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The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1100 to 800 Ma

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Abstract

Well-dated paleomagnetic poles for the interval 1100–800 Ma have been compiled for the Laurentia, Baltica, São Francisco, Congo and Kalahari cratons in order to construct apparent polar wander paths (APWPs) for this interval. Laurentia's APWP consists of a well-determined Keweenawan track for 1100–1000 Ma and a 1000–800 Ma Grenville loop. We use a counterclockwise APW loop for the Grenville poles based on ages for post-metamorphic cooling through ~ 500°C for the Grenville Province between 1000 and 950 Ma, and the temporal and spatial similarities with Proterozoic counterclockwise APWP's for other cratons. Baltica's APWP is comprised of seven dated poles that define a similar loop, counterclockwise and hinged at 950 Ma, that can be superimposed on the Laurentian Grenville loop. This loop is also seen in the seven poles of the APWP for the combined São Francisco–Congo craton; superposition of these loops leads to a reconstruction in which the São Francisco–Congo craton is to the south-southeast of Laurentia in present-day coordinates. A long 1090–985 Ma APWP track for the Kalahari is in reasonable agreement with the roughly coeval Keweenawan track, when the Kalahari craton is rotated ~ 40° counterclockwise away from the Congo craton while remaining hinged at the Zambezi belt. The resulting Rodinia reconstruction resembles those previously proposed on geological grounds for Laurentia, East Gondwana, Baltica, São Francisco–Congo, and the Kalahari craton. © 1998 Elsevier Science B.V.

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1. Introduction

Precambrian continental reconstructions have recently become the subject of renewed interest following the proposal that all major continental blocks were part of a long-lived late Proterozoic supercontinent: Rodinia [1]. While the existence of a major long-lived (~ 2500–500 Ma) Proterozoic supercontinent had earlier been advocated on the basis of paleomagnetic data by Piper [2–4], the more recent reconstructions of a shorter-lived Rodinia have largely been based on geological evidence linking truncated Meso-Proterozoic mobile belts [5–7]. In the latter scenario the assembly of Rodinia is marked by Grenville-aged deformation (~ 1.1 Ga) on the margins of Laurentia, East Gondwana, Amazonia and Baltica [8], with the western margin of Laurentia facing East Antarctica in the so-called SWEAT connection (southwest U.S.A.–East Antarctica; [5]). This hypothesis has received partial support from paleomagnetic data in that the apparent polar wander

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paths (APWPs) for Laurentia and East Gondwana are in relatively good agreement for the time period of 1050–750 Ma in a SWEAT fit [9,10]. Breakup and redistribution of the continental elements of Rodinia seems to have been initiated at ~750 Ma with the separation of East Gondwana from the western margin of Laurentia [9,11,12]. This rifting event and subsequent drift of the rifted elements eventually led to the amalgamation of East and West Gondwana at ~550 Ma [13–15].

However, other links in the Rodinia reconstruction remain poorly substantiated, especially where it concerns the paleopositions of the individual South American and African elements, for the interval following Grenville-aged assembly, i.e., 1100–800 Ma. In this paper, we review the existing paleomagnetic database available for this interval for several major Proterozoic cratons (Laurentia, Baltica, Kalahari, and the São Francisco and Congo blocks), and use these compilations to generate independent APW paths for each of them. We then use these APWPs to test and modify proposed continental fits for this time period.

2. Assumptions and methods

Testing Precambrian plate reconstructions relies heavily on paleomagnetic data in addition to correlations between the fragmented geological records of the various continental nuclei and their deformed margins. However, for the use of paleomagnetic data for paleogeographic reconstructions for this time period to be valid the following assumptions must be granted: (1) the geomagnetic field must have been that of a geocentric dipole when averaged over a sufficiently long period of time; and (2) the Earth's radius has not changed significantly. These assumptions have been shown to be reasonable for the Phanerozoic [16], but are largely untested for the Proterozoic. A controversy has arisen, in fact, about possibly asymmetric reversals at ~1.1 Ga, that will be discussed below.

Along with these assumptions, one must also recognize that there are generally greater uncertainties in many of the Precambrian paleomagnetic data than for Phanerozoic paleopoles [17,18]. Included in these uncertainties are poorly controlled magnetization ages, absence of local structural control, increased scarcity of results per unit of time, and ambiguous polarity assignments. The most important uncertainty in Proterozoic paleomagnetism is usually the poor control on the age of magnetization; it is notoriously difficult to date sedimentary sequences without faunal data and studies from metamorphic rocks rely heavily on reset isotopic ages, which may or may not record the age of remanence acquisition. Incorrect age assignments can therefore lead to misleading APWPs with inherently negative consequences for the reconstructions derived from those paths.

With this in mind, we have reviewed the available 1100–800 Ma paleomagnetic data from the Laurentian, Baltic, Congo, São Francisco and Kalahari cratons, paying special attention to the age assignments for the individual poles. Nearly all paleopoles so selected have age uncertainties believed to be less than ±80 Myr, and about half of them less than ±40 Myr. The approach we have taken has been to generate individual APWPs for each of the cratons, with the most accurately dated key poles providing an age calibration, and we have examined these paths for similarities in their geometries and time progression. Where these paths exhibited similarities in both their shapes and age progressions, we rotated the paths into coincidence with each other and used the resulting Euler poles to fit the individual cratons into paleomagnetically constrained reconstructions. This approach differs from that of Piper [4] who assembled all paleopoles into a single common global APWP for his Proterozoic supercontinent. The construction of a single global APWP a priori assumes the existence of a supercontinent and forces all available paleomagnetic poles, regardless of their reliability or age constraints, to fall somewhere on an APWP based on a preconceived continental configuration. When dealing with the Proterozoic data-set it is almost always possible to create a common, albeit convoluted, path that is within the (ample) errors that are typical of Precambrian paleomagnetic data [17,18]. However, Piper's reconstruction has remained ambiguous and is unreliable for intervals without intercontinental agreement between well-dated paleopoles, as shown by Van der Voo and Meert [18], Meert et al. [19] and Torsvik and Meert [20].

3. A review of 1100–800 Ma paleomagnetic data

3.1. Laurentia

The Proterozoic data-set for North America (Laurentia) constitutes the most complete of any of the major continents. The Keweenawan sequence (1.1–1.0 Ga) of the Lake Superior region has yielded a fairly long APW track based on the most extensively studied rocks of the entire Precambrian. Characterized by good stratigraphic, geochronological and structural control, over 60 paleopoles, forming the well-known ‘‘Logan Loop’’, have been compiled [21]. The Keweenawan rocks have experienced very little penetrative deformation since their formation, and magnetizations are generally regarded as primary. A good review of the available paleomagnetic poles of Keweenawan age can be found in Halls and Pesonen [21].

There may exist, however, a potential problem in the Keweenawan APWP in that some coeval normal and reversed polarity directions (e.g., at Mamainse Point) are distinctly and perhaps repeatedly non-antipodal [22–24], which may indicate asymmetric reversals of the field. This, in turn, could imply that the geomagnetic field was not, on average, dipolar [25]. In contrast, Lewchuk and Symons [26] and Symons [27] have argued that their own observations of multiple reversals provide strong evidence against the concept of asymmetric reversals and that the Mamainse Point record incompletely averaged secular variation. Regardless of the eventual outcome of this debate, it appears prudent to keep the possibility of asymmetric reversals in mind when assessing the precision of 1.08–1.11 Ga paleopoles, which may therefore have an inherent uncertainty of about ±15°.

The combined Keweenawan APW track defines the earlier part of Laurentia’s 1100–800 Ma APWP. Individual paleopoles are listed in Table 1. Clustering of poles and time progression at the older end of the track (1100–1070 Ma) is as complete for the Precambrian as can be hoped for and forms a southwest-younging path. We assume here that the Pacific APWP of Laurentia represents northpoles. While this path leads, without discontinuity, into the 1000–800 Ma poles from the Grenville Province (Fig. 1), the paleopoles for ~1020–1010 Ma scatter from ~25°N, 150°E to 10°S, 185°E. Many of the paleopoles in this interval are from Keweenawan sediments (Fond du Lac, Eileen, Middle River, Freda, Jacobsville in Table 1). They differ much more in declination than inclination, which may suggest some relative rotations between the sampling areas (located in Minnesota, Wisconsin, Michigan, and Ontario). We have drawn our generalized Laurentian path through the western part of this grouping, passing the equator at ~150°E. While a more convoluted APWP is not precluded, we note that a smoother APWP at ~1.0 Ga will serve our attempts to match APWPs just as well.

The time progression of paleopoles from the Grenville Province of northeastern Laurentia has generated considerable debate in the last few decades [4,28–33]. While all studies agree that the Grenville-aged paleopoles (~1.0–0.8 Ga) fall in the southwest Pacific quadrant (Fig. 1), there are arguments about the sense of younging along the APWP, either clockwise or anticlockwise, for this period. The temporal uncertainties arise from the highly metamorphic nature of the rocks of the Grenville Province, as high as amphibolite grade, in which all magnetizations must have been thermally (and/or chemically) reset. Consequently, magnetization ages are not easily obtained; while age constraints for the Grenville APWP limit the ensemble of paleopoles to the interval of 1.0–0.8 Ga, ages of individual results are uncertain.

Some researchers have used the Ar/Ar isotopic system to derive empirical cooling curves based on mineral blocking temperatures as a method for sequencing Grenville multi-component magnetizations [28,29,32,34–36]. The assumption in this method is that, given two or more magnetic components from an area that appear to be of different ages, a younging sequence of magnetizations can be derived from specific mineral cooling histories (e.g., hornblende and biotite) that relate to unblocking temperatures of the magnetic minerals. The main problem with this technique seems to be with the contradictory results of the relative age assignments. Magnetic sequencing tied to cooling curves has produced results showing APWP younging trends in both clockwise (Fig. 2) and anticlockwise directions. The inherent difficulty in obtaining ages of isotopic system closure relative to remagnetization ages, especially those of metamorphic rocks [37,38], does not help resolve APWP younging trends.

Table 1
Proterozoic paleomagnetic northpoles used for Rodinia APWP construction

Pole	Age range	Age assigned	Pole long. (E°)	Pole lat. (°)	*K*	A_{95}	*Q*	Reference
Laurentia / Keweenawan Track[a]								
Seabrook Lake carbonatites	1077–1149	1113	180	46	13	11	6	[27]
Mean Logan sills	1106–1112	1109	220	49	976	3	5	[21]
Mean Logan dikes	~ 1100	1100	181	35	165	10	6	[21]
Lower Normal, Upper Osler Group	1095–1101	1098	178	34	82	9	4	[67]
Portage Lake volcanics	1094–1098	1095	181	27	49	2	4	[68]
Mamainse Point volcanics	1083–1097	1090	188	38	28	1	4	[69]
Chipman Lake carbonatites	991	1090	186	38	25	8	5	[27]
Mamainse Point Intrusive Unit	1083–1088	1085	166	24	17	31	3	[69]
Clay–Howells Carbonatite Complex	1060–1090	1075	179	27	26	7	5	[26]
Michipicoten Island volcanics	1088	1075	175	25	9	8	4	[69]
Copper Harbor conglomerate	982–1095	1060	176	35	239	4	5	[70]
Nonesuch Shale	1000–1092	1046	177	10	22	6	5	[71]
K1 Fond du Lac sandstones / shale	950–1088	1020	160	16	58	61	3	[37]
Eileen sandstones	950–1040	1020	156	20	10	10	3	[37]
Middle River sandstones / shale	950–1041	1020	148	25	16	9	3	[37]
Freda sandstones	982–1075	1020	180	1	31	3	4	[71]
Jacobsville sandstones	950–1040	1010	183	−9	29	6	5	[72]
Grenville Thermochron Zone A	~ 1000	1000	159	1	140	6	3	[28]
Archean Greenschist Reset	950–1000	990	152	−5	22	11	1	[73]
Nipissing Diabase Reset	950–1000	975	141	−27	12	8	3	[73]
Granodiorites Reset	950–1000	960	150	−37	18	8	2	[73]
Baltica								
Laanila dyke swarm, Finland	998 ± 80	1020	218	−4	29	6	2	[43]
Within Protogine Zone	~ 950	950	211	−44	86	11	3	[43]
East of Protogine Zone	~ 950	950	210	−42	–	–	2	[43]
West of Protogine Zone	~ 950	950	217	−45	34	5	4	[43]
East of Protogine Zone	~ 850	850	242	0	–	–	2	[43]
West of Protogine Zone	~ 850	850	241	4	66	10	3	[43]
West of Protogine Zone	~ 850	850	231	−25	131	7	4	[43]
Congo								
Nyabikere, Burundi	~ 950	950	137	43	25	14	3	[74]
Gagwe lavas, Tanzania	788–838	813	93	25	5	10	5	[14]
Bukoban intrusives, Tanzania	776–836	806	101	11	5	19	4	[75]
São Francisco								
Olivenca dikes (O_R)	1078 ± 18	1078	100	−10	17	9	4	[46]
Calculated mean Itaju do Colonia pole	~ 1050	1055	111	8	11	10	4	[46]
Olivenca dikes (O_N)	~ 1050	1030	107	16	12	8	4	[46]
Ilheus dikes	1012 ± 24	1012	100	30	79	4	4	[46]
Kalahari								
Post-Waterberg Diabase, Botswana	1076–1106	1091	231	−65	31	8	5	[76]
Umkondo dolerites, Zimbabwe	1082^{+140}_{-25}	1080	223	−65	66	6	2	[77]
Umkondo combined, Zimbabwe	1081^{+140}_{-25}	1075	208	−64	20	8	3	[78]
Umkondo lavas, Zimbabwe	1080^{+140}_{-25}	1070	196	−63	13	15	2	[78]

Table 1 (continued)

Pole	Age range	Age assigned	Pole long. (E°)	Pole lat. (°)	K	A_{95}	Q	Reference
Kalahari								
Kalkpunt Fm. (Koras Grp.)	1049–1080	1065	183	−57	67	7	3	[79]
O'Okiep intrusives, S. Africa	~ 1030	1030	155	−15	28	15	1	[80]
Central Namaqua Metamorphic Zone	~ 1000	1000	150	−8	26	10	3	[55]
Port Edward Charnockite, S. Africa	960–1010	985	148	5	57	9	1	[55]

[a] Other Grenville poles can be found in Hyodo and Dunlop [32] (their table 5). All poles are inferred to be northpoles Q is the quality factor [16,18].

The Grenville paleopoles plotted in Fig. 1 have been taken from Hyodo and Dunlop [32]; because of space restrictions, they have not been listed in Table 1. The Grenville paleopoles derived from multi-component magnetizations typically fall into two groups related to their effective magnetic unblocking temperatures; an ''A Group'' that is thought to reflect the time of peak Grenville regional metamorphism or metamorphic cooling from high temperatures (poles falling near ~ 30°S), and a ''B Group'' that includes poles (near the equator) thought to be related to the later cooling at lower temperatures and/or post-orogenic uplift [35]. However, it is generally accepted that post-metamorphic cooling through ~ 500°C occurred between 1000 and 950 Ma in the Grenville Province [39–42]. If this is true, then few or no Grenville A-group poles would be expected to fall on the return (northward) path with an age range from 950 to 800 Ma. This indeed appears to be the case if the counterclockwise loop is accepted (see Fig. 1), but does not agree with recent proposals for the clockwise loop (Fig. 2). This argument, combined with the temporal and geometric progression of poles from Baltica, to be discussed below, leads us to prefer a counterclockwise Grenville Loop.

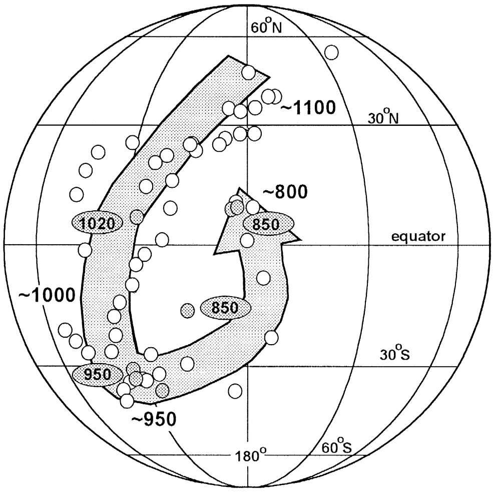

Fig. 1. Grenville and Keweenawan paleopoles (from Table 1) from Laurentia (*white*), and Baltica (*grey*) for the 1100–800 Ma time interval. Notice the counterclockwise time progression with the inclusion of Baltic paleopoles. Baltica has been rotated according to Piper's [4] Late Precambrian fit (Table 2).

3.2. Baltica

Baltica's APWP for the 1100–800 Ma interval is comprised of seven mean poles (Table 1; [43]) that define a loop, hinged at 950 Ma, similar to the

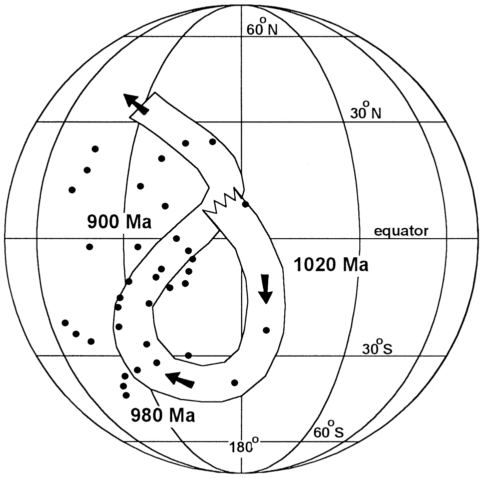

Fig. 2. Grenville poles used by Hyodo and Dunlop [33] (their table 5), representative of the alternative clockwise APWP.

Table 2
Euler poles used for Rodinia reconstruction in Fig. 6

Continental block/w.r.t. other continent	Pole lat.	Pole long.	Rotation	Reference
Baltica/Laurentia	80.5	274.0	−66.5	[4]
Greenland/Laurentia	67.5	−118.5	−13.8	[83]
Congo/Laurentia	7.0	150.0	185.0	This study
São Francisco/Congo	53.0	−32.2	57.5	[50]
Kalahari/Laurentia	−15.0	156.0	147.0	This study
Rio Plata/Laurentia	9.5	315.0	−96.5	This study
Amazonia/Laurentia	9.5	315.0	−96.5	This study
Siberia/Laurentia	29.3	341.2	19.6	[45]
India/Laurentia	53.1	145.1	168.0	[84]
Madagascar/Laurentia	28.6	123.8	170.2	[8]
Australia/Laurentia	28.9	126.1	132.1	[8]
East Antarctica/Laurentia	12.8	119.9	134.8	[8]

Rotation pole to rotate Laurentia in Fig. 6 relative to globe is [0°, 230°, 92°, clockwise] for 1010 Ma, using the paleopoles for that time [32].

Laurentian loop, as just described. Age assignments are taken from Pesonen et al. [43] and define a counterclockwise geometry (Fig. 1). Superposition of the Sveco-Norwegian paleopoles of Baltica and the Grenville poles of Laurentia has previously been attempted [44,33,3,4,16], and in all cases a juxtaposition without continental overlap of the two continental blocks is achieved. We find that Piper's [4] fit for the Late Precambrian between Baltica and Laurentia provides the best estimate of the Euler parameters that superpose the two APWPs (see Table 2). It differs somewhat from the recent fit of Torsvik et al. [45], which is based on the less well-constrained paleopoles of Laurentia and Baltica for the interval 0.8–0.6 Ga.

After rotation, Baltica's paleopoles come into good coincidence with the Laurentian counterclockwise loop (Fig. 1). Moreover, the two paths show identical time progression, with a correlative hinge at ~950 Ma. Results from both continents combined will be used next in comparisons with APWPs from other blocks.

3.3. Congo and São Francisco blocks

The Congo craton of Central Africa and the São Francisco craton (SF) of the Bahia State region of Brazil, South America, have long been recognized as having had a long-lived Precambrian connection [46–48], perhaps extending back as far as ~3.0 Ga [49]. When restored to their pre-Atlantic rift configuration (according to de Wit et al. [50] or Rabinowitz et al. [51]), the two cratons are surrounded, but not dissected, by Braziliano and Pan-African mobile belts of late Proterozoic age.

Until recently, the paucity of paleomagnetic poles from these two cratons, for the interval 1100–800 Ma, has made it difficult to make any substantive comparisons between the APWP of the combined São Francisco–Congo craton and those for the remainder of Rodinia. Therefore, reconstructions have been based mainly on geologic similarities and have been rather different from each other [7,8]. However, four paleopoles from mafic dikes in Brazil have now become available [46] from an area in the São Francisco craton that is well to the east of the Espinhaço–Sententrional–Paramirim transcurrent zone, and therefore a part of the stable São Francisco/Congo craton [48]. Two of these dike sets are well-dated [52] so that a well-constrained APWP segment can be constructed. Similarly, three well-dated results from the East African part of the Congo craton have become available, although these are for a younger time interval than those from Brazil [14].

Given that the Congo and São Francisco cratons were connected throughout the 1100–800 Ma interval, a common APWP is constructed, after restoring the two parts to their pre-Atlantic configuration. This APWP, assumed to be southpoles, reveals a clockwise loop near present-day South America (Fig. 3). The corresponding northpole APWP falls in the cen-

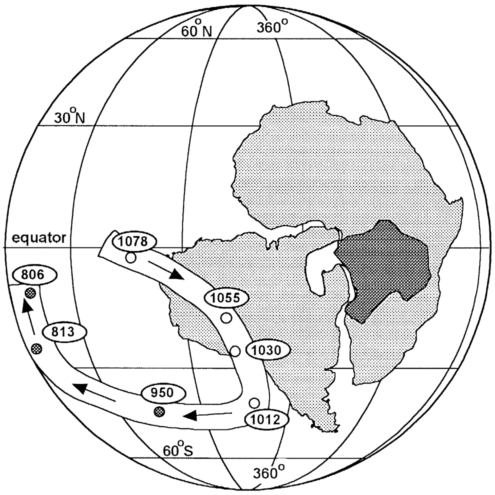

Fig. 3. South America is rotated with respect to a fixed Africa (for Euler poles, see Table 2). The Congo craton of Africa (*dark grey*) and the São Francisco craton of South America (*white*) are plotted with their respective (south) paleopoles (Table 1).

tral-west Pacific and shows a counterclockwise loop. When rotated about an Euler Pole at 7.0°N, 150.0°E, with a 185° counterclockwise angle (Table 2), a satisfactory correlation is achieved with the combined Laurentia–Baltica APWP in North American coordinates (Fig. 4). Agreement between the Congo–São Francisco and Laurentia–Baltica poles with similar ages is generally within 15°.

The corresponding Congo–São Francisco–Laurentia paleoreconstruction, derived from the above rotation with respect to Laurentia, loosely resembles Dalziel's [8,53] reconstructions (Fig. 4). As seen in Fig. 4, the Congo–São Francisco blocks end up east-southeast of Laurentia and differ from Dalziel's [8] reconstruction by ~ 15°, which is probably about the minimum accuracy of the paleomagnetic method for the Neoproterozoic. This similarity is noteworthy in that Dalziel's fit is based on geologic similarities, and not on any paleomagnetic pole data. Our fit has lesser similarities with that of Hoffman [7], because he juxtaposes the Irumide and Kibaran belts of East Africa and the Grenville belt of southeastern Laurentia. Such a connection has the Congo–São Francisco craton rotated by ~ 180° from this study. Incidentally, the earlier reconstruction of Piper [3,4], who inferred that West Gondwana was a coherent cratonic block during the entire Proterozoic, had the Congo block much further to the south with

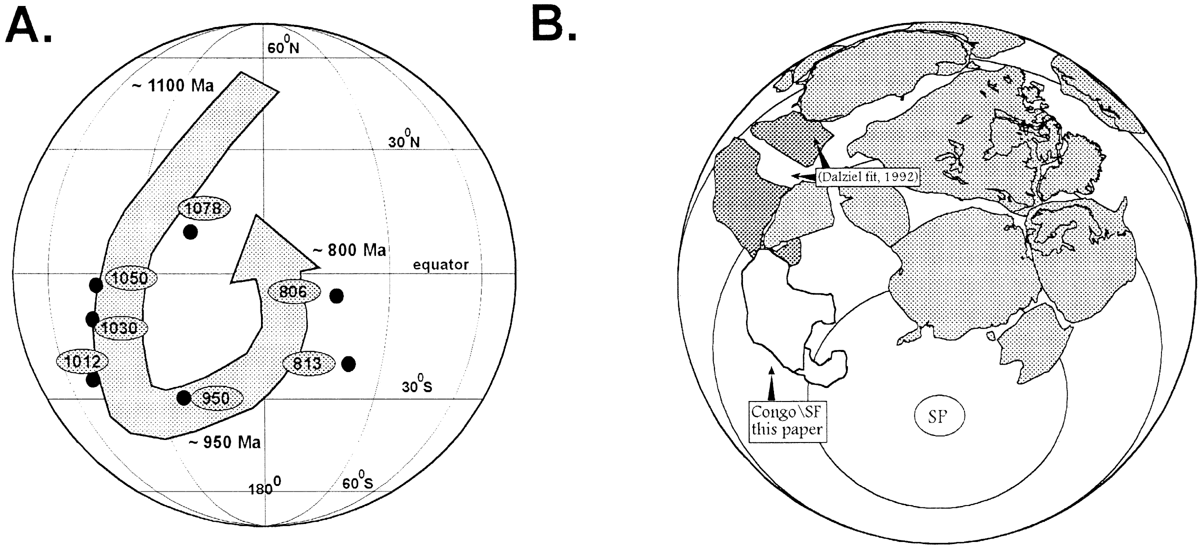

Fig. 4. (A) Schematic APWP for Laurentia and Baltica (*grey swath*), and Congo and São Francisco paleopoles (*dots*) plotted in a Laurentian reference frame. Congo's APWP has been rotated with respect to Laurentia according to the Euler Pole: 150°, 7°, 185° counter clockwise. For pole references see Table 1.

(B) Corresponding reconstruction of Rodinia according to a 1010 Ma Laurentian pole, with the Congo craton (*white*) rotated as above. Also shown is Dalziel's [8] Congo reconstruction (*dark grey*) based on geologic observations.

respect to Laurentia than is the case in the Rodinia configurations; Piper's configuration is not supported by our study.

3.4. Kalahari

The Kalahari craton of southern Africa, like the Congo, has previously been positioned within Rodinia with rather large uncertainties. The main issue of contention stems from two schools of thought regarding the tectonic history of the Damara belt between the Congo and the Kalahari cratons: the recently prevailing argument is for an ensimatic origin for this Pan-African mobile belt [54,55,7,8], whereas an earlier model of an ensialic origin [56–58] invokes instead a tectonothermal event affecting a previously coherent cratonic Kalahari–Congo block.

The Kalahari craton has yielded eight paleomagnetic poles that are dated between 1100 and 985 Ma (Table 1). These poles define a long track of APW that shows temporal continuity and a reasonable rate of continental motion with respect to the pole distribution. When the (presumed north) poles are rotated about an Euler Pole at 15.0°S, 156.0°E, angle 147° counterclockwise (Table 2), Kalahari's APWP comes into good coincidence with the Laurentia–Baltica APWP (Fig. 5). Unfortunately, no Kalahari paleopoles are available for the upward leg of the Laurentia–Baltica (Grenville-aged) loop.

The resulting paleogeographic reconstruction of the Kalahari craton with respect to the rest of Rodinia (Fig. 5) shows a reasonable similarity to previous reconstructions. Dalziel [6] placed the Kalahari in juxtaposition with Antarctica, the Ellsworth–Whitmore Mountains and southern Laurentia, and close to its present-day position with respect to the Congo craton (Figs. 4 and 5). Similarly, Hoffman [7] places the Kalahari craton near East Antarctica and southern Laurentia, matching the Lurian and Namaqua–Natal belts of Kalahari with the Grenville-aged belts of Antarctica and southeastern Laurentia. A third reconstruction [52] compared the paleopoles from the São Francisco craton [46] and those from the Kalahari, resulting in a counterclockwise rotation of ~ 90° around the edge of the Congo craton. Several other recent reconstructions [59,60,47] place the Kalahari rotated counterclockwise by ~ 30–40° with respect to a similar hinge in the Zambezi belt southeast of the Congo craton. Most recently, Gose et al. [61] have shown that paleomagnetic results

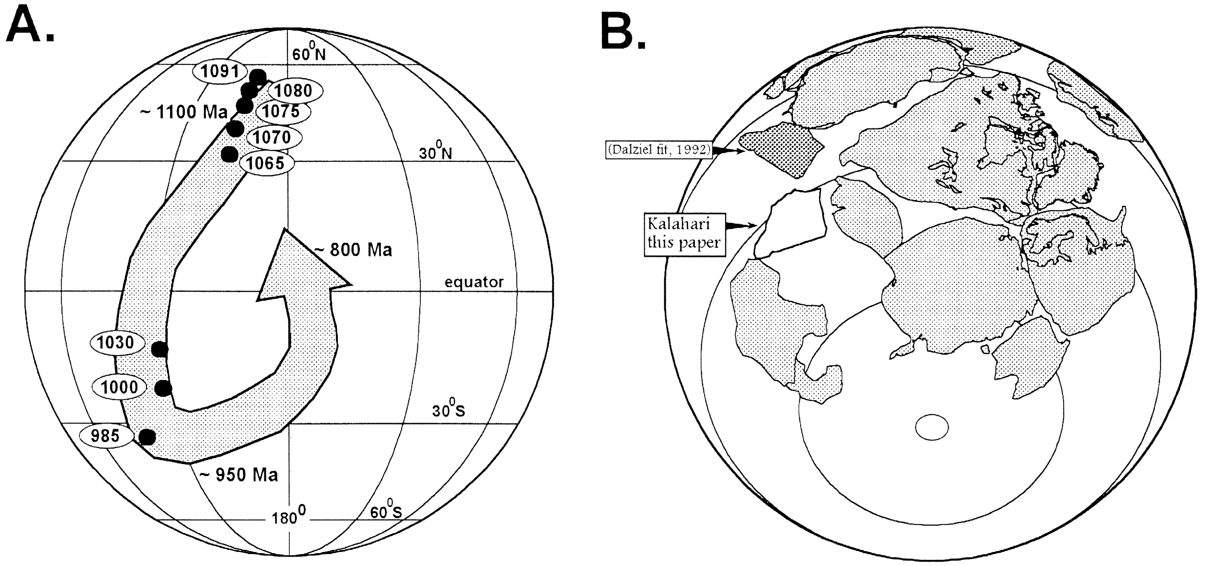

Fig. 5. (A) Schematic combined Laurentia–Baltica APWP (*grey swath*), with the seven Kalahari paleopoles (*dots*; Table 1) for the 1100–950 Ma time interval, rotated into coincidence and plotted in a Laurentian reference frame (refer to Table 2).
(B) Corresponding reconstruction of the Kalahari craton with respect to the rest of Rodinia with paleolatitudes according to a 1010 Ma Laurentian pole. Also shown is Dalziel's [8] Kalahari fit.

from Coats Land and sections of western Dronning Maud Land (CMG), Antarctica, were linked to the Kalahari craton at 1.1 Ga, and not to the East Antarctic Interior as previously suggested. Their subsequent Rodinia reconstruction places the Kalahari and CMG near the other cratons of West Gondwana, similar to the position proposed here, with a later suturing to East Gondwana as the Mozambique Ocean closed interior to (present day) East Antarctica [62–64].

The paleopoles used in this study (Table 1) create a paleogeographical position for the 1100–950 Ma interval (Fig. 5) with the Kalahari rotated ~35° counterclockwise away from the Congo craton. This reconstruction is in good agreement with geologic evidence found in the intervening Pan-African belts of southern Africa. There is a recent general consensus that a Neoproterozoic westward widening rift structure created an embayment of oceanic floor in the Khomas basin of the Damara belt. This embayment terminated at a transform type boundary located near the Zambezi belt on the northeastern margin of the Kalahari craton [65]. Other geologic evidence, such as sediment transport direction analysis, subsidence advancement, and structural evidence also support an eastward narrowing rift between the Congo and Kalahari [66,60].

4. Discussion

The paleomagnetic evidence for Rodinia's configuration is still quite scant, but steadily improving as new results become available. The Baltica–Laurentia fit [4] as supported by this study and the reconstructions between Laurentia and East Gondwana (i.e., Australia; [9]) and Congo–São Francisco as well as Kalahari (this study) are removing some of the previously large uncertainties about the relative positions of Rodinia's continental constituents. The paucity of paleomagnetic data still plays a limiting role in our ability to test the reconstruction involving other continental blocks, such as Siberia, South China, Amazonia and the Rio de la Plata craton. In Fig. 6, we have positioned the latter two South American cratons adjacent to the Appalachian margin of Laurentia. Given that there are no paleopoles from these cratons, their positions are paleomagnetically untested, as are the locations of smaller terranes (Arequipa, Precordillera, etc.).

This paper shows that sequential paleopoles (when dated and numerous enough per unit of time) can give sufficient character or ''fingerprint'' to APWPs to generate intercratonic Proterozoic reconstructions with a resolution of ~15°. Congruence of looping APWP tracks suggests that there was no relative motion between the separate cratonic blocks, and that they, to first approximation, were part of a single supercontinent during the time involved. Geometric similarities and temporal sequencing of the individual APWPs have been used in this paper to demonstrate evidence for a Rodinia reconstruction (Fig. 6) that resembles those previously proposed [5–8,53,61] for Laurentia, East Gondwana, Baltica, Kalahari and São Francisco–Congo.

Fig. 6. Proposed Rodinia reconstruction with all cratons rotated with respect to a 1010 Ma Laurentian paleopole according to the Euler poles of Table 2. Grenvillian orogenic belts *highlighted in black stipple* after Hoffman [7]. Uncertainties in the position of the cratons can be as large as 15°. *AM* = Amazonia craton; *A* = Australia craton; *BA* = Baltica (Fennoscandia); *C* = Congo craton; *CMG* = Coates Land–Maudheim–Grunehogna Province [61]; *E* = Ellsworth–Whitmore Mountain Block; *EA* = East Antarctica; *G* = Greenland; *I* = India; *K* = Kalahari craton; *M* = Madagascar; *RP* = Rio de la Plata craton; *S* = Siberia craton; *SF* = São Francisco craton; *WA* = West Africa craton. Not included are the North and South China blocks, believed by some to border the western margin of Laurentia [81,82]. For discussions of proposed fits for Siberia, see [45,82].

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