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ORIGINAL PAPER

The role of true polar wander on the Jurassic palaeoclimate

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Abstract From the Late Carboniferous until the Middle Jurassic, continents were assembled in a quasi-rigid supercontinent called Pangea. The first palaeomagnetic data of South America indicated that the continent remained stationary in similar present-day latitudes during most of the Mesozoic and even the Palaeozoic. However, new palaeomagnetic data suggest that such a scenario is not likely, at least for the Jurassic. In order to test the stationary versus the dynamic-continent model, we studied the Jurassic apparent polar wander paths of the major continents, that is, Eurasia, Africa and North America that all in all show the same shape and chronology of the tracks with respect to those from South America. We thus present a master path that could be useful for the Jurassic Pangea. One of the most remarkable features observed in the path is the change in pole positions at ~197 Ma (Early Jurassic), which denotes the cessation of the counter-clockwise rotation of Pangea and commencement of a clockwise rotation that brought about changes in palaeolatitude and orientation until the end of the Early Jurassic (185 Ma). Here, we analyse a number of phenomena that could have triggered the polar shift between 197 and 185 Ma and conclude that true polar wander is the most likely. In order to do this, we used Morgan's (Tectonophysics 94:123–139, 1983) grid of hotspots and performed "absolute" palaeogeographical reconstructions of Pangea for the Late Triassic and Jurassic. The palaeolatitudes changes that we observe from our palaeomagnetic data are very well sustained by diverse palaeoclimatic proxies derived from geological and palaeoecological data at this time of both the southern and northern hemispheres.

Keywords Palaeomagnetism · Jurassic · Palaeogeography · Pangea · Palaeoclimate

Introduction

From the Late Carboniferous until the Middle Jurassic, continents were assembled in a quasi-rigid supercontinent called Pangea, which occupied most of a hemisphere while the rest of the Earth's surface was made up of a large ocean called Panthalassa. From the time the first palaeomagnetic data were obtained in South America, it has been taken for granted that during most of the Mesozoic and the end of the Palaeozoic, the continent remained more or less stationary in similar present-day latitudes, based on the fact that palaeomagnetic poles clustered close to the geographic pole (e.g. Valencio et al. 1983; Oviedo and Vilas 1984; Rapalini et al. 1993; Beck 1999). In contrast, Iglesia Llanos (1997), Vizán (1998), and Iglesia Llanos et al. (2006, 2008) argued that the Early Jurassic South American palaeomagnetic poles fell away from the geographic pole. Here, we present the apparent polar wander (APW) paths of Eurasia, North America and Africa that were part of Pangea at that time, made up of high quality poles. We rotated them to South American coordinates using the kinematic model that produced the best clustering of poles, demonstrate that paths depict the same shape, length and chronology of the different tracks, and constructed a master APW path for Pangea. The resultant path shows a long track between the Late Triassic (215 Ma) and the lowermost Jurassic (197 Ma) followed by another track until 185 Ma (late Early Jurassic). The intersection of these

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tracks defines a cusp at ~197 Ma. From 185 Ma on, that is followed by a small track that lasts until 170 Ma (Middle Jurassic), and a standstill that would have lasted until the Late Jurassic. We analyse here the likely phenomena that could have caused the shift in the pole positions between 197 and 185 Ma (Early Jurassic), such as, basically (1) lithospheric motion or and (2) true polar wander (TPW) defined as the drift of the spin axis relative to the rigid Earth. In order to accomplish this, we used Morgan's (1983) grid of hotspots (HS) that goes back to 200 Ma and thus constitutes a unique tool to perform our analysis. In addition, since TPW produces rapid latitudinal changes in different regions, we provide palaeolongitudinal-controlled ("absolute") reconstructions of "crude" Pangea for the Jurassic, assuming that during this time, HS were more or less fixed to the mantle. Finally, the palaeolatitudinal changes that we observe are confronted with the palaeoclimatic proxies derived from biogeographical and geological data from both the northern and southern hemispheres.

Pangea's apparent polar wander path

APW paths depict the past positions of the Earth's spin axis (=averaged palaeomagnetic pole) with respect to a certain lithospheric plate, hence the name "apparent" (Creer et al. 1954). The path is constructed as a sequence of palaeomagnetic poles tracking away from the geographic pole with increasing age. Tracks represent rotations about Euler poles whereas cusps symbolise times of reorganization of the lithospheric plate boundaries and resulting driving forces (Gordon et al. 1984). In other words, a cusp establishes the precise time when the motion of plates changed relative to the spin axis.

For Jurassic times, major continents from the northern hemisphere yield rather well-defined APW paths. In particular, that of Eurasia is highly reliable, for a great number of the corresponding palaeopoles belong to tectonically stable areas and bear precise geological/palaeomagnetic ages. In the case of the southern hemisphere, however, the quality and number of poles vary considerably, giving way to radically different geodynamical models for the Gondwana supercontinent (Iglesia Llanos et al. 2006).

This study was performed using selected data of the major lithospheric plates whose relative positions for this time are well-known, such as, Eurasia, North America, Africa and South America. Palaeomagnetic poles (PP) were drawn mainly from the Global Palaeomagnetic Database v.4.6 2005 (http://www.tsrc.uwa.edu.au/data_bases), from Torsvik et al. (2001, 2008), van der Voo and Torsvik (2004), Kent and Irving (2010) plus a few poles from the literature (Table 1). Selection of PP was stringent and required to pass minimum reliability criteria such as: (1) coming from sections bearing well-constrained geological ages, (2) unsuspected of being subjected to rotations around vertical axis, (3) full demagnetisation and vectorial analysis of palaeomagnetic data and, (4) palaeomagnetic field tests and/or mineralogical studies to restrain magnetisation ages. This is important, because it states that all selected poles bear a comparable good quality.

APW paths from Eurasia, North America and Africa were rotated to South American present-day coordinates (Fig. 1). In order to do so, we tried all classical palaeoreconstructions to bring continents to South America looking for those that provided the best clustering of poles. In all cases, the latter was achieved by considering Africa and South America as single rigid plates, in opposition with other models that divide these continents in at least three different plates (e.g. Torsvik et al. 2008; Moulin et al. 2010). In this study (Table 2), Africa was rotated to South American coordinates using the palaeoreconstructions proposed by Lawver and Scotese (1987). Eurasia was translated first to North America using the palaeoreconstruction of Frei and Cox (1987), then to Africa, and subsequently to South America using Lawver and Scotese (1987). North American on the other hand was first moved to Africa with the palaeoreconstruction of Klitgord and Schouten (1986) and then to South America with the parameters of Lawver and Scotese (1987). By averaging non-overlapping poles with 5–10 Ma windows, a master path was derived for Pangea (Fig. 2; Table 3). The resultant curve shows, when observed from South America, a W–E track between 215 and 197 Ma (Late Triassic to lowermost Jurassic), followed by a SE–NW track between 197 and 185 Ma (Late Sinemurian to Early Pliensbachian). The intersection of these two tracks defines a cusp at ~197 Ma. After 185 Ma until 170 Ma (Middle Jurassic), a smaller track and consecutive standstill that might have lasted until the Late Jurassic are observed. The 197–185 Ma track reveals a c. 50° shift in the pole positions during this time, and a minimum angular change of poles of approximately 4° Ma^{-1}.

The Eurasian APW path of this study was confronted with other curves from the literature. Such comparison was performed using the curves from Edel and Duringer (1997), Torsvik et al. (2001, 2008) and Besse and Courtillot (2002), after bringing them to South American coordinates (Table 2). The selection of these authors was made on the basis that, some authors like Edel and Duringer, did observe the Late Triassic–Early Jurassic loop, Others, like Torsvik and co-authors and Besse and Courtillot, report no major pole shifts at this time. Some similarities between those authors' and the curve we constructed (Fig. 3) are observed, although there are noticeable differences as well. For instance, we observe that Torsvik's path (Fig. 3)

Table 1 Selected palaeopoles from the GPDB v. 4.6 (http://www.tsrc.uwa.edu.au/data_bases) and more recent South American poles

Code/rock unit	Mean age (Ma)	Lat °S	Long °E	A_{95}	References	Ref no
North America						
1. Passaic Fm.	210	57.6	310.6	7.0°	Kodama et al. (1994a, b)	2869
2. Newark Rutgers core[a]	215[d]	56.4	277.8	3.1°	Kent et al. (1995)	2967
3. Chinle Fm. Upp. Shale[a]	218[d]	57.4	267.8	5.6°	Bazard and Butler (1991)	2380
4. Newark Somerset Core[a]	213[d]	57.2	276.5	2.8°	Kent et al. (1995)	2967
5. Newark Weston Core[a]	210[d]	58.0	271.5	2.5°	Kent et al. (1995)	2967
6. Redonda Fm.[a]	212[d]	57.7	259.1	4.2°	Reeve and Helsley (1972)	152
7. Newark Mart.[a]	206[d]	58.6	278.4	2.4°	Kent et al. (1995)	2967
8. Culpeper Basin[a]	200[d]	65.5	253.1	4.8°	Kodama et al. (1994a, b)	2791
9. Wingate Sdt.	202	57.4	236.6	6.4°	Molina-Garza et al. (2003)	3560
10. Sugarloaf Fm.	200	57.7	261.3	9.1°	McEnroe and Brown (2000)	3393
11. Holden Diab.	197	60.1	260.5	5.1°	McEnroe and Brown (2000)	3393
12. Chinle Red Mb.	198	51.3	251.7	8.8°	Molina-Garza et al. (2003)	3560
13. North Mount. Bas.1[a]	190[d]	66.4	251.9	10.7°	Hodych and Hayatsu (1988)	1932
14. Copper Mt. Intr.	195	57.3	191.8	3.6°	Symons and Litalein (1984)	1679
15. Pelham-Loudv. Diab.	197	65.3	275.6	3.8°	McEnroe and Brown (2000)	3393
16. Newark Supergr. Volc.[a,b]	201[d]	68.0	268.6	3.9°	Prévot and McWilliams (1989)	2278
17. Sil Nakya Volc.[a]	193	74.4	260.1	7.6°	Cohen et al. (1986)	1807
18. Caraquet Dyke	190	74.1	294	8.5°	Seguin et al. (1981)	1877
19. Noth Mt. Bas.2	190	73.0	284	5.0°	Carmichael and Palmer (1968)	471
20. Kayenta Fm. 1[a]	210[d]	61.9	254.4	6.8°	Steiner and Helsley (1974)	153
21. Kayenta Fm. 2[a]	192[d]	59.0	246.6	3.3°	Bazard and Butler (1991)	2380
22. Mulberry Wash	185	61.5	34.9	6.1°	Cohen et al. (1986)	1807
23. Diabase Anitcosti	183[d]	76.0	265	1°	Larochelle (1971)	139
24. Teslin Crossing Pl.	181	84.5	69.4	8.8°	Harris et al. (1998)	3257
25. White Mt. Volc.[b]	180	85.5	304.5	4.0°	Opdyke and Wensink (1966)	325
26. Picton Dyke	173	76.0	166	2.6°	Barnett et al. (1984)	1908
27. Stump-Twin Fm.	170	64.0	342	8.0°	McWhinnie et al. (1990)	2305
28. Summerville Fm.[a]	159[d]	67.0	289.8	4.3°	Steiner (1978)	1121
Eurasia						
1. Sunnhordland dikes[c]	212	50.0	305	4.5°	Walderhaug (1993)	–
2. Volc. N Pyrenees1	205	62.1	294.2	7.3°	Girdler (1968)	481
3. Pre-Azov	200	38.0	278.0	3.0°	Mikhaylova et al. (1989)	2622
4. Donbass	200	70.0	268.0	4.0°	Rusakov (1971)	919
5. Rhaetian Seds.[a]	208[d]	50.0	292.0	7.6°	Edel and Duringer (1997)	3141
6. Hett.-Sinem. Limest.[a]	201[d]	55.0	280.0	9.0°	Edel and Duringer (1997)	3141
7. Paris Basin Seds.[a]	198[d]	51.3	285.0	3.1°	Yang et al. (1996)	3029
8. Kerforne dikes[a,b]	198[d]	61.3	258.8	7.5°	Sichler and Perrin (1993)	2743
9. Main Caucasus	197	43.0	337.0	5.0°	Sinitsin and Shevlyagin (1986)	2019
10. Liassic Volcs.[a]	198[d]	64.9	323.6	6.7°	Girdler (1968)	481
11. N Caucasus Volc.	185	68.0	72.0	12.0°	Asanidze and Pechersky (1982)	2010
12. E Donbass	190	85.0	41.0	11.0°	Mikhaylova et al. (1989)	2622
13. Liassic Seds.[a]	184[d]	76.9	314.7	3.0°	Hijab and Tarling (1982)	1467
14. Thouars and Airvault Sections[a]	184[d]	70.5	276.3	11.8°	Galbrun et al. (1988)	1427
15. Scania Basalts[a,b]	179[d]	69.0	282	6.8°	Bylund and Halvorsen (1993)	2720
16. Alsace Bajocian Seds.[a]	178[d]	63.0	300	6.0°	Kadzialko-Hofmokl et al. (1988)	1514
17. Subtatric Nappe Seds.[a]	159[d]	71.7	312.2	4.0°	Kadzialko-Hofmokl and Kruczyk (1987)	1948
18. Limestones. Krakow-Czest.[a]	159[d]	72.3	330.4	7.3°	Kadzialko-Hofmokl and Kruczyk (1987)	1948

Table 1 continued

Code/rock unit	Mean age (Ma)	Lat °S	Long °E	A_{95}	References	Ref no
19. Terres Noires[a]	158[d]	77.6	309.7	7.0°	Aubourg and Rochette (1992)	3156
20. Oxfordian Seds.[a]	157[d]	70.1	327	4.0°	Kruczyk and Kadzialko-Hofmokl (1988)	616
Africa						
1. U. Triassic Sed.[a]	221.5	54.9	43.3	11.5°	Ghorabi and Henry (1991)	3020
2. Dolerites Morocco[a]	200	72.1	37.7	6.3°	Westphal et al. (1979)	1859
3. Foum-Zguid	200	67.9	67.9	3.9°	Palencia-Ortas et al. (2011)	–
4. Ighrem	200	78.4	58.2	6.7°	Palencia-Ortas et al. (2011)	–
5. Zarzaitine Fm.[a]	206.5	70.9	55.1	2.6°	Kies et al. (1995)	2932
6. Karroo Comb.[a]	198	65.4	75.1	9.5°	McElhinny and Jones (1965)	317
7. Freetown Cplx.[a,b]	193	82.9	32.7	6.2°	Hargraves et al. (1999)	3287
8. Hank Volc. Mauri[a]	187[d]	60.4	52.0	4.1°	Dalrymple et al. (1975)	140
9. Hodh Volc. Mauri[a]	187[d]	71.4	60.2	6.1°	Sichler et al. (1980)	3259
10. Diabase dykes[a,b]	185.5[d]	68.5	62.4	7.4°	Dalrymple et al. (1975)	140
11. Karroo Ign.[b]	186	62.9	98.3	3.0°	Hargraves et al. (1997)	3430
12. Marangudzi Cplx.[a]	186	70.7	106.7	8.7°	Brock (1968)	470
13. Stormberg Lavas[a]	185	71.6	93.5	3.2°	Kosterov and Perrin (1996)	3090
14. Lembobo Bas.	183	68.7	94.5	7.0°	Henthorn (1981)	3114
South America						
1. Los Colorados Fm.	210	76.0	280.0	8.0°	Vizán et al. (2004)	–
2. Anari-Tapirapua Fm.[a,b]	196.6 ± 0.4	65.5	250.0	3.5°	Montes-Lauar et al. (1994)	3316
3. Neuquén basin 1[b]	197	51.0	223.0	6.0°	Iglesia Llanos et al. (2006)	–
4. Lepá-Osta Arena Fm.[b]	180–186	75.5	129.5	6.0°	Vizán (1998)	3314
5. Neuquén basin 2[b]	185	74.0	67.0	5.0°	Iglesia Llanos et al. (2006)	-
6. Marifil Complex[b]	168–178	83.0	138.0	9.0°	Iglesia Llanos et al. (2003)	3535
7. El Quemado Complex (N of 48°S)[a,b]	153–157	81.0	172.0	5.5°	Iglesia Llanos et al. (2003)	3535

A_{95} 95% confidence interval. *References/RefNo* Reference number in the GPDB

[a] in Torsvik et al. (2008)

[b] in Kent and Irving (2010)

[c] in Van der Voo and Torsvik (2004)

[d] Ages in Torsvik et al. (2008)

depicts an Upper Triassic–lowermost Jurassic track and a Lower Jurassic (198 Ma) cusp. However, the latter as well as the likely standstill does not move in a SE–NW direction but straight to the geographic pole. Thus, in this case, there is no remarkable change in the polar position from the end of the Lower Jurassic (c. 185 Ma) onward. A similar situation is observed in Besse and Courtillot's path, although the Upper Triassic–lowermost Jurassic track is less defined. In the case of Edel and Duringer, the path begins at 200 Ma and like the others moves straight to the South Pole. However, the path bears a 183 Ma (late Early Jurassic) pole that falls in a similar position to those we present in this study. We think that apart from the different selection criteria that might have been used, a key argument to explain the discrepancies among the curves could lie in the time windows and/or controversial chronological/magnetic ages. For instance, Besse and Courtillot work with 20 Ma windows, Torsvik and co-authors with 10 Ma windows, and Edel and Duringer with biostratigraphically dated poles.

What prompted the polar shift?

A primary issue that arises when a significant difference in pole positions is observed is related to whether the PP in question effectively represents a geocentric axial dipolar (GAD) geomagnetic field, as it would occur when fast-changing long-term, non-dipole components prevail. Alternatively, the shift would have been caused by some sort of geodynamic phenomenon such as: (1) lithospheric motion, or (2) true polar wander (TPW), which is the drift of the spin axis relative to the global solid Earth. We will herein discuss the likely influence of these phenomena.

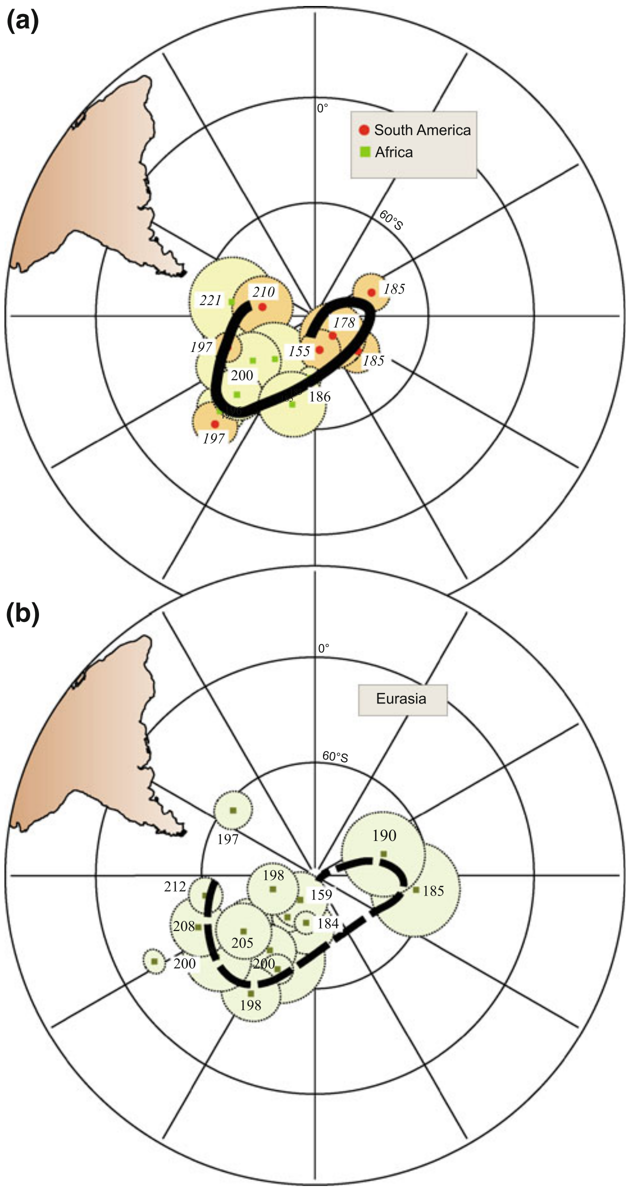


Fig. 1 Jurassic APW paths with mean ages for **a** South America and Africa and **b** Eurasia. The latter have been rotated to South American present-day coordinates using the kinematic models in Table 2. Palaeopoles were mostly drawn (Table 1) from the Global Paleomagnetic Database v.4.6 (http://www.tsrc.uwa.edu.au/data_bases)

Geomagnetic field

According to many authors, the contribution of the non-dipole components during the Phanerozoic was very small (~5–10°), thus corroborating that the Earth's magnetic field behaved essentially as a geocentric dipolar (e.g. McElhinny and Brock 1975; Evans 1976; Livermore et al. 1983, 1984). A stronger argument, however, is the consistency in the pole positions from different continents that occurs only when the Earth's magnetic field is essentially dipolar.

Lithospheric motion

To illustrate this phenomenon, we put forward the case of the South American continent. Here, palaeomagnetic data indicate that, during the Late Triassic and lowermost Jurassic, the continent rotated 50° CW (Fig. 3). Had such rotation resulted from sole lithospheric motion, South America would have been forced to override the trench as well as the Pacific plate, thus causing major compression in the overriding plate (Fig. 3a). It is well-known, however, that the birth of the Andes comprised two main deformation stages. The first stage (~200–90 Ma) conveyed a retreating type of margin (Fig. 3b) for South America characterised by comprehensive extension in the overriding plate (Royden 1993). Thus, during this stage, major rift systems developed in the southern Andes mostly as backarc basins like those found in Peru, northern Chile (e.g. Cobbing et al. 1981; Åberg et al. 1984; Mpodozis and Allmendinger 1993) and Argentina (e.g. Giambiagi et al. 2008). Along with this extensional regime, there came the onset of widespread injection of dykes in the Jurassic arc and local alkaline magmatism (e.g. Mpodozis and Ramos 1989). The other stage on the other hand took place during the mid-Cretaceous and portrayed a major compressional regime that gave birth to the Andean Cordillera (Somoza and Zaffarana 2008).

True polar wander

TPW is the drift of the spin axis with respect to the global solid Earth, over geological time. The phenomenon is

Table 2 Finite rotation parameters to translate North America, Eurasia and Africa to South American present-day coordinates

Plates	Lat° S	Long° E	Angle	Reference
Eurasia				
Eurasia–North America	88.0	−145.0	−42.0	Frei and Cox (1987)
North America–Africa	62.2	−15.9	78.8	Lawver and Scotese (1987)
Africa–South America	45.5	−32.2	−58.2	Lawver and Scotese (1987)
North America				
North America–Africa	67.0	347.7	75.5	Klitgord and Schouten (1986)
Africa–South America	45.5	−32.2	−58.2	Lawver and Scotese (1987)
Africa				
Africa–South America	45.5	−32.2	−58.2	Lawver and Scotese (1987)

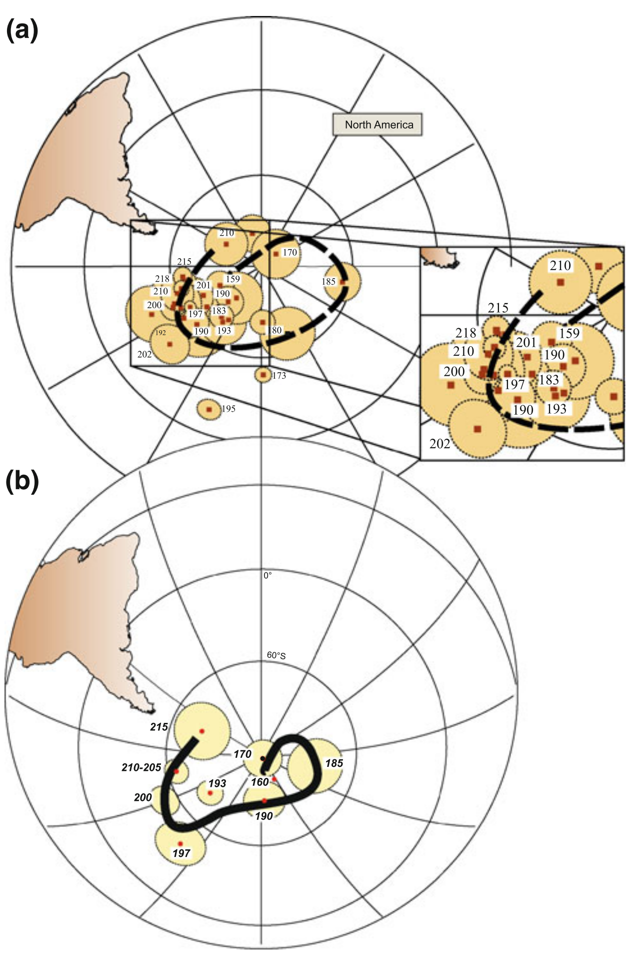


Fig. 2 **a** Jurassic APW path for North America in South American coordinates (Table 1). **b** Master APW path for Pangea with 95 % confidence interval, showing a cusp at around 197–198 Ma

Table 3 Master APW path (Fig. 1) and TPW path (Fig. 5) and associated 95 % confidence interval

Age (Ma)	APW path			TPW path		
	Lat° S	Lon° E	A_{95}	Lat° S	Lon° E	A_{95}
215	70	290.5	9°	59.6	85.8	9°
210–205	62.7	255.4	3.8°	73.5	104.1	3.8°
200	55.6	240.1	4.6°	78.5	143.6	4.6°
197	50.3	218.0	7.4°	68.1	183.2	7.4°
193	69.8	230.8	4°	68.8	131.3	4°
190	75.3	176.2	6.3°	54	134.8	6.3°
185	72.7	103.8	8.7°	40.1	120.3	8.7°
170	88.9	154.7	6°	61.1	112	6°
160	81.3	152.5	–	60.9	127.6	–

Kinematic models in Table 2

determined from HS, which we assume form an array of fixed points in the mantle—mantle reference frame. Defined as it is, TPW makes all continents and mantle plumes rotate around an Euler pole located at the Equator (Goldreich and Toomre 1969; Jurdy and van der Voo 1975). Since TPW is a global event, its signature is recognisable in all APW paths from that time.

The most straightforward way to evaluate TPW, however, is through palaeolatitudes plots (Fig. 4). This is because one important connotation of TPW is the rapid latitudinal change in localities. To perform the rotation of continents to South American coordinates and position them in turn with respect to the mantle, we used Morgan's (1983) grid of HS that assumes they remain more or less fixed to the mantle and date back to 200 Ma. For 185, 193, 197 Ma, and between 200 and 215 Ma, we used interpolated palaeoreconstructions following the methodology proposed by Cox and Hart (1986). Albeit the fixity of hotspots is still a hot matter of debate, some authors argue that there is no evidence of inter-hot spots motion larger than 5 mm a^{-1} for the Indo-Atlantic hemisphere, an order of magnitude less than plate velocities (e.g. Yan and Carlson 1997; Courtillot et al. 2003; Steinberger and Torsvik 2008). For this reason, many authors (e.g. Besse and Courtillot 2002) use this uniquely available tool to determine TPW in the Jurassic.

Two sets of palaeolatitudes were thus calculated (Fig. 4) for two localities, one from west-central Argentina, that is, Chos Malal, and the other from NE Brazil, that is, Fortaleza. One set of palaeolatitudes was derived from the palaeopoles of the master APW path (Table 3). The other set was calculated by rotating the two localities, to the "palaeolatitudes" they might have occupied between 215 and 160 Ma (Table 4). This way, Chos Malal and Fortaleza would have been rotated for the motion of South American in relation with the Atlantic Ocean HS, according to Morgan's (1983) grid of HS. For 215 and 210–205 Ma, we considered the HS position at 200 Ma.

If no TPW occurred, both palaeolatitudinal sets should be coincident. Conversely, the divergence of the curves after 200 Ma could be interpreted as the result of TPW. Nevertheless, it is worth noting that if the main palaeolatitudinal motion of the locality arises from HS rather than palaeomagnetic data, it can be attributed to drift between HS. In this case, localities remained in similar latitudes with respect to the grid of HS. Therefore, it would be reasonable to regard HS as a reliable reference frame for the mantle. We thus agree with, for example, Besse and Courtillot (2002) and Courtillot et al. (2003) over the fact that Morgan's grid of HS is valid to first order. The curves from Fig. 4 show that whereas no evident latitudinal change took place from the hotspots reference frame, the South American continent was actually moving northward. This we interpret as solid evidence of the occurrence of a clear TPW event in the Early Jurassic.

The TPW path on the other hand (Fig. 5; Table 3) was calculated after removing plate motions in the APW path,

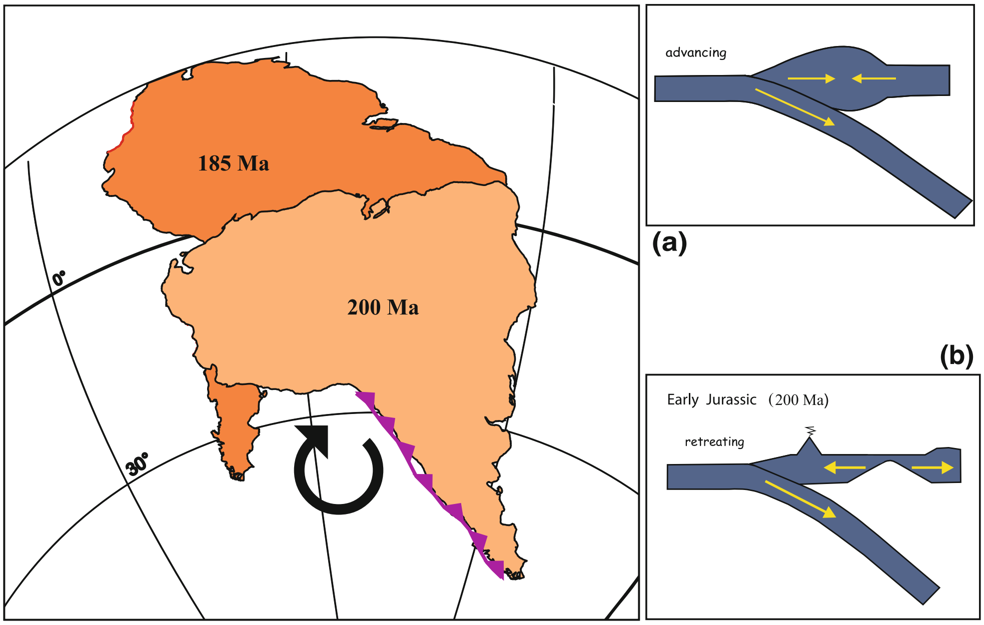


Fig. 3 Palaeomagnetic data show that during the Early Jurassic, South America was subjected to a c. 50° CW rotation. If such rotation were the result of lithospheric motion only, South America would have overridden the trench and Pacific plate, thus becoming an advancing-type of margin (**a** Royden 1993). However, from 200 to 90 Ma, the Andean border was a retreating type (**b**), characterised by comprehensive extension that prompted the formation of the major rift systems in, for example, Peru, northern Chile and Argentina

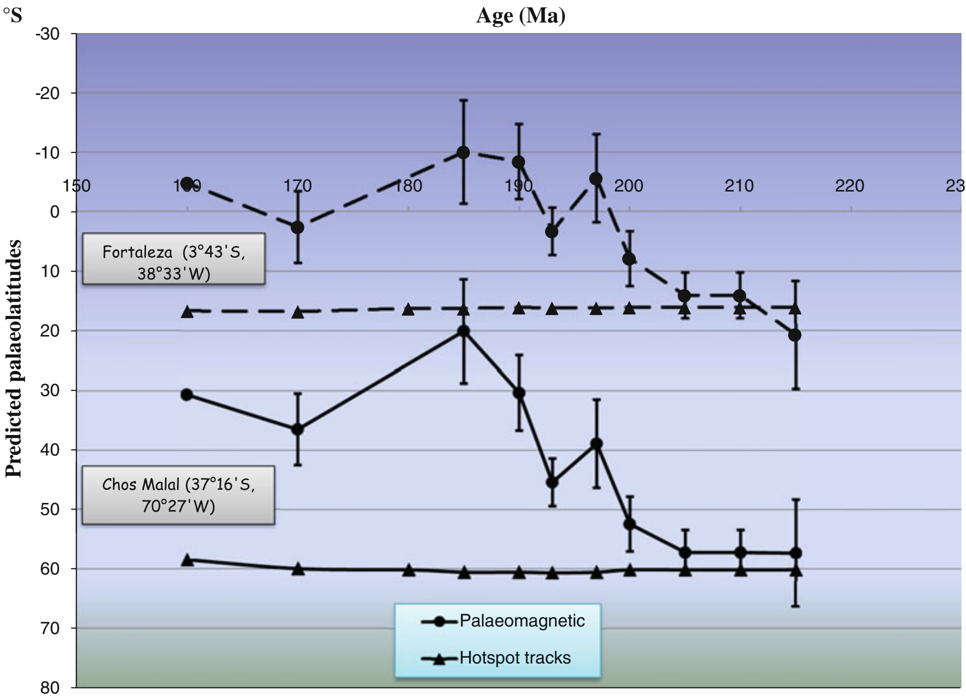


Fig. 4 Palaeolatitudes plots support the occurrence of TPW after 200 Ma. Two palaeolatitude sets are shown for two South American localities, one from Brasil and the other from Argentina, the first representing palaeolatitudes calculated from the master APW path-palaeomagnetic reference frame, and the second set from Morgan's (1983) grid of HS (mantle reference frame). If no TPW occurred, both curves should be coincident

in two steps. First, the pole and its continent were rotated to South American coordinates using the corresponding kinematic model (Table 2). Then, pole and continents were rotated for the motion of South America in relation with the Atlantic Ocean hotspot tracks, with interpolations at 197, 193 and 185 Ma (Table 4). Had there been no TPW, poles should have been grouped around the present southern geographic pole. Conversely, if the entire mantle shifted, PP would fall far off the geographic pole (Cox and Hart 1986; Fig. 5). From the TPW path, we calculated that after ~197 Ma, poles displaced approximately 45° over a 12-Ma period (Fig. 5; Table 3) meaning a minimum

Table 4 Morgan's (1983) grid of HS to rotate for the motion of South American in relation with the Atlantic Ocean HS and interpolations at 197, 193, 185 and beyond 200 Ma

Time (Ma)	Lat° N	Long° E	Ang
160	46.00	7.70	36.00
170	44.70	5.20	40.60
185	43.86	2.49	48.05
190	43.10	1.80	50.90
193	42.31	1.56	53.23
197	41.36	1.29	56.35
200	40.70	1.10	58.70
210–205	40.70	1.10	58.70
215	40.70	1.10	58.70

Kinematic models in Table 2

angular change of approximately 4° Ma^{-1} (0.4 m a^{-1}). This magnitude is consistent with the values predicted by Prévot et al. (2000) of 1°–5° Ma^{-1}, or the 3°–10° Ma^{-1} proposed by Sager and Koppers (2000) for the Pacific plate. Subsequently by the end of the Early Jurassic, the path turned back on itself. From the same path, we determined the separation between palaeopoles and the geographic pole for successive ages, or magnitudes of TPW (Table 5), to confirm that the greatest angular values occurred at 215 (~30°) and 185 Ma (~50°).

The estimated cumulative 45° of TPW produced over a period of 12 Ma is comparable to the >50° interpreted by Maloof et al. (2006) for the Neoproterozoic and lesser than the 90° calculated estimated by Kirschvink et al. (1997) for the same period. On the other hand, the magnitude is greater than the 35° calculated by Marcano et al. (1999) for the Permo–Triassic, and the c. 20° that Besse and Courtillot (2002) estimate have accumulated over the 200 Ma. Some authors interpret, however, that only <10° have occurred since the Early Cretaceous (Somoza and Zaffarana 2008).

"Absolute" palaeogeographical reconstructions of crude Pangea

The palaeomagnetic method is able to provide palaeolatitudes and orientations of the continents to perform palaeogeographical reconstructions, but because the time-averaged geomagnetic field is symmetric about the rotation axis, the methodology alone cannot estimate palaeolongitudes. There are other methods to calculate palaeolongitudes, and in this

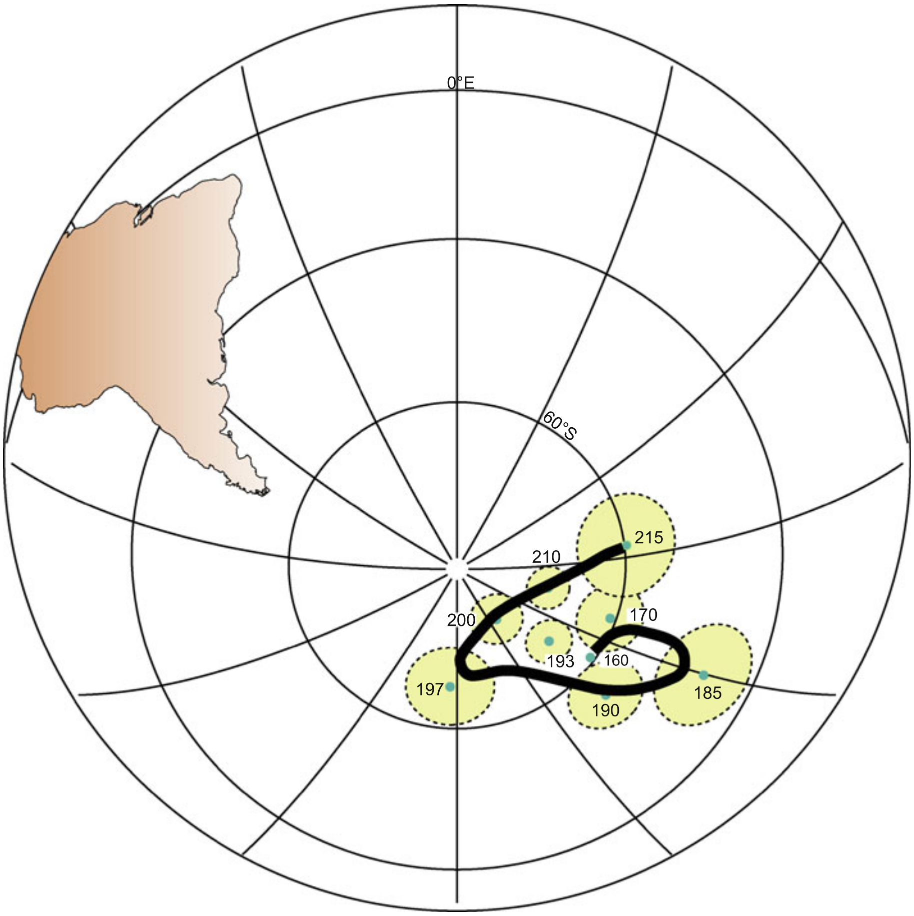


Fig. 5 Pangea's TPW path with corresponding 95 % confidence intervals. Two rotations were performed, the first to move continents and PP to South America and the other to move them for Morgan's (1983) grid of HS, so that PP (=palaeorotation axis) become referenced to the mantle. Had there not been TPW, all PP would have clustered around the geographic pole (GP). Between ~197 and ~185 Ma, there appears a c.45° shift in pole positions over 12 Ma, yielding a minimum angular change of 4° Ma^{-1}

Table 5 Magnitudes of TPW, representing the separation at successive ages between the palaeomagnetic poles and geographic pole

Time (Ma)	Lat° S	Long° E	Ang
160	0	217.6	29.1
170	0	202.0	28.9
185	0	210.3	49.9
190	0	224.8	36.0
193	0	221.3	21.2
197	0	273.2	21.9
200	0	233.6	11.5
210–205	0	194.1	16.5
215	0	175.8	30.4

The greatest angular values occur at 215 and 185 Ma

study, we employed the widely accepted use of HS. Thus, if the motion of, for example, South America can be established in relation with the grid of HS, all other plates can be put together within this frame after applying the corresponding kinematic model (Table 2). Therefore, by combining relative motions of the plates, their motions relative to the hotspots, and palaeomagnetic data that indicate the ancient position of the geomagnetic pole (palaeopole) for a specific locality and time, we can achieve palaeolatitudinally and palaeolongitudinally controlled or “absolute” palaeoreconstructions.

Accordingly, to achieve palaeoreconstructions in Figs. 5 and 6, we first translated Eurasia, Africa and North America to South America and then rotated once again to compensate for the motion of South America in relation with the Atlantic Ocean hotspots (Morgan 1983). Only five scenarios are represented in this study (Figs. 5, 6): (1) Late Triassic–Sinemurian, (2) Late Sinemurian–Early Pliensbachian, (3) Pliensbachian–Toarcian, (4) Middle Jurassic and (5) Late Jurassic. For rotations and figures, we used the GMAP software (Torsvik and Smethurst 1999).

According to our results, during the Late Triassic (215 Ma), Pangea would have been located at its southernmost position. From that time until the Sinemurian (200 Ma), the supercontinent rotated CCW while moving slowly to the north (Fig. 6). Subsequently by the end of Sinemurian, the CCW rotation ceased and at 197 Ma, Pangea commenced a CW rotation of c. 50° for the case of South America but at higher speeds (c. 4° Ma^{-1}). By the Pliensbachian (185 Ma, Fig. 6), Pangea reached its northernmost position, and due to the CW rotation, North America moved towards the north while Europe did it towards the south. At the end of the Early Jurassic (c. 180 Ma), Pangea moved back to the south and occupied similar present-day latitudes by the Middle and Late Jurassic (170 Ma) (Fig. 7).

Palaeoclimatic proxies

Given that latitude is one of the main variables that affects climate, it is possible to correlate palaeomagnetic with palaeoclimatic data derived from fossils having a geographic distribution limited to certain climatic regions. Far from yielding a very quantitative correlation, a qualitative concordance between the results of completely different methodologies is a convincing argument (Lanza and Meloni 2006). In this study, we analyse data derived from the geological and palaeobiogeographic records that could bring light to the palaeoclimate inferred for the Jurassic. The goal is to confront these palaeoclimatic proxies with the palaeolatitudes we got in the northern and southern hemispheres.

Marine invertebrates

Bivalves are considered to be very sensitive to water temperatures. In the Southern Hemisphere, during the Hettangian–Sinemurian (~200 Ma), the boundary between the South Pacific-high latitudes and Tethyan-low latitudes-Realms was located in northern Chile (Damborenea 2001, 2002), coinciding with the time when the supercontinent was in its southernmost position (Fig. 6). Throughout the Early Jurassic, the same boundary shifted to the south (Figs. 6, 7) and by the Toarcian while the continent moved to the north, high-latitude bivalves became restricted to southernmost South America (Damborenea 2001, 2002). During the late Early Jurassic in the Northern Hemisphere, the boundary between the Boreal and the Tethyan realms shifted to the north (Figs. 6, 7) while Eurasia was rotating CW and moving to the south (Liu et al. 1998). The Pliensbachian also marked the first expansion of colonial corals (warm water temperatures) in west-central Argentina. Dinoflagellates from the Northern Hemisphere in the upper Triassic indicate that the Southern Alps were located at low latitudes (Fig. 6), whereas during the upper Sinemurian to lower upper Pliensbachian, they mark warm and humid conditions in Europe (van de Schootbrugge et al. 2005). During the upper Pliensbachian (Fig. 6), dinoflagellates evidence the influx of cool high-latitude waters onto the northwest European shelf and a decrease in the temperature of 6°–10 °C, when the continent reached its northernmost position (van de Schootbrugge et al. 2005). Meanwhile in the Siberian Arctic, the Late Triassic and beginning of the Jurassic was characterised by warm and humid climate (Zakharov 1992). Significant cooling events took place at the end of the Pliensbachian and the beginning of the Middle Jurassic (Fig. 7), separated by a climatic maximum in the Early Toarcian (Early Jurassic) (Zakharov 1992). The drop recorded in the Pliensbachian–Toarcian boundary in

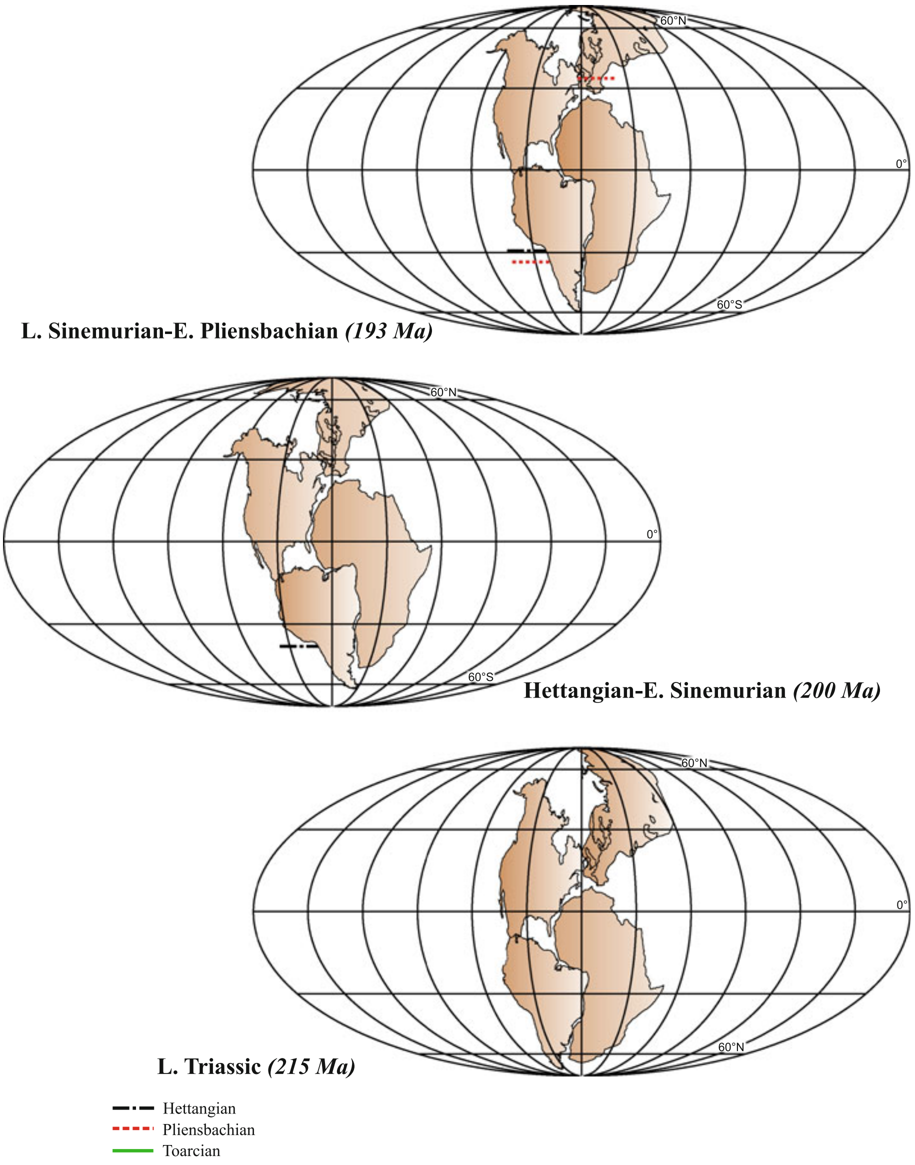
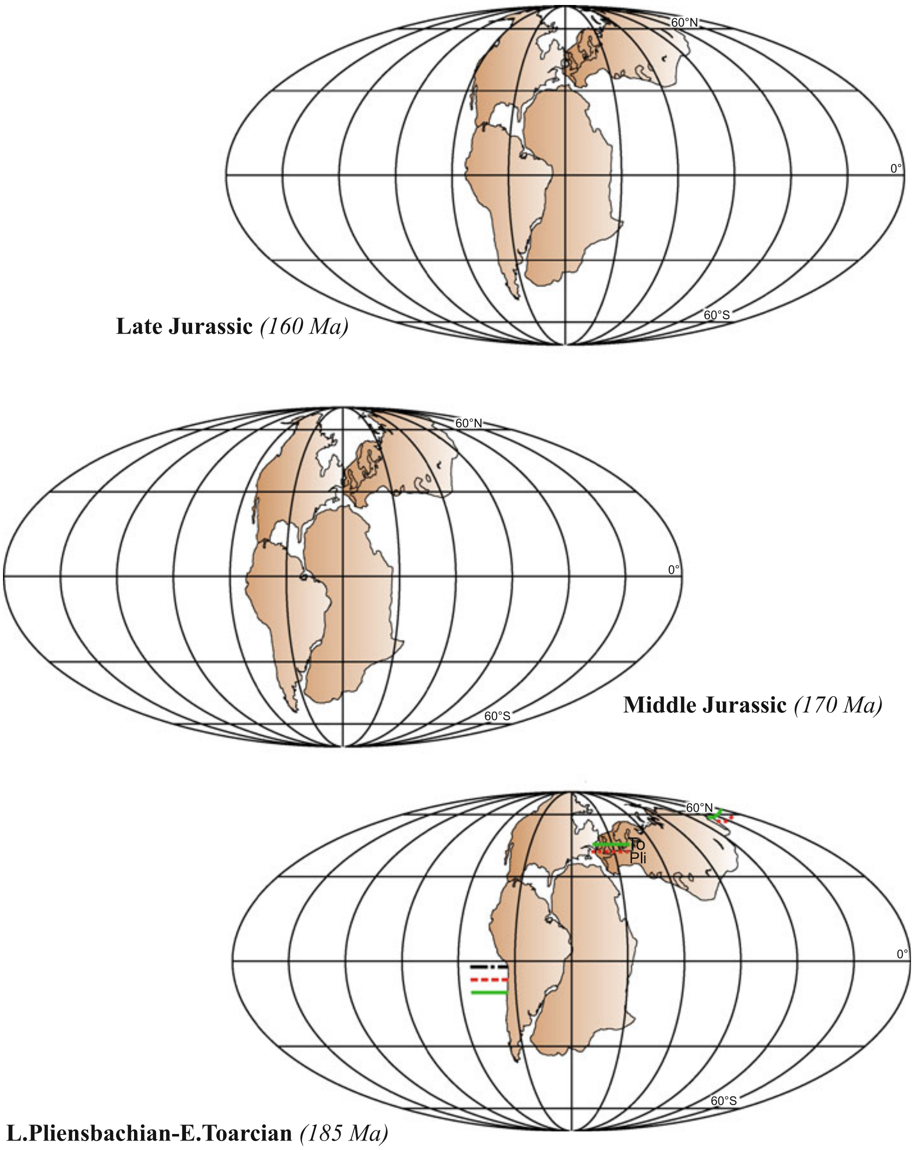


Fig. 6 “Absolute” palaeogeographical reconstructions of crude Pangea for the Early Jurassic. During the Late Triassic–Early Sinemurian, Pangea was placed at its southernmost position. At this time, the boundary – *dashed-dotted line* – between the South Pacific (high latitudes) and Tethyan (low latitudes) realms of bivalves was located in northern Chile (Damborenea 2001, 2002). Subsequently and throughout the Early Jurassic, Pangea, moved northward and rotated CW, until the Late Pliensbachian–Early Toarcian when the supercontinent reached the northernmost position

Europe also took place in the Arctic and was the likely cause of the significant turnover registered in Boreal marine invertebrates such as ammonites, ostracodes, foraminifers and particularly bivalves at that time. The restoration in the biota that followed during the late Early Toarcian was gradual: first, the Boreal-Arctic reappeared followed by the Tethyan taxa (Zakharov et al. 2006). Moreover, the Subtethyan and Low Boreal bivalves that dwelt the epicontinental seas northward of 68°N—present-day coordinates—in the terminal Pliensbachian migrated southward to the latitude 55°N at the beginning of the Toarcian, just to return back to North Siberia only in the Late Toarcian (Zakharov et al. 2006), when Eurasia started to move to the south (Figs. 6, 7). On the other hand during most of the Early Jurassic, ammonites of the Tethyan Realm kept moving to the north until the Late Pliensbachian, when the Boreal Realm commenced to shift southward replacing the Mediterranean fauna. Subsequently throughout the Late Pliensbachian and Earliest Toarcian, ammonites were affected by a major extinction that caused particularly the Tethyan species to disappear and be replaced in the Early Toarcian (Macchioni and Cecca 2002). During the Toarcian, belemnites from Spain, England and Germany indicate a rapid warming (van de Schootbrugge et al. 2005), the time when Eurasia would have started to move southward (Fig. 7). Palaeotemperatures measured in the Iberian platform show that during the uppermost Pliensbachian Spinatum Zone were of about 12 °C, which is considered low (Fig. 7) for a palaeotitude for Central Spain of about 35° (Osete et al. 2000). Subsequently during the Tenuicostatum to Bifrons Zone in the Toarcian, water temperatures increased 8 °C in this part of Europe (Gómez and Arias 2010).



Late Jurassic *(160 Ma)*

Middle Jurassic *(170 Ma)*

L.Pliensbachian-E.Toarcian *(185 Ma)*

Fig. 7 During this uppermost Pliensbachian–lowermost Toarcian time, the boundary between realms—*dotted line*—kept shifting towards the south until in the Early Toarcian—*solid line*; high-latitude bivalves became restricted to the southern extreme of the continent. By the end of the Early Jurassic, the continent ceased to rotate and started to move southward again, reaching similar present-day latitudes

Palaeoflora

In the Southern Hemisphere, Volkheimer et al. (2008) record that the content of the warm temperatures pollen *Classopollis* in the Neuquén Basin in west-central Argentina was not greater than 60 % during the Sinemurian–Early Pliensbachian. At this time, the Neuquén basin, presently at c. 37°S, was located at c. 50°S (Fig. 6). Conversely, in the Late Pliensbachian–Early Toarcian, the pollen *Classopollis* increased to 91–99 %. By this time, also the first appearance of new group of Araucariaceae (*Callialasporites* spp.) indicates a climatic amelioration (Volkheimer and Quattrocchio 1981). This time coincides with the recorded northernmost position of the Neuquén basin-around 25°S (Figs. 6, 7). Meanwhile in the Northern Hemisphere, a type of wood known as *Xenoxylon* that characterised wetter and cooler climate conditions and was widespread in Western Europe attained two main stages of maximum occurrence, the first during the Late Pliensbachian–Early Toarcian (Philippe and Thevenard 1996). In the Siberian Arctic, the cooling event at the end of the Late Pliensbachian was also recorded from spores. Like in the case of the Southern Hemisphere, the continent at this time was located at higher palaeolatitudes (Figs. 6, 7).

Vertebrates

In the central southern Andes in Argentina, abundant marine crocodiles, turtles and frogs have been reported. Although the interpretation of vertebrates as reliable palaeoclimatic proxies should be handled with some caution, they seem to indicate rather warm waters during the Middle and Late Jurassic (Volkheimer et al. 2008 and References therein).

Geology

During the lowermost Jurassic in the Southern Hemisphere, cool conditions prevailed. This primary interpretation is based on the fact that carbonates were absent, whereas siliciclastic deposits were dominant (e.g. Spalletti et al. 1999; Gómez-Pérez 2003). During this time, it is interpreted that the continent was located at its southernmost position (Fig. 6). Conversely, by the Late Early to Middle Jurassic, climate became humid, as indicated by the frequent occurrence of coal and well-preserved flora (Volkheimer et al. 2008). Meanwhile in the Northern Hemisphere, a major change in the sedimentological record affected the Tethyan sections at the Pliensbachian–Toarcian boundary, leading the limestone-dominated deposits to be replaced by marls, as the result of a major crisis in Europe that affected the carbonate platforms. This has been attributed to the cooling phase that overtook at the Pliensbachian–Toarcian boundary and supports the hypothesis of icecap development at high latitudes (Suan et al. 2006 and References therein). The Pliensbachian–Toarcian boundary corresponds to the time when Pangea situated at its northernmost position (Fig. 7).

Conclusions

We present a master APW path for the Jurassic Pangea that was constructed using equally selected Eurasian, North American, African and South American high quality poles. When observed from South America, the resultant path reveals a distinctive W–E track between-Late Triassic to lowermost Jurassic, followed by a SE–NW track from Sinemurian to Pliensbachian, defining a cusp at ~197 Ma. The lowermost Early Jurassic to late Early Jurassic (197–185 Ma) segment reveals a c. 50° shift in the pole positions during this time, and a minimum angular change of poles of approximately 4° Ma^{-1}. This path clearly shows that Pangea would have been subjected to considerable CW rotation between the Sinemurian (~197 Ma) and Pliensbachian (~185 Ma), while it moved to the north.

The significant motion of the supercontinent is interpreted to be primarily caused by TPW defined as the drift of the spin axis with respect to entire solid Earth, rather than other type of phenomenon such as lithospheric motion or an artefact produced by non-dipole components. Our interpretation is mainly based from palaeolatitude plots in which we calculate palaeolatitudes from the master path (=palaeomagnetic reference frame) on the one hand, and hotspots (=mantle reference frame) on the other hand. Accordingly, a remarkable discrepancy between both palaeolatitudes sets after 200 Ma indicates that these reference frames moved with respect to each other. This is in our opinion, a solid evidence for the occurrence of TPW during that time. A TPW path was calculated and revealed that after ~197 Ma poles displaced approximately 45° over a 12-Ma period meaning a minimum angular change of approximately 4° Ma^{-1} (0.4 m a^{-1}). Therefore, we conclude that the c. 50° rotation is the result of the motion of the lithosphere AND the mantle.

Estimated palaeolatitudes are in good agreement with palaeoclimatic proxies derived from marine invertebrates, palaeoflora, geological data, and water palaeotemperatures, having a geographic distribution limited to certain climatic regions. The good correlation between the two methodologies clearly argues for our results.

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