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

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ABSTRACT

The Gondwana megacontinent was composed of different domains separated by self-lubricated weak lithospheric zones, two of which could have extended into Laurasia. Displacement vectors determined through three consecutive paleomagnetism-constrained paleogeographic reconstructions (Early Pennsylvanian–early Guadalupian, ca. 320–270 Ma; late Guadalupian–Middle Triassic, ca. 260–240 Ma; and Late Triassic–early Late Jurassic, ca. 230–160 Ma) show similar orientations to coeval tectonic stresses along Gondwana. Triggered by slab pull at the northern subduction margin of the Paleotethys Ocean, differential displacements between the Gondwana domains caused localized deformation along their borders, reactivating old weak lithospheric zones (e.g., Ventana fold belt south of Buenos Aries province, Argentina; basins such as Cuvette in central Africa; and Neuquén on the Pacific margin of Gondwana). We propose that the wide extent of these structures was possible due to the transmission of mantle toroidal flow induced by strike-slip movements along these focused self-lubricated weak lithospheric zones, along with the northward drift of Pangea. These processes occurred simultaneously with a major mantle reorganization from a huge cold downwelling to a hot upwelling event caused by thermal energy storage beneath Pangea.

INTRODUCTION

The supercontinent Pangea formed during the Mississippian (Scotese, 2001; Stampfli et al., 2002, 2013; Nance, 2008) due to a powerful slab pull that dragged the megacontinent of Gondwana to collide against Laurasia (e.g., Collins, 2003). The assembly led to the closure of the Rheic Ocean, leaving a vast open sea to the east of the present Iberian Peninsula. This open sea evolved over time, receiving different names (e.g., Paleotethys and Neotethys Oceans; Sengor, 1985) and retaining a large subduction zone on its northern margin. It is known that the force exerted by the Neotethys slab pull must have been strong enough to cause the drift of India from Gondwana to Asia between the Late Cretaceous and the early Eocene at an amazing velocity of 15–20 cm/yr (Patriat and Achache, 1984; Kumar et al., 2007). In a geodynamic context, the global significance of the Neotethys Ocean is highlighted by Keppie (2015) who linked its closure with the opening of the early Atlantic Ocean.

A provocative question arises about what happened with such powerful slab pull during the time between the closure of the Rheic Ocean and the drift of India. A significant tectonic event occurred at the beginning of this time interval and caused the Iberian-Biscay orocline, which Gutiérrez-Alonso et al. (2008) related to Pangea "self-subduction". These authors considered that this orocline resulted from the slab pull of Paleotethys Ocean that changed the stress-strain patterns of the entire supercontinent. In this paper we explore other large Gondwana tectonic features developed between the Early Pennsylvanian (ca. 320 Ma) and the early Late Jurassic (ca. 160 Ma) that might also represent Paleotethys slab-pull footprints, including the Ventana fold belt and the opening of the Neuquén Basin in Argentina.

In this particular time span, the global mantle convection evolved from a pattern with a single upwelling zone below the seafloor of the Panthalassan Ocean, to another with two, the newest one being below the Pangea lithosphere (e.g., Zhong et al., 2007; Zhong and Rudolph, 2015). During the initial evolutionary stage, poloidal flow (i.e., source-to-sink flow) likely predominated on a global scale as Pangea was assembled over a downwelling hemisphere. During the second stage, the supercontinent induced an upwelling system that led to the development of large igneous provinces, widespread rifting, and final Pangea breakup. Concurrently with this global mantle convection evolution, conditions of strong slab pull occurred on the northern margin of the Paleotethys Ocean, evidenced in the accelerated plate motion and attendant subduction leading to the closure of the Rheic Ocean.

Gondwana was composed by distinct domains (cratons or terranes) of different lithospheric thickness separated by old suture zones, so its evolution had to be strongly conditioned by this heterogeneity (e.g., Unternehr et al., 1988; Stampfli et al., 2013). The distinctive response of these different lithospheric domains to the stress field that emerged from these global-scale tectonic processes during the drift of Pangea should have resulted in velocity gradients between adjacent domains. These gradients were accommodated by inherited deformable zones fringing the lithospheric domains.

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The weak zones where tectonic processes concentrated may have acted as self-lubricated zones in the sense of Bercovici (2003) and Bercovici et al. (2015), that is, zones where movements and deformation are facilitated through hydro-fracturing, pore-pressure reduction of friction, and simple lubrication, leading to strike-slip shearing and toroidal motions in the underlying asthenosphere (e.g., Bercovici et al., 2000; Bercovici, 2003).

Based on paleomagnetically constrained paleogeographic reconstructions between the Early to Middle Pennsylvanian (323–310 Ma) and the early Late Jurassic (160 Ma), and the premise of weak lithospheric intra-Gondwana zones accommodating velocity gradients of Gondwana rigid blocks, we depict a kinematic evolution consistent with the coexistence of Paleotethys slab pull and localized deformation along the self-lubricated weak zones. Furthermore, we propose that plate tectonics left its imprint on the toroidal and poloidal flow imposed to the underlying convecting mantle, which in turn is a guide to the movement of drifting plates.

GEODYNAMIC PREMISES: PALEOMAGNETISM-CONSTRAINED PALEOGEOGRAPHIC RECONSTRUCTIONS AND INHERITED INTRA-GONDWANA WEAK ZONES

To calculate the motion of Gondwana between the Early Pennsylvanian and the early Late Jurassic, absolute reconstructions of Gondwana (Fig. 1) were produced using paleomagnetic poles (see Supplemental Material[1]) and assuming 0° longitudinal motion of Africa (Burke and Torsvik, 2004; Torsvik et al., 2008a, 2008b). Instead of working with arbitrary time windows to construct apparent polar wander paths, we used three discrete ages clearly identified by the distribution of paleomagnetic poles (PPs) belonging to the different plates forming Gondwana. We transferred the PPs to present geographical coordinates of Africa using the classical reconstruction parameters proposed by Lawver and Scotese (1987).

It is well known that classical Pangea configurations fail to produce an acceptable fit of paleomagnetic poles, particularly in pre–Late Triassic times (see

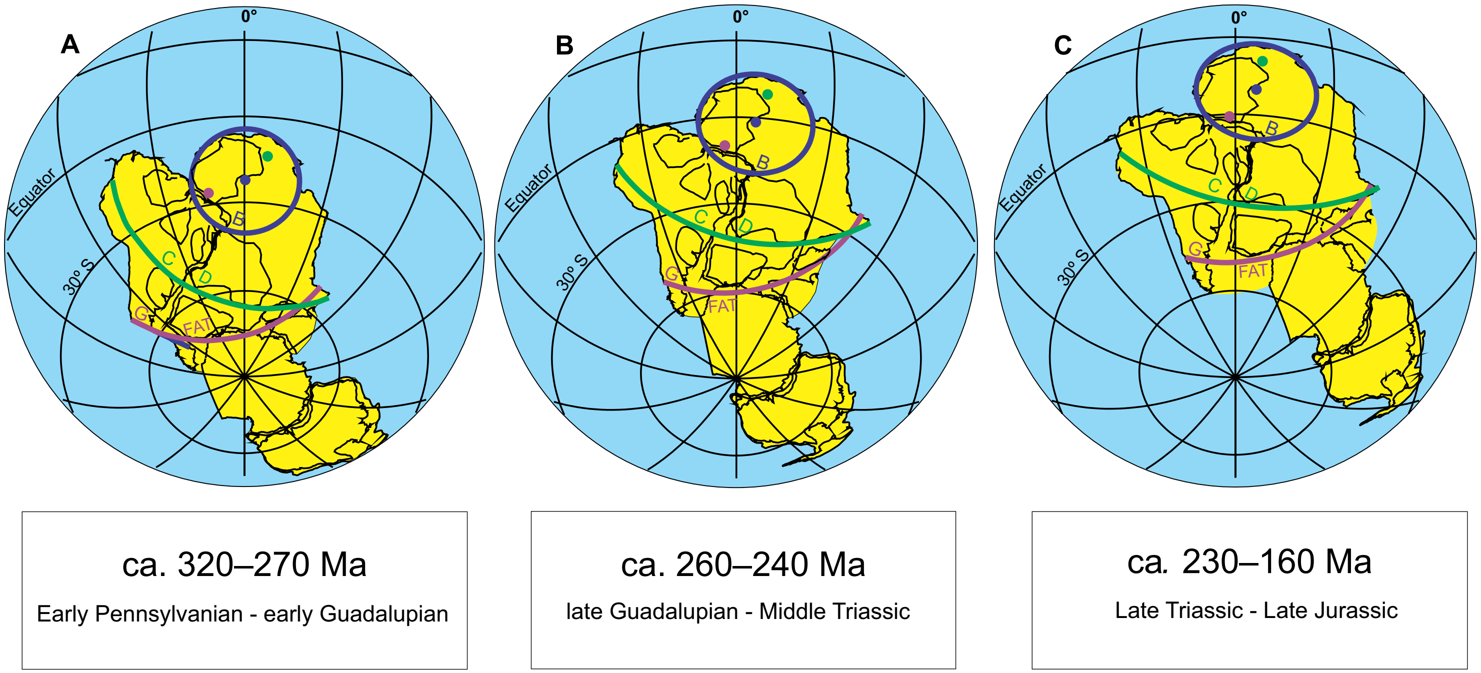
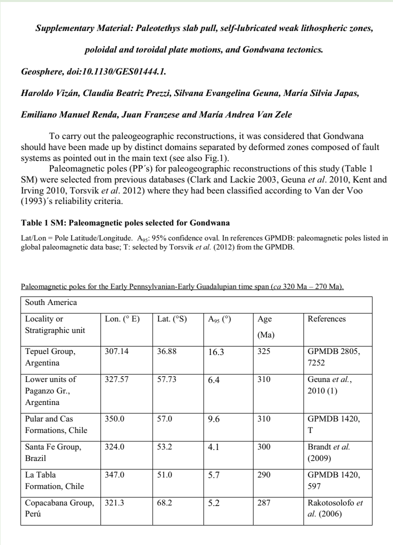


Figure 1. Absolute paleoreconstructions (latitudinal and longitudinal) of Gondwana for a time span between the Early Pennsylvanian and the early Late Jurassic. (A) Early Pennsylvanian–early Guadalupian (ca. 320–270 Ma). (B) Late Guadalupian–Middle Triassic (ca. 260–240 Ma). (C) Late Triassic–early Late Jurassic (ca. 230–160 Ma). Colored arcs of circumferences correspond to deformation belts and their centers in northwest Africa: purple—belt formed by the Gastre fault system (G) and the boundary between Africa-Madagascar and Antarctica-India (FAT—Falkland [Malvinas]–East Africa–Tethys shear system); green—belt formed by the Guapiara-Curitiba fault zone (C) and Damara mobile belt (D); blue—belt that includes the Benue Trough (B) and the boundary between northwest Africa and Laurentia in Pangea reconstructions.



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)

[1]Supplemental Material. Paleomagnetic analysis and paleoreconstructions of Pangea for three consecutive timespans. Please visit http://doi.org/10.1130/GES01444.S1 or the full-text article on www.gsapubs.org to view the Supplemental Material.

Domeier et al. [2012] for a review). This is especially true when considering geometrical rigidity of the crust and lithosphere; alternative reconstructions have tried to incorporate intra-plate deformation along focused belts located between rigid blocks (e.g., Pindell and Dewey, 1982; Unternehr et al., 1988; Reeves et al., 2004).

Some regional intra-Gondwana shear zones remained active during the Early Pennsylvanian–early Late Jurassic (e.g., Visser and Praekelt, 1996; Reeves et al., 2004) and were interpreted as transcontinental deformation belts along self-lubricated weak lithospheric zones (Fig. 1):

1. Gastre fault system and its continuation through the Africa–eastern Antarctica and Madagascar–India boundaries: The existence of a transcontinental shear zone in South America (more precisely in southern Patagonia) was proposed by Rapela et al. (1991) and Rapela and Pankhurst (1992), involving dextral strike-slip movements ("Gastre fault system") prior to the opening of the South Atlantic Ocean (see also Macdonald et al., 2003). While these movements were probably minor during the Jurassic, the Gastre fault system could have had intense activity during the late Paleozoic (von Gosen and Loske, 2004; Zaffarana et al., 2010). Storey et al. (1992) suggested that this fault system formed part of a major belt that extended eastward mainly along the border between Africa and East Antarctica. Visser and Praekelt (1996) considered this intra-Gondwana boundary to be tectonically active during the late Paleozoic. They interpreted lateral lithospheric movements along this weak zone within Gondwana and referred to this belt as the "Falkland (Malvinas)–East Africa–Tethys shear system".
2. Guapiara-Curitiba fault zone and Damara mobile belt: Another significant shear system includes the Damara mobile belt in southern Africa (see Reeves et al., 2004) and the Guapiara-Curitiba fault zone in South America (see Unternehr et al., 1988) located along a circular arc centered in northwest Africa (Vizán et al., 2015). Both belt segments were active during the late Paleozoic–early Mesozoic (Reeves et al., 2004; Milani and De Wit, 2008).
3. West Africa–Congo and West Africa–Laurentia boundaries: Another deformation zone is defined by the circumference arc that separates the West African craton from the Congo craton and goes through the deformation belt that includes the Benue Trough (Pindell and Dewey, 1982; Maurin and Guiraud, 1993). This arc also defines the limit between Laurentia (North America and Greenland) and northwest Africa in Pangea reconstructions (e.g., Scotese, 2001).

The selected transcontinental deformation belts nearly follow small circles whose centers are clustered in northwestern Africa (Fig. 1). In order to match the paleomagnetic poles from different Gondwana continents, small additional rotations were applied to PPs around Euler poles located in those small circle centers (see the Supplemental Material [footnote 1]). The acceptable fit was obtained through movements of Gondwana domains (subplates) along the proposed deformation belts while maintaining the overall appearance of our reconstructed plates relative to those published by other authors (Scotese and McKerrow, 1990; Golonka et al., 1994; Scotese, 2001; Tomezzoli, 2009). Therefore, the movement of Gondwana is similarly depicted regardless of the paleomagnetic pole selection, providing that certain minimum reliability criteria are met (see the Supplemental Material [footnote 1]).

PALEOGEOGRAPHIC RECONSTRUCTIONS AND DISPLACEMENT OF GONDWANA DOMAINS

The ages of available PPs permitted reconstructions for three time windows: Early Pennsylvanian–early Guadalupian (C-P [Carboniferous–Permian], between ca. 320 Ma and 270 Ma; Fig. 1A), late Guadalupian–Middle Triassic (P-Tr, between ca. 260 Ma and 240 Ma; Fig. 1B), and Late Triassic–early Late Jurassic (Tr-J, between ca. 230 Ma and 160 Ma; Fig. 1C).

From reconstructions in Figure 1, displacement vectors were calculated for selected locations in Gondwana. Figure 2A shows the displacement vectors for the first time span (from C-P to P-Tr), traced over the Gondwana C-P reconstruction. A difference arises between the displacement vectors of South America and Africa (West Gondwana) and the rest of Gondwana (East Gondwana: India, Australia, eastern Antarctica). While, in general, vectors of West Gondwana clearly indicate a northeastward drift, those corresponding to Australia and eastern Antarctica indicate practically a pure northward movement. Meanwhile the vectors of India indicate a north-northeastward drift. Remarkably, southern Patagonia (south of the Gastre fault system) shows a drift to the north like Australia and eastern Antarctica as though they were part of the same lithospheric domain, at least until about the late Guadalupian (260 Ma).

On the other hand, the displacement vectors calculated for the second time span (P-Tr to Tr-J; Fig. 2B) for West Gondwana are, besides their different orientation, of lesser magnitude than those corresponding to East Gondwana.

To better visualize the relative motions between plates, we decided to decompose the total vector displacement, removing the northward movement as a plate tectonic drift common to all plates. We considered the northward movement of the Northwest African craton as representative of this component, and used it as a reference (black vectors in Figs. 3A and 3B) against which the displacements vectors of the other Gondwana domains were compared. Then we isolated the vectors that differ from that reference (vectors in black in Fig. 3; compare with Fig. 2) by using rigid rotation calculations. The resulting displacement vectors (RVs) so calculated correspond to counterclockwise rotational movements.

The displacement of South America and Africa domains parallel to the deformation belts is higher for the first time span (C-P to P-Tr; Fig. 3A) than for the second time span (P-Tr to Tr-J; Fig. 3B). Conversely, India, Australia, and eastern Antarctica RVs do not contain movements parallel to the deformation belts during the first time span, but are significant during the second one (Figs. 3A, 3B).

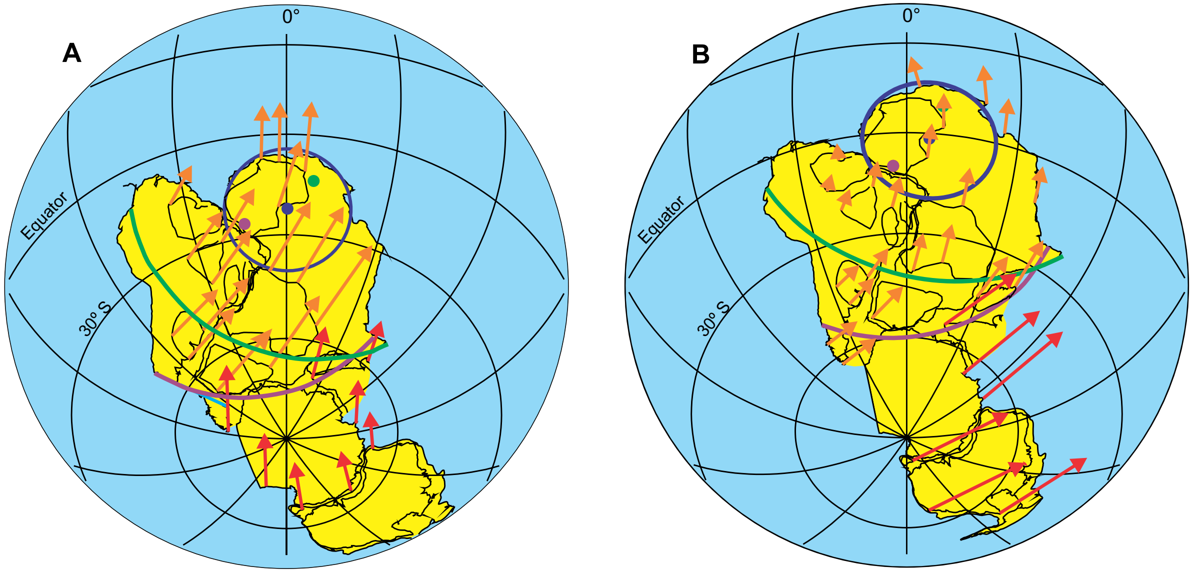

Figure 2. Displacement vectors calculated on the basis of absolute paleoreconstructions. (A) Paleoreconstruction of Gondwana for the Early Pennsylvanian–Early Guadalupian with the displacement vectors calculated between the Early Pennsylvanian–early Guadalupian and the late Guadalupian–Middle Triassic. (B) Paleoreconstruction of Gondwana for the late Guadalupian–Middle Triassic with the displacement vectors calculated between the late Guadalupian–Middle Triassic and the Late Triassic–early Late Jurassic. Note that in both panels there is a significant difference between the displacement vectors of South America–Africa (in orange) and East Gondwana (in red). See Figure 1 for explanation of the colored arcs and points indicating deformation belts and their associated arc center points.

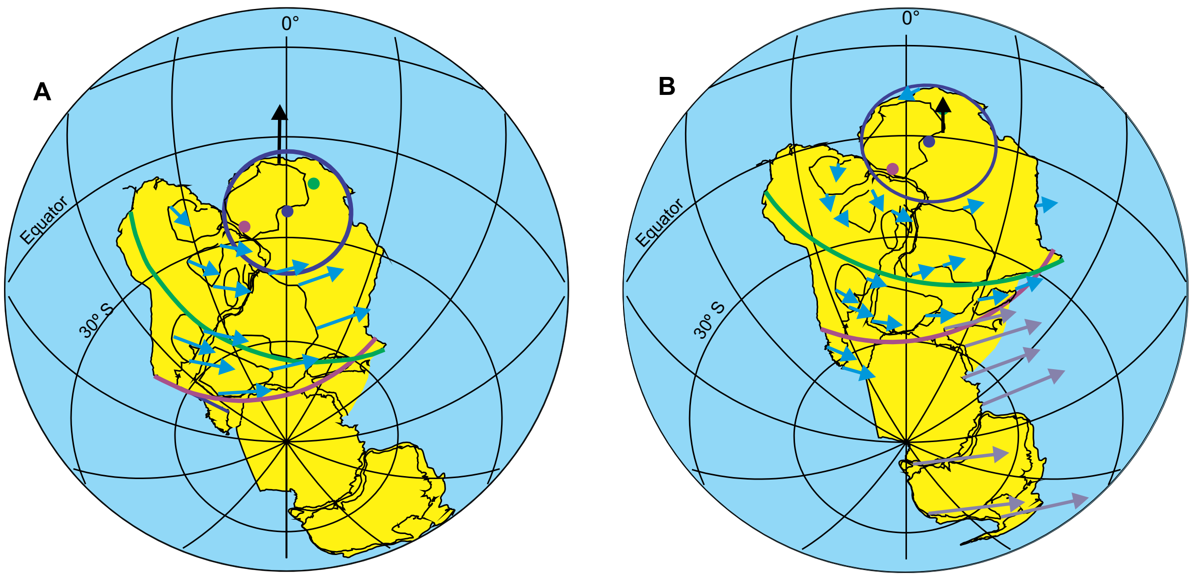

Figure 3. Vector components resulting from the decomposition of the displacement vectors of Figure 2. The vector components indicate two movements for Gondwana domains at different times. In both reconstructions, a south-north displacement is pointed out with black arrows. (A) Gondwana for the Early Pennsylvanian–early Guadalupian with decomposed displacement vectors that indicate a counterclockwise rotation of South America (excluding southern Patagonia) and Africa between the Early Pennsylvanian–early Guadalupian and the late Guadalupian–Middle Triassic. The displacements of Australia, Antarctica, and India were mainly south-north. (B) Gondwana for the late Guadalupian–Middle Triassic with decomposed displacement vectors that indicate a counterclockwise rotation. Note the difference between vectors corresponding to different lithospheric domains (see text for further explanation). See Figure 1 for explanation of the colored arcs and points indicating deformation belts and their associated arc center points.

DISCUSSION

The RVs indicate that different Gondwana domains underwent counterclockwise rotations around Pangea centers located in northwestern Africa (Fig. 4) that were used as Euler poles for our paleogeographic reconstructions. The arcs of circumferences around these centers are coincident with the location of Gondwana deformation belts; we will discuss next how these belts could be extended into Laurasia by segmenting the Paleotethys Ocean floor.

Extent of Transcontinental Deformation Belts

The deformation belt that includes the circular arc of the Gastre fault system and the boundary between eastern Africa–Madagascar and eastern Antarctica–India would continue along the Arabian deformation belt where the "Hercynian orogeny" of Carboniferous age has been proposed (Faqira et al., 2009). Further, this intra-Gondwana deformational belt is projected into Laurasia through the Trans-European suture zone (Winchester et al., 2002) which contains the "Tornquist Line" of Arthaud and Matte (1977). We propose that these shear belts correspond to a transform fault that segmented the Paleotethys oceanic floor and defined the boundaries between different lithospheric domains of Pangea (Fig. 4).

As mentioned above, Unternehr et al. (1988) proposed the existence of an intra-plate boundary in South America extending from the Cochabamba bend in the Andes to the Río Grande rise (Guapiara-Curitiba fault zone; Fig. 1). Based on a subsurface study of the upper Paleozoic glaciogenic infill of the Paraná Basin, Eyles and Eyles (1993) confirmed this proposal. We consider that this intra-plate boundary continues in Africa along the Damara mobile belt, where deep lithospheric faults were identified running through Namibia, northwestern Botswana, Zambia, and northern Tanzania and reaching the present East African coast (the Southern Trans-Africa shear system of Jelsma et al. [2004]). According to Reeves et al. (2004), this shear system (between the Congo and Kalahari cratons) extends into Laurasia along the Ural Mountains, segmenting the Paleotethys oceanic floor as a transform fault. In connection, Hetzel and Glodny (2002) recognized the presence of a crustal-scale orogen-parallel strike-slip fault zone in the Middle Urals (see also Arthaud and Matte, 1977).

In our proposed scheme, these transform faults were activated by Paleotethys slab pull after the amalgamation of Pangea into one supercontinent. A strong slab pull could be expected when subducted lithosphere reached the lower mantle, which in turn would reorganize mantle flow into a wider cell localizing stresses at greater distances from the trench than when subduction was upper-mantle confined (Dal Zilio et al., 2017). The suture between Gondwana and Laurasia (Fig. 4) indicates the location of the subduction zone whose slab pull caused the formation of Pangea and the closure of the Rheic Ocean. The Paleotethys Ocean, located to the east, was the result of the amalgamation of northwestern Gondwana with Laurentia. This ocean had a triangular form with an apex located between the Iberian Peninsula and northwest Africa. The slab pull of the subduction zone of this ocean was responsible for the formation of the Iberian-Cantabrian orocline (Gutiérrez-Alonso et al., 2008). Moreover, this slab pull was transferred into Gondwana domains that moved, reducing the area of the Paleotethys Ocean. Because Gondwana domains were delimited by self-lubricated weak lithospheric zones, the latter suffered differential movements, producing the oceanic transform faults (with the same trend as the continental belts) segmenting the relatively thin floor of the Paleotethys.

Of special geodynamic interest is Cimmeria (Fig. 4). It was composed by several microcontinents rather than constituting a single and extended belt along the northern margin of Gondwana that bordered the southern Paleotethys (e.g., Sengor, 1985; Scotese, 2001; Collins, 2003). This belt of microcontinents separated from Gondwana by the Paleotethys Ocean migrated north and accreted to the southern margin of Eurasia.

According to Stampfli et al. (2001), western Cimmeria consisted of microcontinents that extended from northeastern Africa through the northern Arabian margin to northwestern India. Eastern Cimmeria was composed of a collage of small blocks located along the larger India-Australian margin (e.g., Metcalfe, 2011). The evolution of the dismemberment of Cimmeria microcontinents from the margin of Gondwana and their accretion to the southern Eurasian border is difficult to determine conclusively due to overprints of subsequent tectonic processes (Manafi et al., 2013). In this paper, we infer that they could have accreted to the Eurasian margin in concert with a possible migration of the Paleotethys subduction from west to east. In the Alpine sector of the Mediterranean Sea, a calc-alkaline magmatism was widely distributed during the Pennsylvanian, while in Austria and China, back-arc basins started to develop between the Middle and Late Triassic (Stampfli and Borel, 2002). Robertson (2012) interpreted that the Paleotethys Ocean began to close in Europe at the longitude of Libya during the late Paleozoic. According to Zulauf et al. (2014), the closure of this ocean in Greece occurred between the Middle and Late Triassic. Meanwhile, in the Caucasus, this closure was completed during the Late Triassic–Early Jurassic (Manafi et al., 2013). According to Metcalfe (2011), Cimmerian blocks rifted and separated from the northwestern Australian margin in the Late Jurassic–Early Cretaceous, moved northwards, and accreted to southeastern Sundaland (Southeast Asia) by the Late Cretaceous. As will be discussed later, we propose that this progression in the translation of Cimmeria microcontinents and the closure of Paleotethys from west to east is also accompanied by successive deformational events along transcontinental shear zones caused by the Paleotethys subduction slab pull.

Geological Evidence for Relative Movements along Deformation Belts

The northeast displacement vectors calculated from the paleogeographic reconstructions record both a northward drift of the entire supercontinent and a movement parallel to the deformation belts. A correlation between regional stresses causing intra-plate deformation and relative plate motion has been previously proposed by other authors (e.g., Sbar and Sykes, 1973; Richardson et al., 1979; Amadei and Stephansson, 1997; Zoback and Zoback, 1980; Hurd

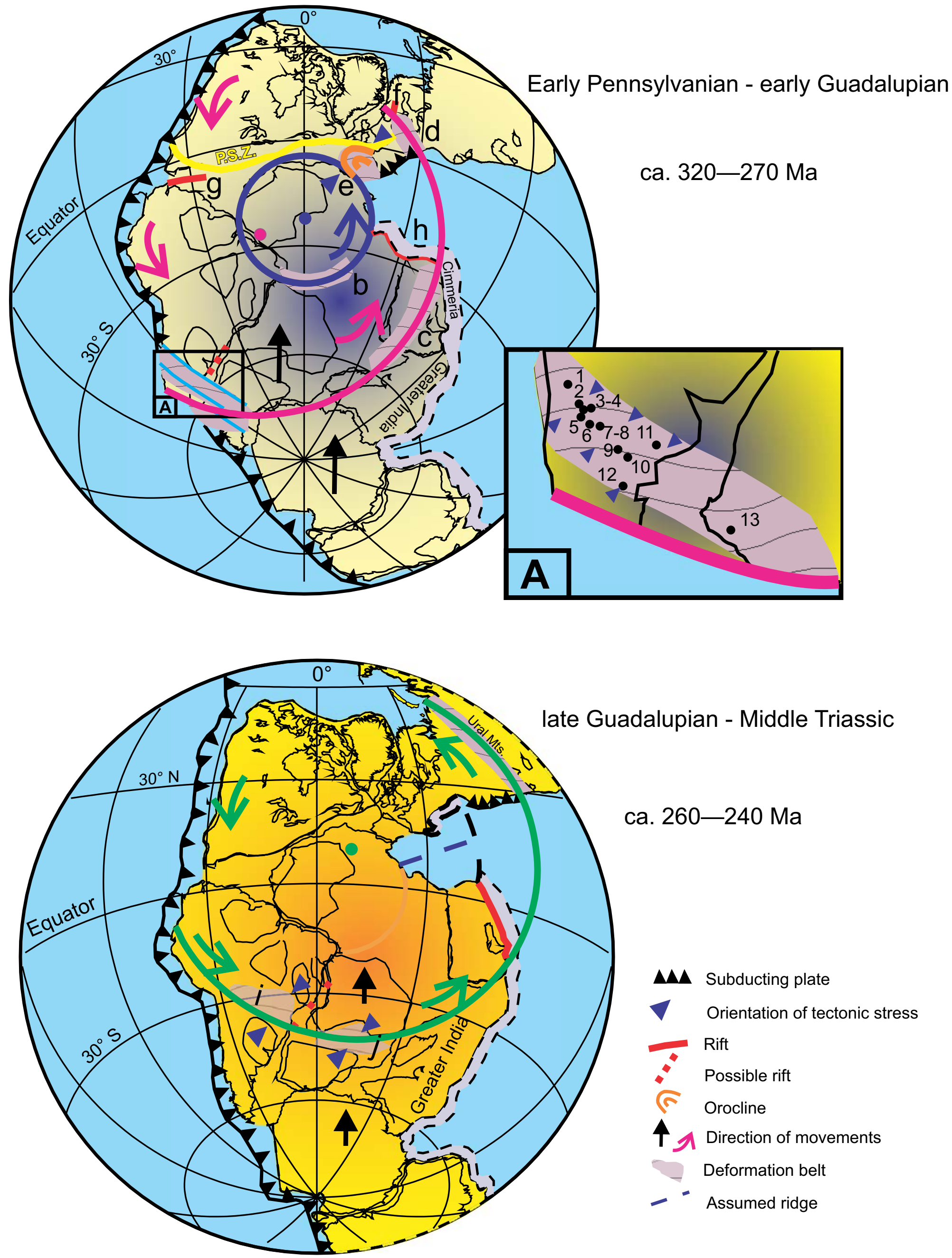

Figure 4. Displacement of different lithospheric domains of Pangea and main tectonic features in absolute reconstructions during the Early Pennsylvanian–early Guadalupian (blue shades are used to indicate that Pangea was assembled in a downwelling area of the mantle) and late Guadalupian–Middle Triassic (slight reddening indicates that the mantle beneath Pangea was changing to a zone of upwelling). Black arrows indicate northward movement of lithospheric domains of Pangea. Blue arrow indicates counterclockwise rotation of Northwest African craton. Pink arrows indicate counter-clockwise movement of Pangea domains between the deformation belts shown with blue and pink colors. Green arrows indicate the movements along the deformation belts along the green arc that includes Parana Basin, Cuvette Basin, and the shear zone deformation in Ural Mountains. Blue triangles in box A indicate direction of maximum compression. Points of different colors are the centers the arcs that contain the deformation belts. P.S.Z.—Pangea suture zone (yellow solid line). Localities with late Paleozoic–early Mesozoic deformation: A—"Samfrau Geosyncline" in South America and South Africa (particularly at [see inset]: 1—Alto Río Tunuyán; 2—Río Atuel; 3—El Imperial Formation; 4—Jaime Prats drill; 5—La Escondida; 6—Agua Escondida; 7—Lomas Negras; 8—Loma de los Guanacos; 9—Carapacha Basin; 10—Cerro de los Viejos; 11—Ventana fold belt; 12—Valcheta; 13—Cape fold belt); b—Benue; c—boundary between the Arabian Nubian craton and the belt of "Hercynian orogeny"; d—Trans-European suture zone; e—Iberian-Biscay orocline; f—Oslo Rift; g—terranes and/or microplates (Florida, Chiapas, Yucatan, Oaxaquia [in the latter there is evidence of extensional processes]); h—Cimmeria terranes; i—Paraná Basin; j—Cuvette Basin.

and Zoback, 2012). In other words, the stresses that affected the weakest areas would have similar orientations to the displacement vectors. In this regard, the following can be observed about displacement vectors and their relationship to local geological structures.

To analyze the tectonics of Gondwana during 320–160 Ma, we considered that Veevers (1989) proposed an epoch of radical change in the history of Pangea. This time (at 235 ± 5 Ma) was marked by the final coalescence of this supercontinent and its incipient dispersal together with the first major loss of the heat accumulated beneath its lithosphere (Veevers, 1989). We take this epoch as the boundary between two timespans with different tectonic regimes; the first involving two of our paleogeographic reconstructions ranging from 320 to 240 Ma and the second from 230 to 160 Ma (our third reconstruction).

First Time Span (between ca. 320 and 240 Ma)

During the first time span analyzed, calculated displacement vectors have a southwest-northeast direction (Fig. 2A), similar to the maximum stress axis orientations (in paleogeographic coordinates) identified in different localities (Fig. 4). During the late Lopingian–Early Triassic, the Cuvette Basin (Central Africa) resulted from a southwest-northeast major contractional deformation (Daly et al., 1992). Milani and De Wit (2008) considered that a maximum stress with southwest-northeast direction affected the cratonic interior of Gondwana, reactivating old basement structures beneath the Paraná Basin during the Guadalupian–Early Triassic time span. In Argentina, the stress regime that led to the deformation of the San Rafael block (Mendoza) during the late Paleozoic also had a south-southwest–north-northeast orientation in present-day coordinates (Kleiman and Japas, 2009), which becomes southwest-northeast in paleogeographic coordinates. This Paleozoic tectonic setting extends further south by analysis of the structures of Paleozoic rocks in Sierra Grande (Río Negro Province, Argentina) where Japas (2001) proposed a strain ellipsoid that corresponds to a south-southwest–north-northeast maximum principal stress. For the region from the North Patagonian Massif to the Chadileuvú block in La Pampa Province (Argentina), von Gosen (2003) proposed a southwest-northeast–directed maximum stress to explain the late Paleozoic deformation processes affecting different localities within the South American plate (Fig. 4).

Among the tectonic events analyzed, a special case is the formation of the Ventana fold belt (Sierras Australes of Buenos Aires Province, Argentina) and its South African counterpart, the Cape fold belt. Some authors suggested that the Ventana fold belt was caused by the amalgamation of an allochthonous or parautochthonous Patagonian block (e.g., Ramos, 1984, 2008; Rapalini, 2005; Tomezzoli, 2012; Pángaro and Ramos, 2012). Others have considered mechanisms that involve flat subduction along the western margin of Gondwana (e.g., Lock, 1980; Kleiman and Japas, 2009), transpressional processes between Patagonia and the rest of Gondwana possibly induced by oblique subduction in the proto-Pacific margin (Sellés-Martínez, 1989; Rossello et al., 1997; Gregori et al., 2008), or deformation due to stress transmission caused by the collision of a southern Patagonian block that would have involved the Deseado Massif (Pankhurst et al., 2006). Although the location of Patagonia with respect to Gondwana during the Paleozoic has been controversial, radiometric (Pankhurst et al., 2006, 2014; Uriz et al., 2010; Rapalini et al., 2013), paleomagnetic (e.g., Rapalini and Vilas, 1991), and paleontological data (González et al., 2011) indicate that the North Patagonian or Somuncura Massif (Argentina) was not an allochthonous block from the rest of Gondwana since at least the early Paleozoic.

The displacement vectors determined from our reconstructions closely parallel the direction of convergence determined for the Ventana fold belt (Japas, 1989, 2007; Cobbold et al.,1991; Rossello et al., 1997; von Gosen et al., 1990; Arzadún et al., 2016). This fold belt is located in a weak lithospheric zone along an arc that extends across South America, including localities that were deformed during the late Paleozoic (Fig. 4 inset).

Based on radiometric ages and the presence of growth folds, López-Gamundi et al. (2013) assigned an age of ca. 280 Ma to the syndepositional deformation of the Tunas Formation (the uppermost unit of the Paleozoic Ventana fold belt stratigraphic column) due to distal effects of the San Rafael orogenic phase (see Fig. 4 inset) bracketed between 280 and 265 Ma by Kleiman and Japas (2009). In other words, the age of the deformation of the Ventana fold belt is also consistent with our geodynamic and tectonic model.

Second Time Span (between ca. 230 and 160 Ma)

During the second time span, extensional tectonics leading to the formation of large igneous provinces (LIPs) took place. Figure 5 shows the location of the principal LIP eruptive centers in Gondwana (Torsvik et al., 2008b; Encarnación et al., 1996), reconstructed to their absolute position: Central Atlantic magmatic province (CAMP), Paraná-Etendeka-Angola, and Karoo–Ferrar–Lonco Trapial. They are distributed along segments of those arcs that depict the deformational belts discussed in this work, including the younger Paraná-Etendeka-Angola (134–132 Ma; Thiede and Vasconcelos, 2010; Rocha-Júnior et al., 2012).

Figure 6 illustrates the full extent of Mesozoic LIPs according to Eldhom and Coffin (2000), Pankhurst et al. (2000), Sempere et al. (2002), Whiteside et al. (2007), and Lagorio (2008), reconstructed for this time span. It can be clearly observed that LIP magmatic products are widely distributed around the main eruptive centers. They seem to spread from sectors of the previous deformation belts, in coincidence with areas of low seismic wave velocity (Fig. 7), and to follow radial directions of extension. For example, the CAMP (ca. 200 Ma) extends from northern South America through the east coast of North America, north-northwest Africa, and the Iberian Peninsula (Marzoli et al., 1999). The Karroo lavas in southern Africa and Ferrar Dolerites in eastern Antarctica (ca. 180 Ma; e.g., Encarnación et al., 1996; Jourdan et al., 2007) have their counterpart in the eruptive rocks of the Lonco Trapial and Marifil Formations along the Gastre fault system (e.g., Rapela and Pankhurst, 1992; Zaffarana and Somoza, 2012). The Paraná-Etendeka-Angola province would extend further west in the

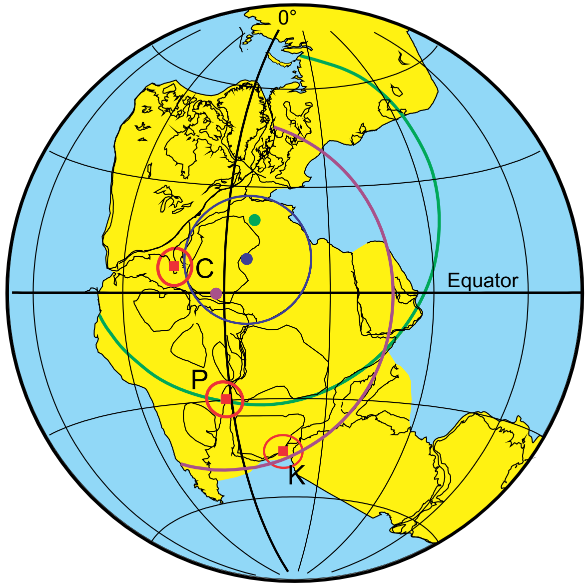

Figure 5. Absolute reconstruction of Gondwana for the Late Triassic–early Late Jurassic time span and main eruptive centers (red squares) of three large igneous provinces: C—Central Atlantic magmatic province; K—Karroo–Ferrar–Lonco Trapial and Marifil province; P—Paraná-Etendeka-Angola province. Note that the eruptive centers are located on the late Paleozoic–early Mesozoic deformation belts discussed in this paper (colored arcs; see Fig. 1 for explanation of colored arcs and associated center points). Although province P is younger, ca. 134–132 Ma, it was reconstructed using the parameters for the Late Triassic–early Late Jurassic to show the possible control of older structures on its location.

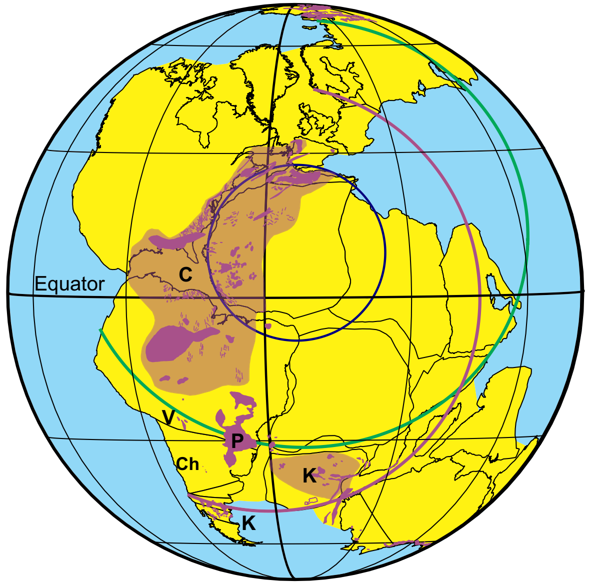

Figure 6. Absolute reconstruction of Gondwana for the Late Triassic–early Late Jurassic time span, showing the extent of Mesozoic volcanism. C—Central Atlantic magmatic province (after Whiteside et al., 2007); K—Karroo–Ferrar–Lonco Trapial and Marifil province (after Eldhom and Coffin, 2000; Pankhurst et al., 2000); P—Paraná-Etendeka-Angola province (after Eldhom and Coffin, 2000); V—Velasco volcanics (Bolivia; after Sempere et al., 2002); Ch—Sierra Chica de Córdoba (after Lagorio, 2008). Solid colors indicate the area of present-day volcanic flows or sills, while shading marks the possible former extent of the volcanic provinces. Notice that eruptive centers locate over previously deformed areas, and volcanism spreads out following directions of possible radial extension. See Figure 1 for explanation of the colored arcs and points indicating deformation belts and their associated arc center points.

alkaline province of Alto Paraguay and the alkaline Velasco province of Bolivia (e.g., Unternehr et al., 1988).

We consider that this volcanism was caused by the thermal energy accumulated beneath Pangea but not due to plumes from the core-mantle boundary, as has been already proposed by Coltice et al. (2009) and Ganne et al. (2016). The feeder channels of this volcanism were established in the previously deformed weak areas that caused an upside-down drainage flow (Favela and Anderson, 2000; Vizán and Lagorio, 2011; Buiter and Torsvik, 2014).

Comparison between the paleoreconstructions corresponding to 260–240 Ma (Fig. 4) and 230–160 Ma (Fig. 8) reveals a widening of the breach between Patagonia and eastern Antarctica. This departure was probably caused by a faster movement of eastern Antarctica, India, and Australia relative to South America and Africa (see the decomposed vectors illustrating the counterclockwise motion in Fig. 3B). The difference in movement is only present south of the arc containing the Gastre fault system and the boundary between East and West Gondwana, where extensional tectonics would have concentrated. In this scenario, sinistral strike-slip could have occurred between the Kalahari and Congo cratons, as proposed by Fairhead and Green (1989), at ca. 180 Ma (compare Fig. 4 and Fig. 8).

It is noteworthy that according to Somoza and Zaffarana (2008), the above-mentioned counterclockwise rotation continued in West Gondwana due to the Tethys slab pull until the Late Cretaceous (ca. 90 Ma), suggesting that the Pacific margin of South America moved away from the western subduction zone. This is consistent with the development of extensional conditions in the Andean margin (e.g., Vicente, 2005, and references therein).

During the Triassic to Late Jurassic, sedimentary basins opened successively along this margin, progressing roughly from north to south: the Cuyo Basin during the early Middle Triassic (Anisian) to early Late Triassic (Carnian) (between ca. 246 and 230 Ma; Zavattieri and Arcucci, 2007; Spalletti et al., 2008; Barredo et al., 2012), the Neuquén Basin during the Norian to early Sinemurian

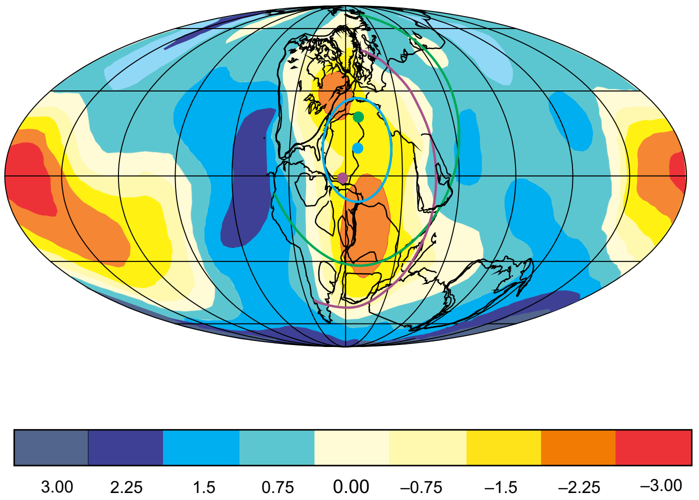

Figure 7. Pangea absolute reconstruction for the Late Triassic–early Late Jurassic with a model of seismic wave velocities anomalies (model named S16B30 of Masters et al., 1996) for the lower mantle (~2750 km deep). Different colors correspond to perturbations of the S-wave velocity with respect to the global average for that depth. Notice that Pangea locates over a zone corresponding to interpreted higher temperatures in the lower mantle (e.g., Zhong and Rudolph, 2015). It is possible that this area does not extend beneath Eurasia because the mantle has been refreshed by the slabs that sank at the south of this continent. For scale, different colors correspond to perturbations of the S-wave velocity with respect to the global average for that depth.

(between ca. 223 Ma and 199 Ma; Riccardi et al., 1991, 1997; Riccardi and Iglesia Llanos, 1999; Naipauer et al., 2015), the Chubut Basin during the late Pliensbachian to early Toarcian (between ca. 185 and 180 Ma; Musacchio and Riccardi, 1971; Blasco et al., 1979; Vizán et al., 1996), and the Rocas Verdes Basin during the Late Jurassic to Early Cretaceous (between ca. 150 Ma and 140 Ma; Dalziel et al., 1974; Stern and de Wit, 2003).

The Cuyo Basin (Fig. 8) was developed under a sinistral transtensional regime with a north-northeast–oriented axis of maximum extension (Japas et al., 2008) that is similar to the orientation of the displacement vectors (Fig. 2B). The opening of the Neuquén Basin (Fig. 8) had a north-northeast axis of maximum extension during its opening (e.g., Bechis et al., 2009), also in agreement with our displacement vectors (Fig. 2B). The Chubut Basin was a northwest-trending back-arc basin, where shallow marine and continental deposits interbedded with volcanic flows of the Lonco Trapial and Marifil Formations (Suárez and Márquez, 2007). The Rocas Verdes Basin (Fig. 8) was a back-arc (marginal) basin opened between a volcanic island arc and the South American continent (e.g., Dalziel et al., 1974; Stern and de Wit, 2003).

While the subsequent evolution of these basins was different, their openings probably responded to a common geodynamic cause. They all are located south of the Guapiara-Curitiba deformation belt in an area that during the Triassic–Jurassic was possibly pulled by the slab of Paleotethys, while Pangea was moving slightly northward. Jacques (2003) pointed out that these basins were linked to preexisting basement fault systems. These old fractures possibly acted as inherited zones of weakness, with strike-slip motions between the lithospheric domains (as in the model of Bercovici and Ricard, 2014) pulled by slabs subducting in the northeastern sector of the Paleotethys Ocean (Fig. 8).

In other words, we consider that the western margin of South America was fragmented by fault systems, and different domains between them moved away from the Pacific trench, whose slab remained anchored to the mantle (as in a tensional Mariana-type back-arc region proposed by Uyeda and Kanamori [1979]). The slab pull of the Paleotethys subduction would have intensified eastwards, shifting the different domains successively to the east and generating diachronous basins with progressively younger ages toward the south of South America (Fig. 8).

Geodynamic Interpretations

During the first analyzed time span (Early Pennsylvanian–Middle Triassic), Pangea was probably located over a huge mantle downwelling (e.g., Zhong et al., 2007; Zhong and Rudolph, 2015). On the other hand, during the second time span (Late Triassic–early Late Jurassic), a mantle upwelling probably existed beneath Pangea.

Zhong et al. (2007) proposed that Pangea was assembled in a downwelling hemisphere, inducing the generation of an upwelling system below it. Furthermore, these authors suggest that the two present-day lower mantle antipodal upwellings are mainly the result of mantle convection during Pangea time. While the African upwelling system could be a consequence of Pangea formation, the Pacific upwelling system should be significantly older (e.g., Zhong et al., 2007; Zhong and Rudolph, 2015). The younger upwelling system below Pangea would have contributed to the extensional tectonic processes that took place during the Mesozoic.

Meanwhile, the global pattern of mantle convection would have had substantial differences between the two time spans studied here; the calculated displacement vectors show a northward movement and counterclockwise rotations of domains of Gondwana (Pangea) for both time spans. Consequently, they are probably related to processes that occurred between the late Paleozoic and the middle Mesozoic. There are different interpretations regarding the northward movement. Marcano et al. (1999) proposed that it could correspond to true polar wander—a movement around an equatorial axis of rotation involving the lithosphere and the whole mantle. Based on their studies of mantle convection, Zhong et al. (2007) considered that Pangea did not experience significant true polar wander after Gondwana and Laurasia amalgamated near the equator. According to Scotese (2001), paleomagnetic data only record the drift of Pangea as one lithospheric plate between the late Paleozoic and Mesozoic.

We agree with Scotese (2001) and Zhong et al. (2007) and consider that the northward movement indicated by our displacement vectors corresponds to lithospheric drift of Pangea and not to true polar wander. This movement was

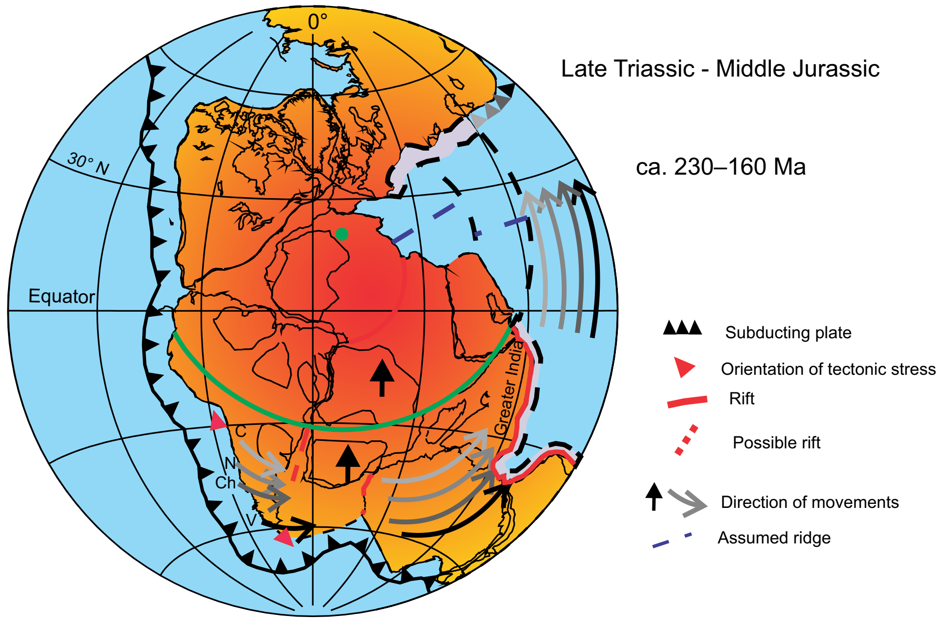

Figure 8. Displacement of different lithospheric domains of Pangea (Late Triassic–Middle Jurassic) and location of Argentinian basins opened along or close to the Pacific margin of Gondwana. C—Cuyana Basin; N—Neuquén Basin; Ch—Chubut Basin; V—Rocas Verdes Basin. Red shades are used to indicate that Pangea was over a superswell. Short black arrows indicate a northward movement of lithospheric domains of Pangea. Shaded black/gray arrows indicate counter-clockwise rotations of different lithospheric domains of Gondwana (lighter to darker tones indicate older to younger movements).

probably caused by linear momentum transfer from Gondwana to Laurasia during the assembly of Pangea.

To explain the counterclockwise rotations of the different domains, it is necessary to consider that according to Gutiérrez-Alonso et al. (2008), the process of self-subduction of Pangea in the boreal Paleotethys margin and its associated slab pull probably generated stress regimes that were transmitted through the whole supercontinent before the segmentation of every microcontinent of Cimmeria. In geodynamic terms, this is consistent with the development of different types of convection in the asthenosphere. Thermal gradients generate upwelling and downwelling flows (with their corresponding areas of convergence and divergence, or subduction and ridges) in what is called poloidal convection. Indeed the lithosphere is the cold upper thermal boundary layer of poloidal convective cells and is formed by extended thick and rigid regional domains separated by relatively narrow, thin, less cohesive, and self-lubricated deformable zones (Bercovici, 2003). However, Earth's plate-tectonic style of mantle convection also involves toroidal flow related to lateral displacement of tectonic plates (Bercovici et al., 2000, and references therein). While poloidal convection is a roll with descending and ascending limbs, toroidal motions are associated with a vertical-axis rotation of a lithospheric plate.

As mentioned before, we envisage Gondwana as a lithospheric plate composed by nearly rigid blocks and self-lubricated weak narrow areas. When there is poloidal convection with forces pushing or pulling the plate, the self-lubricated weak areas tend to deform more readily as shear zones than the more rigid neighboring domains (Bercovici et al., 2000). These weak zones in the lithosphere persist for long periods and are reactivated as shear systems if their orientations, with respect to poloidal convection, favors the movement of tectonic rigid domains (Bercovici et al., 2000, 2015). The differential movement between the rigid domains could generate large shear displacements in the self-lubricated weak lithospheric zones which in turn could induce a toroidal flow in the asthenosphere (Bercovici et al., 2000; Bercovici and Ricard, 2014). In turn, the mantle flow (including the toroidal flow) would exert guidance on further movements of the plate. This proposal, in which the rotation of rigid lithospheric domains affects the convection in the asthenosphere, and subsequently the asthenosphere promotes new lithospheric movements, is consistent with the concept of top-down geodynamics suggested by Anderson (2001).

First Time Span (between ca. 320 and 240 Ma)

In the first time span there was a huge downwelling area where the supercontinent was assembled, and an upwelling zone in the opposite hemisphere below Panthalassa (proto–Pacific Ocean); this suggests downwelling-zone slab pull of extraordinary strength (Fig. 4). A nearly circular Pangea enclosed the large eastward-opening wedge-shaped ocean called Paleotethys (e.g., Gutiérrez-Alonso et al., 2008). As mentioned above, this ocean was probably a remnant of the partially closed Rheic Ocean (see Scotese, 2001), including, to the north, a northward-dipping subduction zone beneath Eurasia. That is to say, a "self-subduction" of the supercontinent took place, such that slab pull of the downgoing oceanic lithosphere was responsible for the internal deformation of continental Pangea (Gutiérrez-Alonso et al., 2008).

As previously noted, this process generated the Iberian-Biscay orocline and radial extension producing the coeval Oslo rift (around the Norwegian capital) (Gutiérrez-Alonso et al., 2008), the dismemberment of some Cimmerian microcontinents, and the rift along which later occurred the separation of Africa and South America (Pastor Galán, 2012). The stresses associated with the Paleotethys slab pull were transmitted through the subducting oceanic plate into the Gondwana continent, in a similar manner as occurred when a new Tethyan slab pull caused the dismemberment of India and its rapid drift toward Eurasia.

During our first time span, the stresses generated by the Paleotethys slab pull caused differential displacements of Gondwana domains. The occurrence of such differential displacements were facilitated and promoted by the existence of the above-mentioned inherited weak zones between the lithospheric domains. In this paper, we propose that the arcs with centers in northwest Africa represent these zones of ancient lithospheric weakness (Fig. 4) and that they were reactivated and deformed by the Paleotethys subduction slab pull, resulting in transcontinental shear belts. The differential displacements of Gondwana domains through these belts induced toroidal flows in the asthenosphere with centers or vortices in northwest Africa. The toroidal flows organized, in turn, the geographical distribution of the rigid Gondwana domains and deformation along the pericratonic weak zones. Speculatively, the toroidal flows induced in the mantle may have affected all of such zones of Pangea, causing lateral displacements along ancient Eurasian areas of lithospheric weakness as the Trans-European suture zone and the crustal-scale orogen-parallel strike-slip fault zone in the Middle Urals.

The centers of the arcs that contain the weakness zones are located relatively close to the centroid of Pangea that, in our interpretation, is linked not to a true polar wander axis as proposed by Torsvik et al. (2012) among others, but rather with centers of movements of lithospheric domains.

Second Time Span (between ca. 230 and 160 Ma)

Beginning in the Late Triassic–Early Jurassic (ca. 230 Ma), an upwelling area developed beneath Pangea (Fig. 7) as proposed by Zhong et al. (2007). That is to say, the arrangement of mantle convection (with two upwelling areas surrounded by downwelling zones) turned into a pattern similar to the present one.

In this second time span, the displacement vectors have the same southwest-northeast orientation in West Gondwana as during the previous one, with the only difference being that this orientation is also registered in southern Patagonia, India, Australia, and eastern Antarctica (Fig. 2).

The decomposed vectors indicate a latitudinal northward movement of all of Gondwana (Fig. 3B) and a counterclockwise rotation that increases to the south. Notably, this counterclockwise movement is larger for India, Australia, and eastern Antarctica. We propose that this counterclockwise rotation was also triggered by the slab pull at the northern margin of the Paleotethys Ocean, but farther east than before. To the west, Paleotethys was already closed through the accretion of some microplates of Cimmeria *sensu lato* (Fig. 4).

CONCLUSIONS

In the Introduction, we posed the question: How did subduction of the Paleotethys influence the Late Pennsylvanian to early Late Jurassic assembly of Pangea?

Given that the lithosphere is composed of different domains, corresponding to cratons and terranes separated by weak lithospheric zones, geodynamic and tectonic processes were analyzed from the Early Pennsylvanian to the early Late Jurassic, in the context of relative movements between lithospheric domains.

Two time spans were studied bearing in mind that the mantle convection pattern, on a global scale, could have changed from a configuration with a single upwelling zone under the seafloor of the Panthalassan Ocean to another one with two. The younger upwelling zone would have developed beneath the major part of Pangea (see Zhong et al., 2007).

During the first time span (Early Pennsylvanian–Middle Triassic), as the supercontinent was in a downwelling area, the Paleotethys subduction slab pull began to affect the interior of Pangea. This slab pull (together with a northward drift throughout Pangea) caused differential displacements among several lithospheric domains, following self-lubricated weak zones concentric around the Pangea centroid. These displacements induced toroidal flows in the asthenosphere which organized, in turn, the geographical distribution of the rigid Gondwana domains and the deformable weak zones. This broad frame explains the stress patterns observed in different parts of Gondwana (e.g., Ventana fold belt and Paraná Basin in South America, and the opening of the Cuvette Basin in central Africa). The extension of the deformable zones into Laurasia along the Trans-European suture zone and parallel to the Ural Mountains would have been possible due to the toroidal flow induced in the mantle.

During the second time span (Late Triassic–early Late Jurassic) the upwelling zone beneath most of Pangea would have contributed to its deformational history. Geodynamic processes induced by Paleotethys slab pull, and related toroidal movement caused by weak zones, possibly caused the Pacific margin of South America to migrate away from its trench, where the oceanic floor of Panthalassa was subducting. Consequently, sedimentary basins of successively younger ages from north to south opened along western Argentina. This age distribution could reflect the migration from west to east of Paleotethys slab pull.

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