Supplementary Material: Paleotethys slab pull, self-lubricated weak lithospheric zones, poloidal and toroidal plate motions, and Gondwana tectonics.

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To carry out the paleogeographic reconstructions, it was considered that Gondwana should have been made up by distinct domains separated by deformed zones composed of fault systems as pointed out in the main text (see also Fig.1).

Paleomagnetic poles (PP´s) for paleogeographic reconstructions of this study (Table 1 SM) were selected from previous databases (Clark and Lackie 2003, Geuna *et al*. 2010, Kent and Irving 2010, Torsvik *et al*. 2012) where they had been classified according to Van der Voo (1993)´s reliability criteria.

Table 1 SM: Paleomagnetic poles selected for Gondwana

Lat/Lon = Pole Latitude/Longitude. A_{95}: 95% confidence oval. In references GPMDB: paleomagnetic poles listed in global paleomagnetic data base; T: selected by Torsvik *et al.* (2012) from the GPMDB.

Paleomagnetic poles for the Early Pennsylvanian-Early Guadalupian time span (*ca* 320 Ma – 270 Ma).

South America					
Locality or Stratigraphic unit	Lon. (° E)	Lat. (°S)	A_{95} (°)	Age (Ma)	References
Tepuel Group, Argentina	307.14	36.88	16.3	325	GPMDB 2805, 7252
Lower units of Paganzo Gr., Argentina	327.57	57.73	6.4	310	Geuna *et al.*, 2010 (1)
Pular and Cas Formations, Chile	350.0	57.0	9.6	310	GPMDB 1420, T
Santa Fe Group, Brazil	324.0	53.2	4.1	300	Brandt *et al.* (2009)
La Tabla Formation, Chile	347.0	51.0	5.7	290	GPMDB 1420, 597
Copacabana Group, Perú	321.3	68.2	5.2	287	Rakotosolofo *et al.* (2006)

Africa					
Oubarakat and El-Adeb Larache Formations, Algeria	47.8	20.3	4.5	317	GPMDB 3484, 8867
Dwyka Group, South Africa	53.6	25.2	12	315	GPMDB 3489, 8894
Lower El Adeb Larache Formations, Algeria	48.3	21.1	4.6	307	GPMDB 2540, 6529
Harsi Barchir Formation, Algeria	49.9	27.8	2.6	310	Derder *et al.* (2009)
deIllizi Basin Sediments, Algeria	51.5	21.1	4.6	309	Derder *et al.* (2001)
Djebel Tarhat red beds, Morocco	62.3	23.3	7.8	285	GPMDB 1080, 2037
Chougrane red beds, Morocco	66.4	33.4	4.7	285	GPMDB 723, 2279
Taztot trachyandesites, Morocco	56.8	38.7	4.6	285	GPMDB 723, 2280
Abadla Formation, Moroco	54.2	26.3	3.6	279	GPMDB 3275, T
Abadla Serie, Algeria	56.5	26.8	3.6	273	GPMDB 1459, T
Australia					
Connors Volcanics	100.0	46.0	14	315	GPMDB 3265, 8406
NewcastleRange	124.5	63.8	7.6	320	GPMDB 3561, 9056
Upper Clifden/Lower Rocky Creek Formations	95.3	49.6	11	317	GPMDB 3463, 8818
Lark Hill Formation	127.0	50.4	6.7	310	GPMDB 3463, 8822
Rocky Creek	136.5	57.6	9	307	GPMDB 3463,

Conglomerate					8821
Featherbed Volcanics	131.7	43.0	8.5	292	GPMDB 3266, 8412
Mt.Leyshon and Tuckers Complex	139.7	44.89	4.2	285	Clark and Lackie 2003(2)

(1) Re-calculated taken the data of Lower Paganzo Gr. from Geuna *et al.* (2010).

(2) Re-calculated taken the data from Clark and Lackie (2003).

Mean paleomagnetic pole for Gondwana in Africa geographic coordinates: N=22 Lon= 54.4° E, Lat= 27.0° S, R= 21.64, A_{95}= 4.1°, K= 57.9

<u>Paleomagnetic poles for the Late Guadalupian-Middle Triassic time span (*ca.* 270 Ma – 260 Ma).</u>

Locality or Stratigraphic unit	Lon. (° E)	Lat. (°S)	A_{95} (°)	Age (Ma)	References
South America					
Independencia Group, Paraguay	325.5	70.7	6.6	255	Rapalini *et al.* (2006)
Tambillos Formation, Argentina	308.3	80.6	5.2	260	GPMDB 2475, 6376
Upper Choiyoi, Argentina	326	75.5	4.1	264	Domeier *et al.* (2012b)
Puesto Viejo Fm., sedimentary rocks, Argentina	293.5	75.1	4.9	245	Domeier *et al.* (2012b)
Puesto Viejo Fm., Volcanic rocks, Argentina	313.4	76	6.4	245	Domeier *et al.* (2012b)
Amana Fm., Argentina	298.5	69.1	7	240	GPMDB 1132, T
Africa					
Casanje Series, South Africa	62.2	49.0	6	248	GPMDB 1960, T
Komandodrifdam Interval, Karoo basin,	63.8	48.0	7.6	251	De Kock and Kirschvink

South Africa					(2004)
Madagascar					
Sakamena Group (Combined)	73.5	68.4	7.6	250.5	GPMDB 3329, T
India					
Khamthi Red Beds, CentralIndia	295.1	9.5	6.5	250.5	GPMDB 163, T
Wargal and Chidru, Pakistan Formations	274.5	10.2	1.8	250.5	GPMDB 2467, T
Panchet , Karanpura Series	289.1	13.4	6	248.5	GPMDB 162, T
Mangli Strata, Central India	290.9	12.2	4.6	243	GPMDB 593, T
Australia					
Gerringong Volcanics	132.0	44.0	11	255	GPMDB 995, 1852
Upper Marine Latites	136.0	46.0	15	253	GPMDB 995,1852
Dundee Ignimbrites and rhyodacites	146.4	34.19	6	247	Lackie (1988) (1)
Patonga Claystones	148.5	31.6	7.8	240	GPMDB 1610,1096

(1) Re-calculated taken the data of both volcanic units from Lackie (1988).

Mean paleomagnetic pole for Gondwana in Africa geographic coordinates. N= 17, Lon= 56.2° E, Lat= 58.2° S, R= 16.82, A_{95}= 3.8°, K= 87.7.

Paleomagnetic poles for the Late Triassic-early Late Jurassic time span (*ca* 230 Ma – 160 Ma)

Locality or Stratigraphic unit	Lon. (° E)	Lat. (°S)	A_{95} (°)	Age (Ma)	References
South America					
Bolivar Dykes, Venezuela	245.6	66.9	4.9	203	MacDonald and Opdyke (1974), T
Cacipore dikes, Brazil	208.6	79.8	5.2	200	Ernesto et al. (2003)
Roraima dikes, Brazil	235.1	80.1	6.6	199	Marzoli et al. (1999)
French Guyana dikes	235.1	81.2	4.0	198	Nomade et al. (2000)
NE Brazil magmatism-2	223.9	78.1	5.2	198	Ernesto et al. (2003)
Anari-Tapirapua Fm., Brazil	250.3	65.5	3.6	197	Montes – Lauar et al. (1994), T
South America, CAMP	237.6	75.9	6.8		Kent and Irving (2010)
Marifil Fm., Patagonia	138	83	11	183	Iglesia Llanos et al. (2003), T
Chon Aike recalc., Patagonia	197	85	13.5	167	Vizán (1998), T
Africa					
Karroo Lavas	98.3	69.2	3.3	183	Hargraves et al. (1997)
Freetown Complex, Sierra Leone	32.7	82.9	5.6	193	Hargraves et al. (1999), T
Hodh volc., South Mauritania	60.2	71.4	6.1	187	Sichler et al. (1980), T
Hank volc., North Mauritania	52	69.4	4.1	187	Sichler et al. (1980), T
Liberian dikes	62.4	68.5	5.3	186	Dalrymple et

and sills					al. (1975)
Foum Zguid dike	79.4	58.0	4.0	184	Hailwood and Mitchell (1971)
Draa Valley sills	50.5	65.5	3.5	184	Hailwood and Mitchell (1971)
Africa CAMP mean	60.4	69.7	7.9	201	Kent and Irving (2010)
Australia					
Tasmanian Dolerite, west dec.	174.5	50.7	5.2	183	Schmidt and McDougall (1977)
Garrawilla and Nombi volcanics	175.2	46.1	10	180	Schmidt (1976)
Prospect Dolerite, Sydney basin	179.5	53	10	168	Schmidt (1982)
Antarctica					
Ferrar Dolerite	223.0	51.0	2.7	183	Lanza and Zanella 1993

Mean paleomagnetic pole for Gondwana in Africa geographic coordinates: N= 21, Lon.= 66.99° E, Lat.= 70.31° S, R= 20.79, A_{95}= 3.3°, K= 95.28.

Original articles were reviewed and in some cases the PP´s were recalculated considering the assigned ages to their remanences and the available geologic information. For example, data corresponding to different localities of Paganzo basin that would have the same age were averaged and one PP was recalculated.

The same criterion was applied to the directions obtained in the igneous complexes of Mount Leyshon and Tuckers (Clark and Lackie 2003) that correspond to the same magmatic event, based on its geochemistry, paleomagnetic data and age. Also data from Rhyodacites and Ignimbrites Dundee (Lackie 1988) were averaged to obtain only one PP.

Previously unaddressed structural complexities were detected in some cases, leading to the exclusion of some PP's. The PP recently published by Domeier *et al*. (2011), present in Torsvik *et al*. (2012) selection, was excluded in this work, because according to Tomezzoli *et al*. (2013) the applied structural corrections were oversimplified. Similarly data in Vizan (1998), selected by Kent and Irving (2010), were excluded because according to Zaffarana and Somoza (2014) they would not have been fully corrected. Paleomagnetic data from regions that may have been affected by tectonic deformations considered in this work were rigorously analyzed according to the literature and eventually excluded from the final selection.

Unlike Geuna *et al*. (2010), we decided not to combine data in the way suggested by McFadden and McElhinny (1995), and therefore restricted our selection to PP´s with 3 or more sampling sites.

Due to the above issues, the volume of data selected in this study is lower than the one used in previous cited works (Clark and Lackie 2003 Geuna *et al*. 2010, Torsvik *et al*. 2012, Kent and Irving 2010).

Even knowing that the factor to correct the magnetic inclinations of clastic sedimentary rocks is variable, the value of 0.6 considered by Torsvik*et al*. (2012) was also used in this paper. Torsvik *et al*. (2012) provided a detailed discussion about the need of this correction citing several cases and considering that the above value is appropriate in accordance with the experimental data and with the statistical model proposed for the geomagnetic field by Tauxe and Kent (2004).

Once completed our data selection, all Gondwana paleomagnetic poles (PP´s) were analyzed in present geographic coordinates of Africa, transferred by using the reconstruction parameters of Lawver and Scotese (1987).

The PP´s form three clusters according to their age. It is clearly seen for South American poles (Fig. 1 SM), since it is the only continent that has enough PP´s for the whole considered time span (from the Early Pennsylvanian till the early Late Jurassic). For South America, each cluster is defined by more than 4 PP´s which according to Van der Voo (1990) is a robust data amount to determine the paleogeographic location of a continent for a time-span.

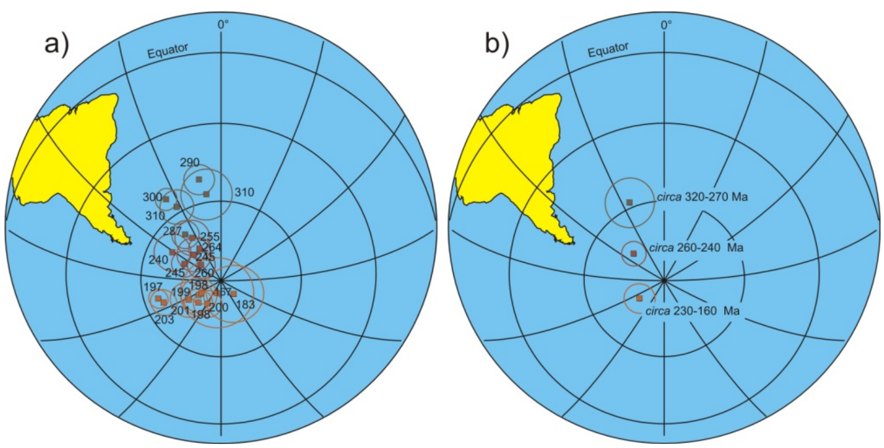

Fig. 1 SM. a) Selected paleomagnetic poles (PP´s) for South America for the Early Pennsylvanian-early Late Jurassic time span. Numbers indicate the age of PP´s. Note that three groups of poles that correspond to different time intervals can be recognized. b) Mean paleomagnetic poles for South America obtained with the selected PP´s. South America geographic coordinates, Schmidt projection.

The three different groups of South America PP´s are represented in Fig. 1a SM (supplementary material), corresponding to the following time spans: Early Pennsylvanian-Early Guadalupian (between circa 320 and 270 Ma), Late Guadalupian-Middle Triassic (between circa 260 Ma and 240 Ma), Late Triassic-early Late Jurassic (between circa 230 Ma and 160 Ma). The clustering is clear, though with some dispersion in each of the groups, particularly in the time span extending between the Late Triassic and the early Late Jurassic (PP´s selected by Kent and Irving 2010). This dispersion could be attributed to incomplete structural restoration or undetected partial overprints; however, it is considered that the group-averaged mean (Fig.1b SM), is representative for determining the paleogeographic position of South America.

Based on the clustering of South American poles, we grouped poles from the other Gondwana continents using the same window ages. Then we performed paleogeographic reconstructions using the parameters of Table 2 SM for the three defined time spans.

Table 2 SM: Reconstruction Parameters (Euler Poles)

Euler poles for Early Pennsylvanian-Early Guadalupian time span (to Africa geographic coordinates)				
Continent	Lat. (°)	Long. (°)	Angle (°)	Reference
South America	45.5	-32.2	58.2	Lawver and Scotese (1987)
Patagonia	37.25	331.72	72.37	This work
Australia	-22.67	-62.34	55.23	Lawver and Scotese (1987)
Madagascar	-3.41	-81.7	19.73	Lawver and Scotese (1987)
India	-27.83	223.55	66.08	Lawver y Scotese (1987)
Antártida	-7.78	-31.42	58	Lawver and Scotese (1987)
Arabia	36.5	18.0	-6.14	McKenzie and Sclater (1971)
Eurasia	46.72	2.38	56.44	(1)
Laurentia	64.1	344.3	78.4	Klitgord and Schouten (1986)
Iberia	50.51	10.68	10.68	(2)
Euler poles for Late Permian-Middle Triassic time span (to Northwest Africa geographic coordinates)				
South America	55.1	-35.7	50.9	Rabinowitz andLa Breque 1979, anomaly 34
Central Africa (Congo Craton)	19	2	-2	Pindell and Dewey (1982) (3)
South Africa (Kalahari Craton)	27.24	0.4	-8	This work (4)
Madagascar	9.9	76.17	-14.56	This work (4)
Arabia	-32.24	193.85	8.02	This work (4)
India	16.9	34.07	-84.45	This work (4)
Antarctica	6.57	128.33	-38.91	This work (4)

Australia	16.4	88.83	-49.75	This work (4)
Laurentia	73.18	-6.75	74.07	This work
Eurasia	56.8	10.59	48.64	This work
Iberia	27.48	179.38	9.83	This work
Euler poles for Late Triassic-early Late Jurassic time span (to Northwest Africa geographic coordinates)				
South America	52.6	-33.2	50.6	Unterneher et al. (1988)
Central Africa (Congo Craton)	19	2	-7	Pindell and Dewey (1982)
South Africa (Kalahari Craton)	19	2	-7	Pindell and Dewey (1982)
Madagascar	13.46	101.17	-11.14	(5)
India	-24.73	218.08	64.52	(5)
Australia	-21.31	-71.12	52.33	(6)
Antarctica	-7.57	-36.35	51.37	(6)
Arabia	27	9.38	-12.9	(7)
Iberia	48.99	12.23	6.16	(2)
Laurentia	67	348	75.6	Klitgord and Schouten (1986)
Eurasia	49.23	5.705	52.56	(1)
Euler poles for absolute reconstructions of Gondwana (Africa)				
ca. 320 – 270 Ma	0	144.4	63	This work
ca. 260 – 240 Ma	0	146.2	31.8	This work
ca. 230 – 160 Ma	0	157.0	19.69	This work

North (South) latitude: positive (negative). East (West) longitude: positive (negative). Negative (positive) rotation angle : clockwise (counterclockwise). (1) Calculated adding the Euler pole of Alvey (2009) with those of Klitgord and Schouten (1986). (2) Calculated adding the Euler poles of Rosenbaum *et al.* (2002), Alvey (2009) and Klitgord and Schouten (1986). (3) Considering just 2° of clockwise rotation instead of 8° in the same sense. (4) Calculated adding to the Euler poles used in Late Carboniferous-Middle Permian reconstructions, a rotation around the centers of the arcs of circumferences where intra-plate deformations are suspected (19º N 2ºE; 30ºN 0º; 7ºN 3ºO). (5) Calculated adding to the Euler poles of Smith and Hallam (1970) a further rotation about: 7°N, 3°W, 8° (clockwise). (6) Calculated adding to the Euler poles of Lawver and Scotese (1987) a further rotation about: 7°N, 3°W, 8° (clockwise).

Once poles were transferred to Africa present geographic coordinates, we observed if there were systematic differences between clusters from the different continents forming Gondwana, in each of the three periods. We decided to ascribe these differences to tectonic processes involving movements of lithospheric domains through the considered arches of deformation.

By using reconstruction parameters whose centers are located in northwest Africa, lithospheric domains were displaced to achieve common means between paleomagnetic poles of different continents. It is noteworthy that only in one case a common mean between PP´s of two continents was not achieved at 95%, though it did at 99% confidence (Table 3 SM). It was considered, therefore, that each paleogeographic reconstruction of Gondwana was valid if they were geologically plausible and the PP's populations of the involved continents shared a common mean.

Table 3 SM: Statistical tests for common means applied to PP's on pairs of Gondwana plates.

Early Pennsylvanian-Early Guadalupian time span

Continent(s)	K?	γ	γ_c	Prob.	f	F (95)	F (99)
SAM + AUS	0.183	10.9	12.0	0.093	5.17	6.271	11.052
AF + AUS	*0.02*	4.1	11.1	0.598	1.05	7.469	12.871
SAM + AF	0.219	6.9	10.0	0.202	3.73	7.902	15.936

SAM: South America (N 5, K 69.14, R 4.94); AF: Africa (N 10. K 104.51, R 9.91); AUS: Australia (N 7, K 36.21, R 6.83).

Late Guadalupian – Middle Triassic time span

Continent(s)	K?	γ	γ_c	Prob.	f	F (95)	F (99)
SAM + AUS	0.067	*13.0*	10.4	0.014	*12.28*	7.772	14.36
SAM + IND	0.086	5.1	10.6	0.367	2.03	8.815	17.136
SAM + AF/MAD	0.284	2.1	9.4	0.791	0.43	8.663	19.046
SAM + AF	0.034	4.2	4.8	0.101	6.24	7.965	13.625
AUS +AF/MAD	0.266	11.4	12.6	0.079	6.92	8.503	14.231
AUS + AF	0.012	9.6	11.1	0.086	8.06	10.693	21.578
AUS + IND	0.454	11.5	12.7	0.087	6.21	7.531	12.007
AF/MAD + IND	0.298	5.7	12.3	0.417	1.85	8.521	17.837
AF + IND	0.013	2.7	10.6	0.718	0.67	10.816	24.188

SAM: South America (N 6, K 230.65, R 5.98); AF/MAD: Africa + Madagascar (N 3, K 103.03, R 2.98); IND: India (N 4, K 82.22, R 3.96); AUS: Australia (N 4, K 74.04, R 3.97)

Late Triassic – early Late Jurassic time span

Continent(s)	K?	γ	γ_c	Prob.	f	F (95)	F (99)
AUS + SAM	0.06	4.9	7.0	0.225	3.37	7.048	11.896
AUS + AF/ANT	0.061	5.5	7.3	0.145	4.27	7.5	12.591
AUS + AF	0.056	5.1	7.3	0.226	3.28	6.863	10.157
SAM + AF/ANT	0.494	0.9	7.6	0.946	0.1	6.43	11.249
SAM + AF	0.459	1.4	8.1	0.912	0.2	6.715	10.813

SAM: South America (N 9, K 82.07, R 8.90); AF: Africa (N 8, K 78.21, R 7.91); AUS: Australia (N 3, K 430.47, R 2.99)
K?: Probability of obtaining a test value greater than the observed, under the null hypothesis of common K. γ: angle between means. γ_c: critical angle. Prob.: Probability of exceeding the critical angle under the null hypothesis of a common mean. f: value for the statistical test of McFadden and Lowes (1981) calculated assuming Fisher distribution (Fisher 1953) and performing simulation as defined by McFadden (1990). F (95), F (99), critical values for the F test at 95% and 99% confidence, respectively. Italics were used for rejected null hypotheses at 95% confidence.

Paleomagnetic poles corresponding to the three selected periods analyzed in present Africa geographical coordinates

Early Pennsylvanian-Early Guadalupian (circa 320 Ma-270 Ma)

For this time 5 PP´s from South America (excluding Southern Patagonia, Table 1 SM), 10 from Africa and 7 from Australia were selected, thus leaving Australia as the only East Gondwana plate with valid paleomagnetic data in this period.

The poles were rotated by using the classical reconstruction parameters of Lawver and Scotese (1987). A good fit was obtained, as shown by positive statistical tests of common means between poles of each pair of plates (South America vs. Africa, South America vs. Australia, Africa vs. Australia, see Fig.2 SM and Table 3 SM). No additional rotations were required for these plates to improve their fit in this time span.

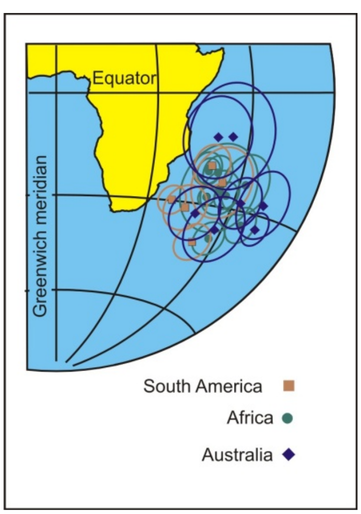

Fig. 2 SM. Selected PP´s of Gondwana for the time interval Early Pennsylvanian-Early Guadalupian (ca. 320 Ma – 270 Ma), reconstructed to Africa geographic coordinates. Schmidt projection.

The situation is different for the domain "Southern Patagonia" (to the south of Gastre Fault System); its position is only constrained by one paleomagnetic pole corresponding to Tepuel Group (Westfalian-Namurian). It was based on 16 sites in two distant locations (separated by about 60 km) and it passed a tilt test (Rapalini*et al.* 1994). Both localities are to the S-SW of Chubut river, relatively close, but outside the Gastre Fault System belt. Tepuel PP is not in agreement with the rest of Gondwana poles when rotated according to Lawver and Scotese (1987), and it could only be approximated to them by applying a rotation to Southern Patagonia, around an Euler pole at 37.25°N and 331.72° E (Table 2 SM). The approach is not perfect (see Fig. 3a SM), as a significant difference persists which cannot be accounted for by rotations in the sense proposed in this study. However, Tepuel PP reconstructed and rotated becomes coincident (Fig. 4b SM) with 3 Westfalian-Namurian Laurentia poles (ages 320, 317 and 303 Ma in Torsvik *et al*. 2012), transferred to Africa present geographic coordinates by using the Euler pole of Klitgord and Schouten (1986). We interpret that the discrepancy between poles from Southern Patagonia and West Gondwana records subsequent relative movements between them (see next section), while coincidence between Southern Patagonia and the most rigid Laurentia PP´s reflects their links through global plate circuits. Notice that Laurentia is considered a rigid plate from the Precambrian Rodinia supercontinent. While further rotation imposed to Southern Patagonia increases the value of the precision parameter Kappa (Fisher 1953) for Laurentia + Tepuel poles by 50%, it is clear that the statistics are based on a poor database, and more data are needed to unravel the complex tectonic history for Patagonia during the Paleozoic.

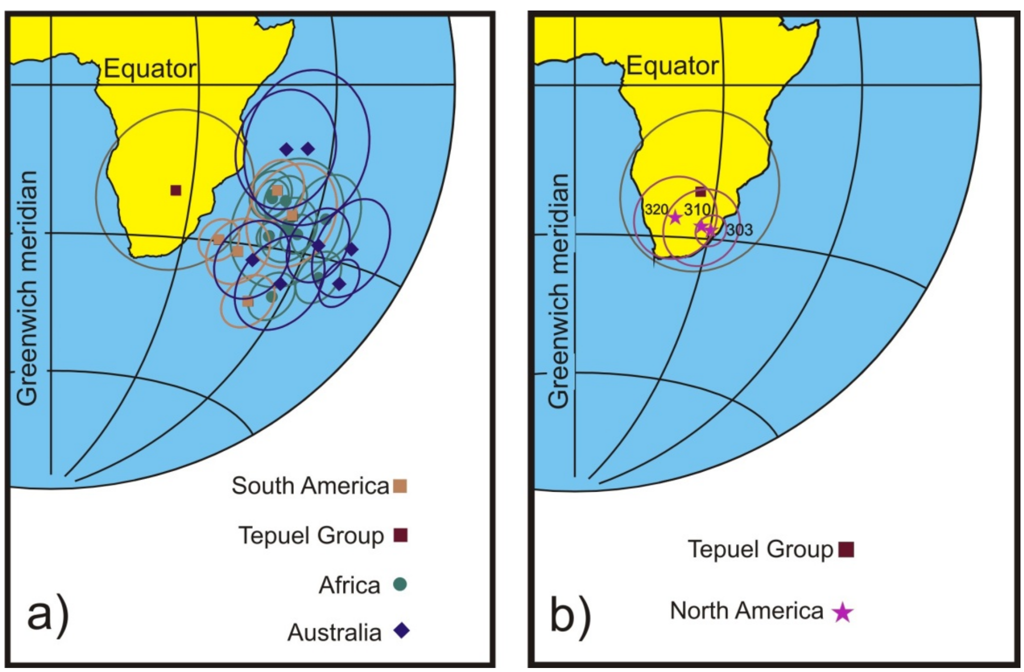

Fig. 3 SM. a) Comparison of the PP of Tepuel Group with those selected of South America for the Early Pennsylvanian-Early Guadalupian (Africa geographic coordinates). b)Comparison of the PP of Tepuel Group with three PP´s of Laurentia with similar ages (all PP´s were reconstructed to Africa geographic coordinates).

Late Guadalupian – Middle Triassic (circa 260 Ma – 240 Ma)

For this time span 6 PP´s from South America (Table 1 SM), 2 from Africa, 1 from Madagascar, 4 from India and 4 from Australia were selected.

The reconstruction to Africa present geographical coordinates by using the Lawver and Scotese (1987) parameters leaves data much more dispersed than for the previous period (compare Figs. 2 and 4a SM). There is a remarkable difference between the East Gondwana (Australia and India) and South American poles (Fig. 4a SM). This difference arising when using classical reconstructions, has already been observed by different authors (Klootwijk 1979, Irving and Irving 1982, Oviedo and Vilas 1984, Rapalini and Vizán 1993).

Our proposal to consider the plates as non-rigid and composed by different domains separated by belts of focused deformation, was used to achieve a better fit between the selected PP's from different continents. Northwest Africa was regarded as a "fixed" domain as the centers of the arcs of the deformation belts considered in this work are located there. The PP´s were transferred to this domain by using the reconstruction parameters of Table 2 SM, constructed as follows: Data from South America were brought to Africa present geographic coordinates using the parameter of reconstruction for the anomaly 34 of Rabinowitz and LaBrecque (1979). This makes a very good fit between the northern coast of South America and the southern margin of northwest Africa, leaving an open space between the southern coasts. This space allowed moving westward the Congo and Kalahari cratons, and consequently East Gondwana continents were also able to be moved westwards. The Euler pole used to move the Congo craton with respect to Northwest Africa was proposed by Pindell and Dewey (1982); it displaces Congo along an arc located in its northern boundary, which would later become the Benue trough. We added an extra movement to the Kalahari craton, along the arc containing also the Guapiara-Curitiba fault-zone (South America), the Damara mobile belt (Africa) and, across the Paleotethys ocean, the trace of the Ural Mountains. A similar movement was applied to the island of Madagascar.

East Gondwana continents, were further rotated around an Euler pole whose center corresponds to that of the arc containing the Gastre Fault System (Patagonia) and the boundary between East and West Gondwana.

The Euler poles constructed by combining classical reconstructions with additional rotations around deformation belts (Table 2 SM) allowed a better fit of Gondwana PP's (Fig. 4b). The PP of Madagascar approaches the two South Africa PP's, and all of them are much closer to those of South America. Moreover, the PP's of Australia and India are located closer to West Gondwana data (*cf* Fig.4a SM and Fig.4b SM).

Statistical tests of common means between poles of each pair of plates were performed, with the only pole from Madagascar assumed to constitute an only population with African poles. Only South America + Australia failed the test of common mean at 95% of confidence, while they passed it at 99% (Table 3 SM). This particular failure could reflect the peculiar distribution of Australian poles which are poorly grouped for this period. However, in general terms pole fitting significantly improved by considering focused internal deformation within plates.

It should be noticed that our best fit was obtained by considering internal movements within Africa. Possible movements in South America cannot be excluded and are discussed in the main text. However, the statistical best fit could be considered as evidence for internal movements in the African plate being more significant.

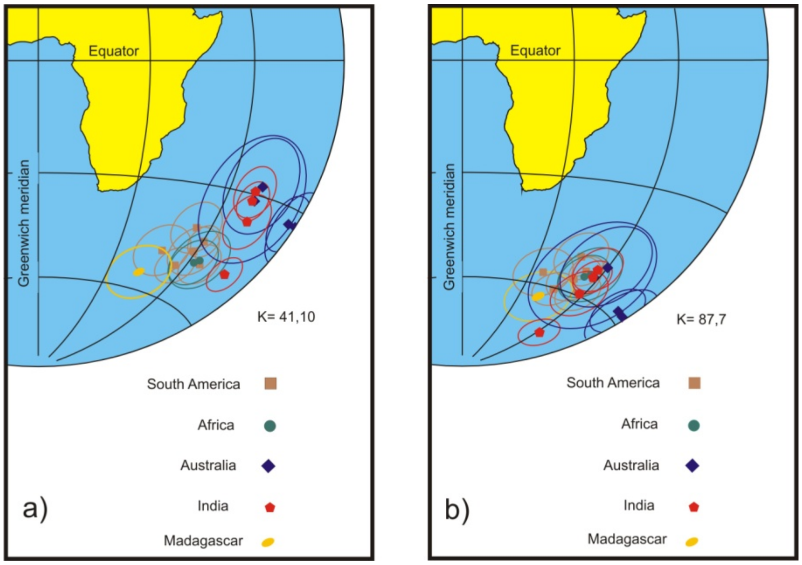

Fig. 4 SM. a) Paleomagnetic poles of Gondwana for the Late Guadalupian-Middle Triassic in Africa geographic coordinates using Lawver and Scotese (1987) reconstruction parameters. b) The same PP´s considering internal deformation of continents (domains rotated by using as Euler poles the centers of arches located in northwest Africa, see Table 2 SM). Note that there is a better grouping of poles of the different continents.

<u>Late Triassic – early Late Jurassic (circa 230 Ma – 160 Ma)</u>

For this time span we followed the selection performed by Kent and Irving (2010), with the only exception of the pole of Vizán (1998) as mentioned previously. Then the selection is composed by 9 PP´s of South America, 8 of Africa, 3 of Australia and 1 of Antarctica.

The reconstruction parameter of Unterneher et al. (1988), which achieves the best fit between the coastlines of northern Brazil and West Africa and considers the flow lines inferred through Walvis Ridge, was used for reassembling West Gondwana (South America and Africa). To select this model, it was taken into account that the configuration of West Gondwana should be consistent with features that would result in both plates during the extensional processes that ultimately would determine the opening of the Atlantic Ocean.

This Euler pole differs little from the one proposed by Rabinowitz and LaBreque (1979) for the anomaly 34 reconstruction that we used in the previous period.

To achieve a good fit between the southern margins of South America and Africa, Congo and Kalahari were rotated around a common Euler pole located at 19° N, 2° E (present geographic coordinates of Africa).

To make the reconstruction of Madagascar to present geographic coordinates of Africa the parameter of Smith and Hallam (1970) was used. This reconstruction is consistent with the extensional tectonics that would have happened in the Morondava basin located between Madagascar and Africa (Schandelmeier et al., 2004). Also considering the extensional processes between the east coast of Madagascar and India during this time span (Plummer and Belle 1995), the reconstruction parameter of Smith and Hallam (1970) was used for India.

Antarctica and Australia were reconstructed to Africa geographical coordinates by using the Euler poles of Lawver and Scotese (1987), plus the rotation imposed (see above) to Congo and Kalahari about 7° N and 3° W (in present geographic coordinates of Africa).

When pole grouping is statistically tested by pairs of plates between Australia, Africa and South America, it supports the hypothesis of a common mean at 95% confidence in every case (Table 3 SM, see also Fig. 5). The same is true if the only pole selected for Antarctica is taken together with the Australian poles, and the whole group tested against Africa or South America.

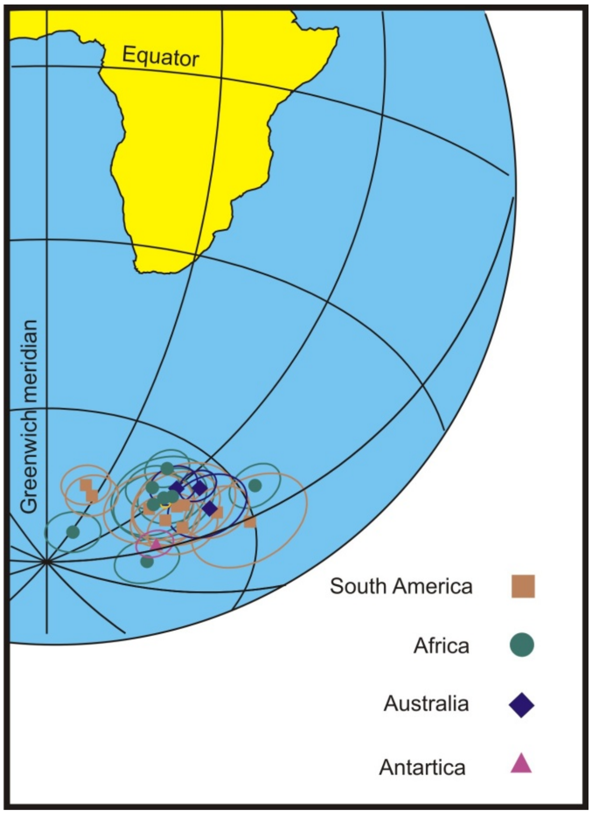

Fig. 5 SM: Paleomagnetic poles of Gondwana continents for the Late Triassic-early Late Jurassic in Africa geographic coordinates (using the reconstruction parameters of Table 2 SM).

Checking the obtained Gondwana reconstructions with models of Wegener - type Pangea

Since the mid-70s until today there has been a scientific debate as to the configuration of Pangea between Late Paleozoic and Early Mesozoic (see Aubele *et al*. 2012). According to Domeier *et al*. (2012a) it would be similar to that proposed by Wegener, also the one with more geological arguments (*e.g.* Hallam 1982, Weil *et al*. 2001, Pastor Galan 2012).

In order to check if our obtained Gondwana reconstructions were consistent with models of Wegener-type Pangea, Laurasia PP´s from Domeier *et al*. (2012a)´s list for the first two periods, and from Kent and Irving (2010)´s list for the third, were selected (Table 4 SM).

Table 4 SM: Paleomagnetic poles of Laurasia to check Wegener´s Type Pangea

Selected Paleomagnetic poles for the mean of the Early Pennsylvanian-Early Guadalupian time span (*ca* 320 Ma – 270 Ma), from the list of Torsvik et al. (2012)

Locality or Stratigraphic unit	Lon. (° E)	Lat. (°S)	A_{95} (°)	Age (Ma)	References
Stable Europe					
Tashkovska Donbas Ukraine	341.5	40.3	2.9	312	Meijers et al. (2010)
Westphalian-Stephanian red beds Czech Rep.	343.0	38.0	9.0	305	GPDB 167,T
Queensferry sill, Scotland	354.0	38.3	5.2	305	GPDB 2447, T
Wakerfield dyke, England	349.0	49.0	3.0	303	GPDB 180, T
Debaltsevo Donbas, Ukraine	342.3	48.2	2.0	303	Meijeres et al. (2010)
Donets basin, Ukraine	337.3	49.9	3.0	301	Iosifidi et al. (2010)
Peterhead dyke, Scotland	342.0	41.0	1.3	297	GPDB 1535, T
Ny-Hellesund sills, Norway	341.0	39.0	2.9	297	GPDB 626, T
Arendal diabase dykes, Norway	339.6	42.5	7.1	297	GPDB 175, T
Silesia volcanic, Poland	354.0	43.0	13.6	296	GPDB 465, T
Thuringer forest volcanic, Germany	350.0	37.1	7.1	295	GPDB 1792, T
Scania dolerites, Sweden	354.0	37.0	11.0	294	GPDB 2211
Scania dolerites, Sweden	348.0	38.0	6.5	294	GPDB 2222, T
Alnwick Sill, High Green and St. Oswald Chapel	337.1	47.1	8.1	294	Liss et al. (2004), T

Dyke, UK					
Cracow volcanic A, Poland	355.0	44.0	4.8	294	Nawrocki et al. (2008), T
Lower Nideck volcanic, France	348.0	47.0	4.0	294	GPDB 174, T
Holy Island Sill and Dyke, UK	346.8	35.4	6.3	294	Liss et al. (2004)
Hadrian´s Wall-Pennines Sill and Hett Dyke, UK	347.1	32.9	3.5	294	Liss et al. (2004)
Great Whin Sill, UK	339.0	44.0	4.8	294	GPDB 585, T
SudeticMountain granitoids, Poland	346.0	42.0	13.0	293	GPDB 2446, T
Nahe volcanic, Germany	347.0	46.0	13.0	291	GPDB 940, T
Stabben Sill, Norway	354.0	32.0	2.4	291	GPDB 1540, T
ThuringerForest sediments, Germany	338.1	45.3	5.8	287	GPDB 1792, T
Black Forest rhyolites, Germany	353.0	42.0	1.0	286	GPDB 2941, Recalculated, T
Exeter Lavas, UK	343.0	48.0	10.0	286	GPDB 411, Recalculated, T
Black Forest volcanics, Germany	356.0	49.0	5.9	286	GPDB 170, T
Exeter Lavas, UK	330.0	50.0	4.0	286	GPDB 461,T
Lower Silesia volcanics, Poland	352.0	40.0	13.2	285	GPDB 465, Recalculated, T
Bohemian Red Beds, Czech Rep.	343.5	44.0	4.0	285	GPDB 167, T
Intrasudetic basin sediments, Poland	339.4	38.5	6.8	285	GPDB 3161, T

Krakow volcanics	345.0	43.0	7.9	285	GPDB 275, T
Lodeve Basin, France	350.2	40.5	2.0	285	GPDB 1813, T
NorthSudeticBasin	354.0	42.0	8.1	285	GPDB 3161, T
Mount Hunneberg Sill, Sweden	346.0	38.0	6.3	285	GPDB 2211, T
Lower Lodeve snadstone	350.6	39.8	7.7	285	GPDB 2211, T
KrkonoseBasin oil Shales, Czech Rep.	345.2	42.4	2.0	285	GPDB 2444, T
NorthSudeticBasin sediments, Poland	4.1	48.6	5.1	285	GPDB 3161, T
IntrasudeticBasin volcanic, Poland	352.0	43.0	3.2	285	GPDB 3161, T
Moissey volcanic, France	352.0	41.0	6.7	285	GPDB 1205, T
Trachytes, Ukraine	359.7	49.4	6.5	283	Yuan et al. (2011)
Sarna alkaline intrusion, Sweden	346.0	38.0	6.9	281	GPDB 1735, T
Ringerike lavas, Norway	337.0	44.6	13.4	281	GPDB 1830, T
Oslo volcanics, Norway	337.0	41.0	7.0	281	GPDB 915, T
Bohemian Massif igneous, Germany	346.0	42.0	7.0	280	GPDB 2356, T
Mauchline lavas, Scotland	337.0	47.0	14.0	280	GPDB 3093, T
Bohemian quartz porphyry, Germany	341.0	37.0	10.0	280	GPDB 3145, T
Scania melaphyre dykes, Sweden	352.0	54.0	11	279	GPDB 2222, T
Bohuslan dykes combined, Sweden	345.0	51.0	8.6	275	GPDB 1155, T

North America					
Mauch Chunk	294.4	22.6	8.3	320	Bilardello and Kodama (2010a)
Shepody Fm, Nova Scotia	298.3	27.2	7.7	317	Bilardello and Kodama (2010b)
Riversdale Group	301.5	30.2	6.0	310	GPDB 1110, T
Glenshaw Fm	299.8	28.7	3.1	303	Kodama (2009)
Lower Casper Fm	314.6	50.5	1.8	303	GPDB 1455, T
Wescogame Fm	306.8	46.3	3.4	301	GPDB 1311, T
Laborcita Fm	313.4	43.0	2.1	301	GPDB 1311, T
Dunkard Fm	300.4	41.5	3.9	300	GPDB 302, T
Upper Maroon Fm	285.1	60.6	12.8	299	GPDB 504, T
Minturn and Maroon Fms	300.8	40.3	2.8	298	GPDB 1685, T
Cutler Fm	301.5	42.6	2.0	292	GPDB 671, T
Ingelside Fm	311.7	46.5	2.0	292	GPDB 1142, T
Cutler Fm, LisbonValley	310.1	42.1	7.1	292	GPDB 1341, T
ElephantCanyon Fm	295.2	35.8	5.0	292	GPDB 671, T
Upper Casper Fm	310.3	56.2	1.5	291	GPDB 1455, T
Piedmont Mafic intrusions	300.8	38.9	10.2	289	GPDB 1527, T
Abo Fm	305.9	48.3	2.1	285	GPDB 1311, T
Fountain and Lykins Fms	308.8	47.8	13.1	283	GPDB 504, T
Artinskian Pictou red beds	306.4	41.4	3.6	280	GPDB 2281, T
Leonardian subset	304.0	53.7	5.0	277	GPDB 688, T

Mean Paleomagnetic pole for Laurasia in North America geographic coordinates: N= 68, Lon.= 316.31°E, Lat.= 43.66° S, R= 66.91, A_{95}= 2.2°, K= 61.69. In Africa geographic coordinates: Lon.= 52.98° E, Lat.= 32.0° S.

<u>Selected Paleomagnetic poles for the mean of the Late Guadalupian – Middle Triassic time span (*ca* 320 Ma – 270 Ma), from the list of Torsvik et al. (2012)</u>

Locality or Stratigraphic unit	Lon. (° E)	Lat. (°S)	A_{95} (°)	Age (Ma)	References
Stable Europe					
Esterel sediments, France	327.7	50.6	5	264	GPDB 165, T
Permian red beds , Lodeve, France	326.4	58.6	0.0	264	GPDB 1207, T
BriveBasin sediments, France	341.7	52.6	4.0	261	GPDB 3144, T
Late Permian sediments, Urals	338.2	54.9	3.5	260	Bazhenov et al. (2008)
Massif des Maures, France	338.1	55.4	4.0	255	GPDB 1408,T
Dome de Barrot red beds, France	324.7	50.0	2.7	255	GPDB 652, T
Siberian traps mean	334.4	52.8	9.7	251	Pavlov et al. (2007)
Moyero River Siberian Traps, Siberia	314.5	58.5	2.7	251	Gallet and Pavlov (1996)
Big Nirundaiver intrusión, sedimenta, Siberia	323.0	54.3	5.0	251	Pavlov et al. (2007)
Stolbovaya River Siberian Traps, Siberia	330.3	53.3	5.3	251	Pavlov et al. (2007)
Sudetes sediments, Poland	336.5	59.3	5.0	251	GPDB 3161, T
KotuyRiver Siberian Traps, Siberia	328.4	52.7	13.9	251	Pavlov et al. (2007)
Taimyr Siberian Traps, Siberia	330.0	59.0	10	250	GPDB 2832, T
German Trias,	341.0	58.8	3.3	249	Szurlies et al.

Lower Buntstein					(2003)
Taimyr basalts, Siberia	325.8	59.3	7.8	248	Walderhaug et al. (2005)
Volpriehausen Fm, Germany	344.7	57.0	3.8	246	Szurlies (2004)
Upper Buntsandstein, France	322.2	47.8	5.0	243	GPDB 1028, T
Bunter and Musschelkalk, Germany	318.6	56.5	15.0	239	GPDB 158, T
North America					
Guadalupian red beds	311.6	54.8	5.0	263	GPDB 688, T
Ochoan red beds	302.2	57.3	15.0	258	GPDB 688, T
Bernal Fm	300.0	51.6	8.0	255	GPDB 2489, T
DeweyLakeFm	310.3	51.6	5.0	250	GPDB 2303, T
Lower Fundy Group	271.1	45.5	7.2	248	Symons et al. (1989)
LowerRedPeak Fm	306.1	50.5	7.0	235	GPDB 1134, T

Mean paleomagnetic pole for Laurasia in North America geographic coordinates: N= 24, Lon.= 305.93° E, Lat.= 56.61° S, R= 23.8, A_{95}= 2.8°, K= 113.26. In Africa geographic coordinates: Lon.= 47.90° E, Lat.= 55.27° S.

Selected Paleomagnetic poles for the mean of the Late Triassic – early Late Jurassic time span (*ca* 320 Ma – 270 Ma), from the list of Kent and Irving (2010)

Locality or Stratigraphic unit	Lon. (° E)	Lat. (°S)	A_{95} (°)	Age (Ma)	References
Stable Eurasia					
Rochechouart impact, France	294.9	54.6	5.2	214	Carporzen and Gilder (2006)
Kerforne dykes, Brittany, France	259.0	61.0	7.5	198	Sichler and Perrin (1993)
Scania Basalts, Sweden	283.0	69	6.8	179	Bylund and Halvorsen

					(1993)
North America					
Princeton NBCP core	286.6	54.2	2.0	227	Kentand Olsen (1999) and KentandTauxe (2005)
DanRiver basin sediments	279.8	58.5	1.1	221	Kent and Olsen (1997) and Kent and Tauxe (2005)
Nursery Road NBCP core	281,6	60.5	2.5	221	Kent and Olsen (1999) and Kent and Tauxe (2005)
Titusville NBCP core	279.5	59.9	1.7	217	Kent and Olsen (1999) and Kent and Tauxe (2005)
Manicouagan melt rocks	269.9	58.8	5.8	215	Larochelle and Curie (1967), Robertson (1967) and Hodych and Dunning (1992)
Rutgers NBCP core	277.1	60.1	1.4	214	Kent and Olsen (1999) and Kent and Tauxe (2005)
Somerset NBCP core	275.3	61.7	2.0	211	Kent and Olsen (1999) and Kent and Tauxe (2005)
Weston NBCP core	266.5	66.6	2.9	207	Kent and Olsen (1999) and Kent and Tauxe (2005)

Martinsville NBCP core	276.1	67.8	2.9	204	Kent and Olsen (1999) and Kent and Tauxe (2005)
Newark + Hartford volcanics	277.3	66.3	5.0	201	Prévot and McWilliams (1989) and Hames et al. (2000)
Hartford basin sediments	268.2	66.6	2.3	200	Kent and Olsen (2008)
WhiteMt. plutons	304.5	85.5	5.2	180	Opdyke and Wensink (1966)
Moat volcanics	269.7	81.6	5.6	169	Van Fossen and Kent (1990)

Mean paleomagnetic pole for Laurasia in North America geographic coordinates: N= 16, Lon.= 272.82° E, Lat.= 66.17° S, R= 15.76, A_{95}= 4.7°, K= 62.2. In Africa geographic coordinates: Lon.= 55.89° E, Lat.= 68.39° S.

The poles from Europe and Asia were transferred to North American coordinates by using reconstruction parameters of Alvey (2009), and then averaged with Laurentian PP´s. The three poles obtained in this way, one for each time span, were compared with Gondwana poles after reconstructing them to African coordinates with Klitgord and Schouten (1986) rotation poles. For the Late Guadalupian-Middle Triassic span, a slight modification was introduced to Klitgord and Schouten (1986) pole (see Table 2 SM), which improved the paleomagnetic fit while still being geologically akin.

Fig. 6 SM shows that the obtained Wegener- type models of Pangea are paleomagneticaly possible for the three periods since there is an overlap of the confidence intervals of the PP´s of Gondwana and Laurasia in each case.

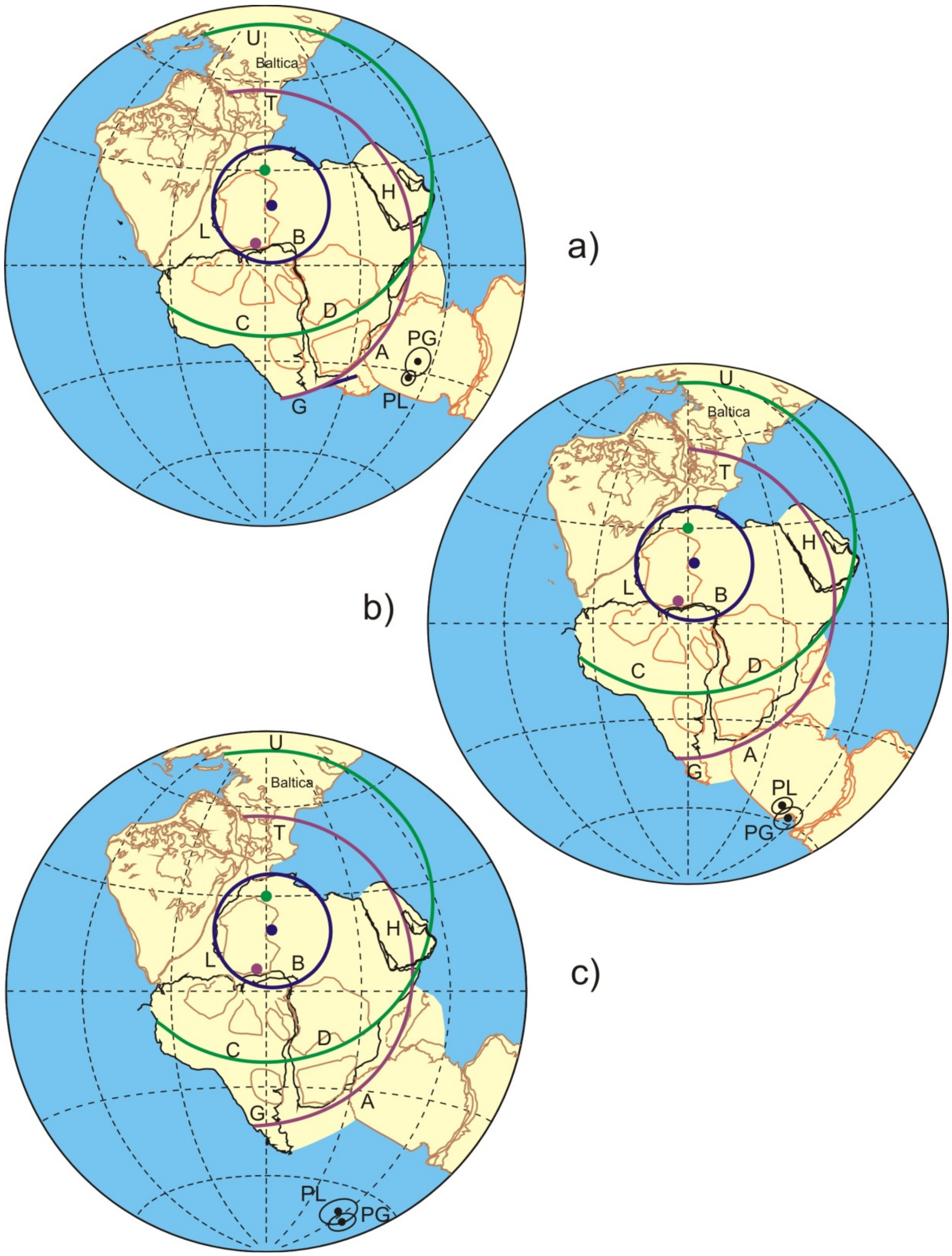

Fig. 6 SM. Models of Wegener Type Pangea in present Africa geographic coordinates, obtained by using the reconstruction parameters of Table 3 SM. PG: Mean PP of Gondwana, PL: Mean PP of Laurasia. The purple arc includes Gastre Fault Belt (G), the boundary between Africa-Madagascar and Antarctica-India (A), the Arabian "Hercynian" Orogeny (H) and the Trans-European Suture Zone (T). The green arc includes the Guapiara-Curitiba Fault Zone (C), the Damara Mobile Belt (D) and Ural Mountains (U). The blue circumference includes the Benue Trough (B) and boundary between Africa and Laurasia (L). a) Early Pennsylvanian - Early Guadalupian time span (about 320 – 270 Ma). b) Late Guadalupian – Middle Triassic time span (about 260 – 240 Ma). c) Late Triassic – Middle Jurassic time span (about 230 – 160 Ma). Note the overlap of the confidence intervals of the mean PP´s for every time span.

Absolute Reconstructions (latitudinal and longitudinal)

To determine the displacement vectors of Gondwana and make the presented geodynamic analysis, three absolute reconstructions of Gondwana were made based on the mean PP´s for each period. For that purpose we considered, following Scotese (2001) and others, that Africa had a negligible longitudinal motion at least from the formation of Pangea (Burke and Torsvik 2004, Torsvik*et al*. 2008).

Although our pole selection may differ from other previous selections (for example by Scotese 2001, Kent and Irving 2010, Torsvik*et al*. 2012, among others), the overall appearance of the reconstructions are roughly similar to ours, which means that the gross trends of Gondwana / Pangea drift are evident independent of the differences in selected poles; also the discrepancies between poles of different plates are visible no matter the selection used. The improvement achieved in grouping of paleomagnetic poles supports the plausibility of our hypothesis of internal deformation of plates along focused belts, compatible with geological evidence.

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