position against the present-day western margin of Laurentia (AUSWUS connection). On the other hand, Sears and Price (2000) dismiss the SWEAT fit (and its variants) and propose that Siberia lie adjacent to the western Laurentian margin during the Neoproterzoic.

Paleomagnetic data from Siberia at c. 540-580 Ma (Pisarevsky et al., 1997; Smethurst et al (1998), fig 6b) can be used to place Siberia near the western margin of Laurentia; however, this placement creates a mismatch of the passive margin sequences used by Sears and Price (2000) to argue for the connection and requires an alternative polarity choice for the Siberian craton at 543 Ma (Figures 3, 6b).

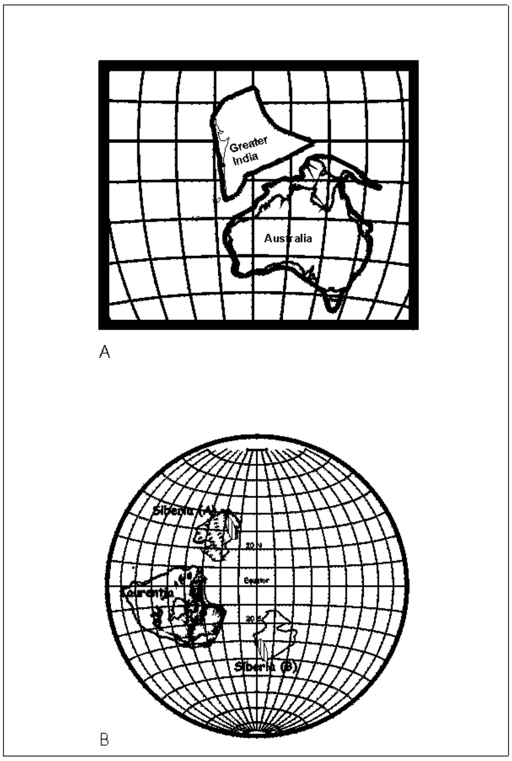

Figure 6: (a) Reconstruction of India against Australia using the 750 Ma paleomagnetic poles in Table 2. There is no geological support for such a reconstruction suggesting that either one of the poles is incorrect or East Gondwana may not have been a coherent landmass and (b) Early Cambrian reconstruction showing alternative fits of Siberia and Laurentia. Siberia (A) requires a polarity inversion of the Siberian poles and position (B) is the preferred polarity interpretation for Siberia (Pisarevsky et al., 1998). The Cambrian passive margin sequence is denoted by hatches.

Similarly, the argument made by Pelechaty (1996) for a Siberian conjugate margin with northern Laurentia until 543 Ma is at odds with the paleomagnetic data at 580 Ma which would require a sizeable ocean between the two cratons (Figure 3). I wish to express caution regarding both of these conclusions since paleomagnetic data from Laurentia during the interval from 520-565 Ma are contentious (see Meert, 1999b).

Conclusions

Paleomagnetic, geologic and isotopic data indicate that the final amalgamation of Gondwana occurred during the interval from 550-530 Ma. Tectonic events leading to the formation of Gondwana and breakup of a preceding supercontinent are controversial. The extant database also tentatively corroborates the notion of a polyphase accretion of Gondwana cratons-- including those formerly thought to comprise a united East Gondwana. Paleomagnetic data supporting the conventional SWEAT model are ambiguous. On the one hand, paleomagnetic data from India-Seychelles (Torsvik et al., in press) support the SWEAT model at 750 Ma whilst paleomagnetic data from Australia do not (Wingate and Giddings, 2000). The SWEAT model is only weakly substantiated by older paleomagnetic data (Wingate and Giddings, 2000; Karlstrom et al., 1999) and has come under fire most recently by Sears and Price (2000) who suggest that Siberia lay adjacent to the present-day Laurentian margin until 550 Ma. Although paleomagnetic data from Laurentia and Siberia can be manipulated to place the continents near one another, the paleogeographic and geologic links do not match up in these configurations. Professor Yoshida has long held that East Gondwana existed as a coherent landmass since Mesoproterozoic times with significant reactivation along the margins during Pan-African times (Yoshida, 1995). He will no doubt challenge some of the conclusions of this paper and, in doing so, continue his long distinguished career in Gondwana geoscience.

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