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Permian-Triassic Tethyan realm reorganization: Implications for the outward Pangea margin

Nicolas Riel [a, *], Etienne Jaillard [a], Jean-Emmanuel Martelat [b], Stéphane Guillot [a], Jean Braun [c]

[a] Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, 38000 Grenoble, France
[b] Univ. Lyon 1, UMR 5276, Laboratoire de Géologie de Lyon LGLTPE, ENSL, 69622 Villeurbanne, France
[c] Helmholtz Centre Potsdam, German Research Center for Geosciences (GFZ), Telegrafenberg, Potsdam, Germany

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ABSTRACT

We present a new conceptual model to explain the first order Permian-Triassic evolution of the whole > 30 000 km long Pangea margin facing the Panthalassa ocean. Compilation of available geological, geochemical, geochronogical and paleomagnetic data all along this system allowed us to distinguish three part of the margin: western Laurentia, western Gondwana and eastern Gondwana. These segments record distinct tectonic and magmatic events, which all occur synchronously along the whole margin and correlate well with the main geodynamic events of this period, i.e. subduction of the Paleotethys mid-ocean ridge at 310-280 Ma, opening of the Neotethys at 280-260 Ma, counterclockwise rotation of Pangea at 260-230 Ma and closure of the Paleotethys at 230-220 Ma. Between 260 and 230 Ma, the reorganization of the Tethyan realm triggered the up to 35° rotation of Pangea around an Euler pole located in northernmost South America. This implied both an increase and a decrease of the convergence rate between the margin and the Panthalassa ocean, north and south of the Euler pole, respectively. Thus, the Permian-Triassic Pangean margin was marked: in western Laurentia by marginal sea closure, in western Gondwana by widespread bimodal magmatic and volcanic activity, in eastern Gondwana by transpressive orogenic phase. Therefore, we propose that the Permian-Triassic evolution of the outward margin of Pangea was controlled by the Tethyan realm reorganization.
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1. Introduction

From Early Permian to Late Triassic, the Earth surface recorded drastic modifications including: (1) final amalgamation of the Pangean supercontinent, (2) Tethyan realm reorganization marked by the subduction of the Paleotethys ridge under the Laurussia and Asian margins (310-280 Ma), the onset of the Neotethys opening at 280-260 Ma (Stampfli and Borel, 2002), and the northward drifting of Cimmerian blocks synchronous with the subduction of the Paleotethys until ~225 Ma (Pullen et al., 2008), (3) mantle activity expressed by the outpouring of Large Igneous Provinces (LPs) (Golonka and Bocharova, 2000), and (4) early rifting of Pangea coeval with the Cantabrian orogen in western Europe (Gutiérrez-Alonso et al., 2008) (Fig. 1).

Based on compilation of worldwide geological data, Gutiérrez-Alonso et al. (2008) proposed that between 310 and 280 Ma, the subduction of the Paleotethys mid-ocean ridge under Laurussia triggered a redistribution of the stress-strain regime throughout the Pangea supercontinent during rigid-body rotation. This plate-scale model, based on the Paleotethys slab pull, accounts for the widespread radial rifting systems recorded all around the core of the Cantabrian orogen in Early Permian times (including the Neothethys, Madagascar, Oslo, North Sea and Siberian rifts). Following this event, the Neotethys opened at ca. 280-260 Ma and inner Pangean deformation and magmatism abruptly ended.

Here, we explore the evolution of the outward Pangea margin facing the Panthalassa subduction. For this, we use a compilation of available geochronological, geochemical, geological and paleogeographic data along the outward Pangean margin, from Laurussia to eastern Gondwana. Along this outward Pangean margin. We distinguish three main segments on the basis of their self-consistent evolution: western Laurentia, western Gondwana and eastern Gondwana (Fig. 1). These segments show synchronous but

* Corresponding author.
E-mail address: a.nicolas.riel@gmail.com (N. Riel).

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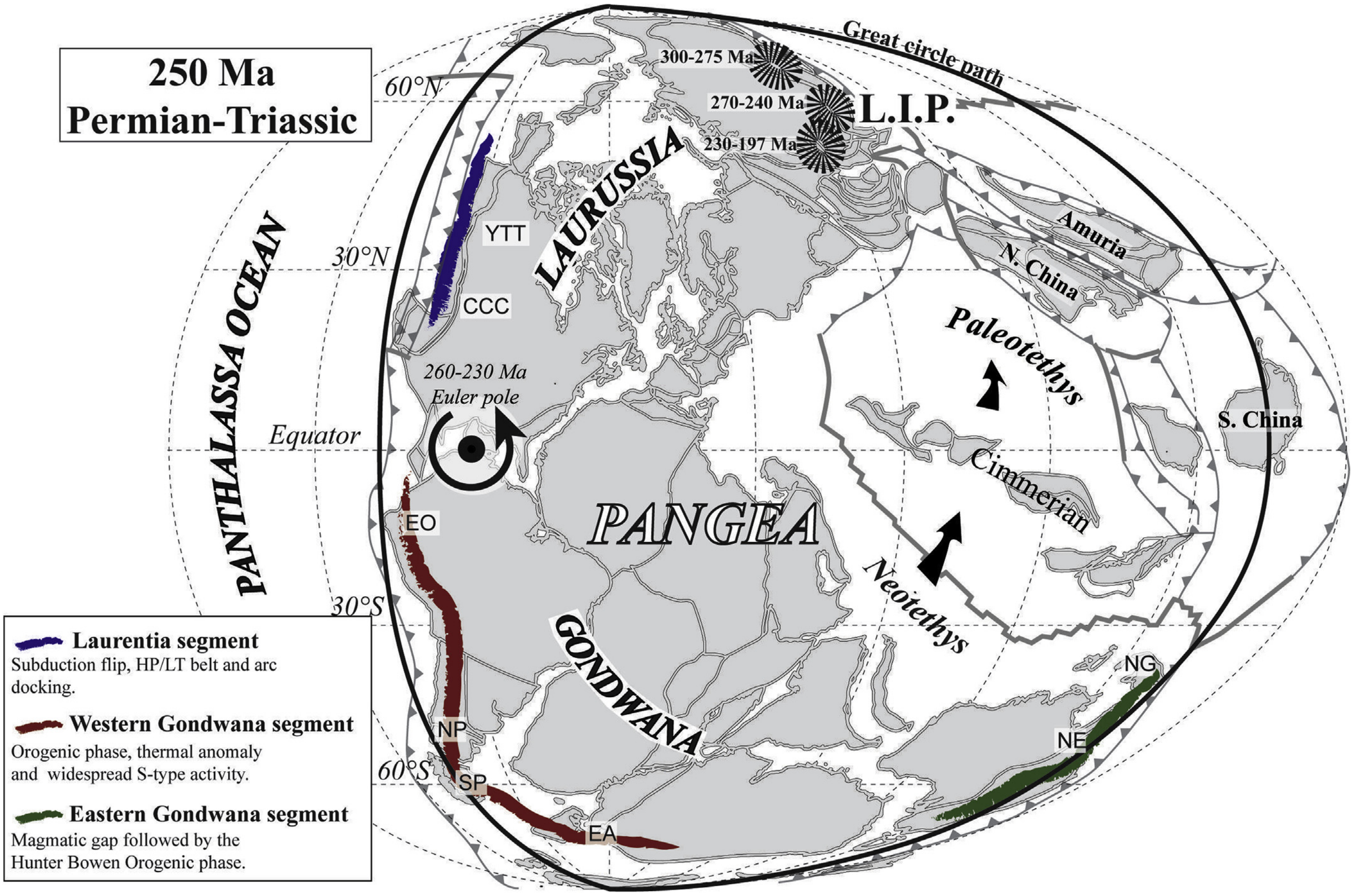

Fig. 1. Geodynamic setting along the outward Pangaea margin during Permian-Triassic times. Note that the average position of the Permian-Triassic Euler pole of rotation of Pangea is after Torsvik et al. (2012). YTT: Yukon-Tanana terrane; CCC: Cougar Creek Complex; EO: El Oro; NP: North Patagonia; SP: South Patagonia; EA: East Antarctica; NE, New England, NG, New Guinea. The positions of the Large Igenous Provinces (LIP) in Central Asia are after Yarmolyuk and Kuzmin (2011).

distinct changes in their magmatic and tectonic setting at 280–265, 265–230 and 230-220 Ma. These changes coincide with subduction of the Paleotethys ridge, opening of the Neotethys ocean and closure of the Paleotethys ocean, respectively, and with overall changes in apparent pole wandering path of Pangea. As no other investigated model can explain such plate-scale and synchronous events, we hypothesize that the Permian-Triassic counterclockwise rotation of Pangea shown by paleomagnetic and paleoenvironment studies (Marcano et al., 1999; Golonka, 2007; Torsvik et al., 2012), likely caused by opening of the Neotethys, triggered the major changes in tectonic and magmatic setting recorded all along the margin. Considering the position of the studied segments with respect to the position of the Permian-Triassic Euler pole of rotation of Pangea, the conceptual model presented here fairly explains the observed tectono-magmatic changes along the whole outward Pangea margin, i.e. on more than 30 000 km long.

2. Permian Triassic evolution of the outward Pangea margin

We compiled the salient available data of the Late Paleozoic to early Mesozoic evolution of the Panthalassa margin from northwestern Canada to east Australia (Fig. 2 and supplementary data). We describe this large-scale geodynamic system by studying the main three representative segments of the margin: western Laurentia, western Gondwana and eastern Gondwana. We do not integrate the evolution of north Laurussia as very few data are available. The Permian-Triassic evolution of the Asian continental blocks will not be presented as they were not constitutive of the Pangea supercontinent.

2.1. The western Laurentian margin (Alaska, Canada, United-States)

In northwestern Canada, east-directed subduction was active during Carboniferous times to the west of the 1200–2400 km marginal sea. The latter ceased at 275-269 Ma and was replaced by a west-directed subduction well illustrated by high-pressure metamorphism, which formed as a response to the closure of the marginal sea (Ruks et al., 2006, Fig. 2). Between 260 and 252 Ma, the arc collided against the Laurentia margin under dextral strike-slip conditions, triggering the Klondike orogenic phase in the Yukon-Tanana Terrane to the north, and the Sonoman orogenic phase in the Sierra Nevada to the south. U-Pb Ages on detrital zircons indicate moderate felsic magmatic activity at ca. 242, 236 and 222 Ma. Gabbro and diorite sills are also recorded in western Yukon and eastern Alsaka at 232-226 Ma (e.g. Dusel-Bacon et al., 2006). In Late Triassic times, a new flip in subduction resulted in an east-directed Cordilleran subduction (Beranek, 2009). Farther south, in the western United States, the Wallowa arc of the Cougar Creek Complex is dominated by silicic magmatism between 265 and 250 Ma. Subsequently, the Wallowa magmatic arc vanished at 250-230 Ma, and voluminous mafic to intermediate, MORB-like, mantle derived magmatism occurred at 230 Ma, which is interpreted as resulting from the subduction of the spreading ridge of the marginal sea at 229 Ma (Kurz et al., 2012). The synchronicity of the

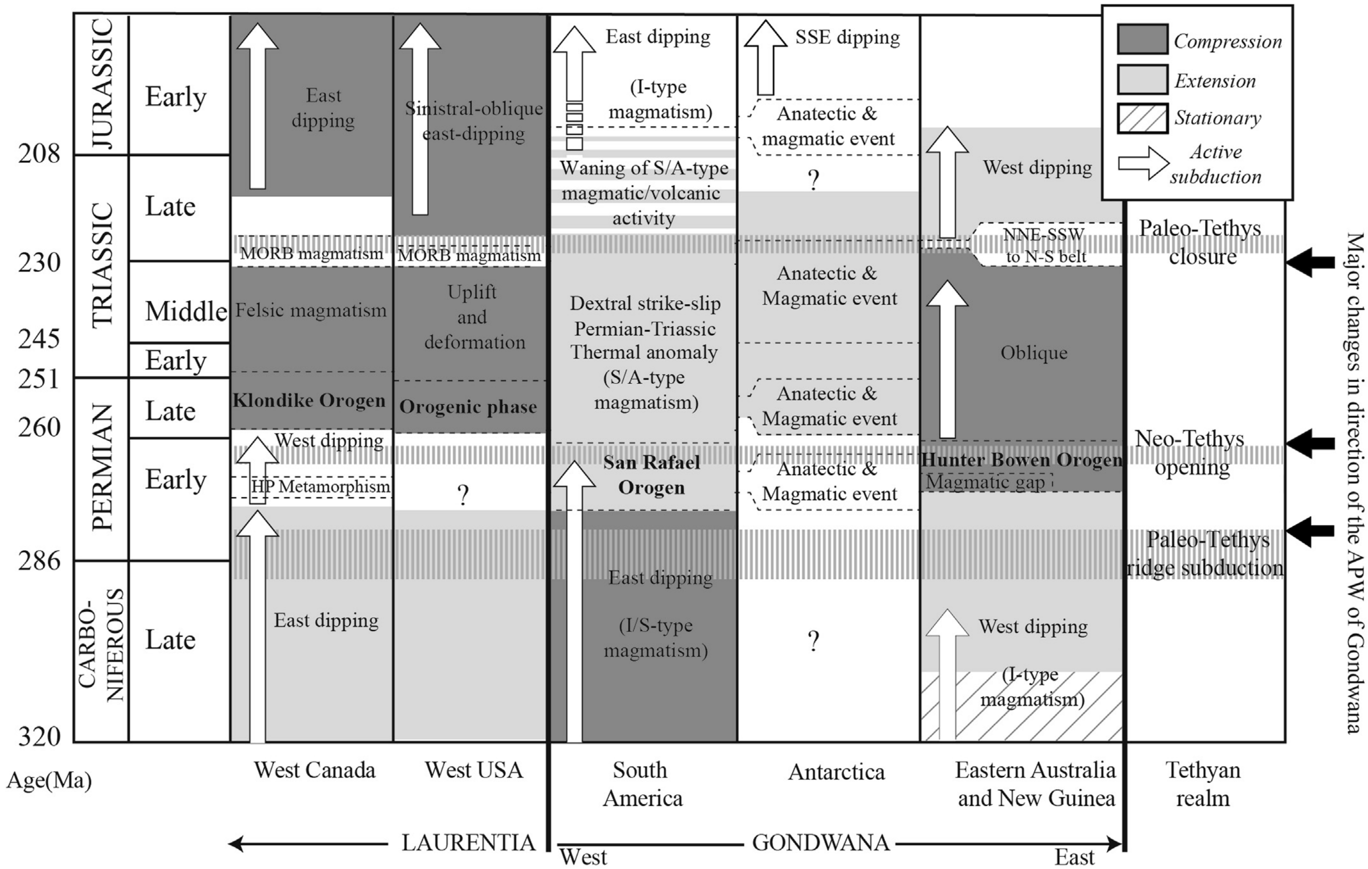

Fig. 2. Synthetic diagram of the main tectonic and magmatic and geodynamic events occurring between 320 and 200 Ma all along the western Laurentia and Gondwana margin.

contractional event along western North America at 260-250 Ma implies that the driving forces for the closure of the marginal ocean are related to a significant plate tectonic event (Beranek, 2009).

2.2. The western Gondwana margin (South America and east Antarctica)

Compilation of geochronological and geochemical data in western South America led us to distinguish the following succession of events during late Paleozoic times. (1) Subduction of the Panthalassa Ocean below South America in the Carboniferous is evidenced by isotopic, geochronological and geochemical studies (e.g., Mišković et al., 2009; Kleiman and Japas, 2009; Deckart et al., 2014; Maksaev et al., 2014; del Rey et al., 2016; Creixell et al., 2016) and characterized by calc-alkaline/silicic magmatic/volcanic activity. Available U–Th–Pb ages of plutonic and volcanic bodies (see Supporting Information, reported on Fig. 3a) show that magmatism exhibits an increase of crustal involvement between 275 and 260 Ma (Fig. 3A). At the same time, transition from a transpressive to a transtensional regime is widely observed in South America (e.g. Mišković et al., 2009 and supplementary data) (Fig. 3a). These changes were synchronous over a broad latitudinal range (5°N to 55°S) and coeval in South America with the so–called San Rafael Orogenic Phase (e.g., Caminos, 1979; López Gamundi, 2006). (2) The emplacement of Large Igneous Provinces (LIP) made of granites together with voluminous bimodal magmatism/volcanism occurred in an extensional regime between 265 and 230 Ma (e.g., Ramos and Kay, 1991) and was followed by minor intrusions between 230 and 205 Ma (e.g., Maksaev et al., 2014). This period of voluminous silicic activity resulted from a long period of high mantle heat flow and crustal anatexis known as the Choiyoi event (Kay et al., 1989). Although several studies postulated that this event occurred in the absence of subduction (e.g., Kay et al., 1989; Spikings et al., 2016), an increasing number of studies have recently shown that subduction was active from at least latest early Carboniferous to early Jurassic (Vásquez et al., 2011; del Rey et al., 2016; Coloma et al., 2017; Oliveros et al., in press). (3) The last stage occurred in the westernmost forearc areas, but also in the arc and backarc regions between 235 and 215 Ma.

We define the important period of crustal magmatic activity between 265 and 215 Ma all along the South American margin (e.g., Kay et al., 1989) as the Permian-Triassic thermal anomaly. These metamorphic/magmatic events are well known in northern Colombia (Restrepo et al., 2011; Villagómez et al., 2011), Ecuador (Cochrane et al., 2014; Riel et al., 2013, 2015), northern Peru (Mišković et al., 2009; Spikings et al., 2016), southern Peru (Clark et al., 1990; Reitsma et al., 2010; Spikings et al., 2016), Bolivia (Farrar et al., 1990), northern Chile (Pichowiak et al., 1990; Hervé et al., 2014), Argentina (Kay et al., 1989; Spalleti et al., 2008; Rocha-Campos et al., 2011; Poma et al., 2014; Rocher et al., 2015; Sato et al., 2015), northern Chile (Munizaga et al., 2008; Maksaev et al., 2014; Charrier et al., 2014; Coloma et al., 2017; Oliveros et al., in press) and southern Chile (Martin et al., 1999; Vásquez et al., 2011). The location of the Permian-Triassic thermal anomaly roughly coincides with that of the Carboniferous arc (Fig. 3c) and exhibits a southward widening of the margin area affected by the S-type igneous activity (Fig. 3b). Although in the northern Andes, Mesozoic docking of oceanic terranes against the margin narrowed the Late Paleozoic belt in Colombia and Ecuador (e.g. Jaillard et al., 2009), the width increase can be traced from Peru to

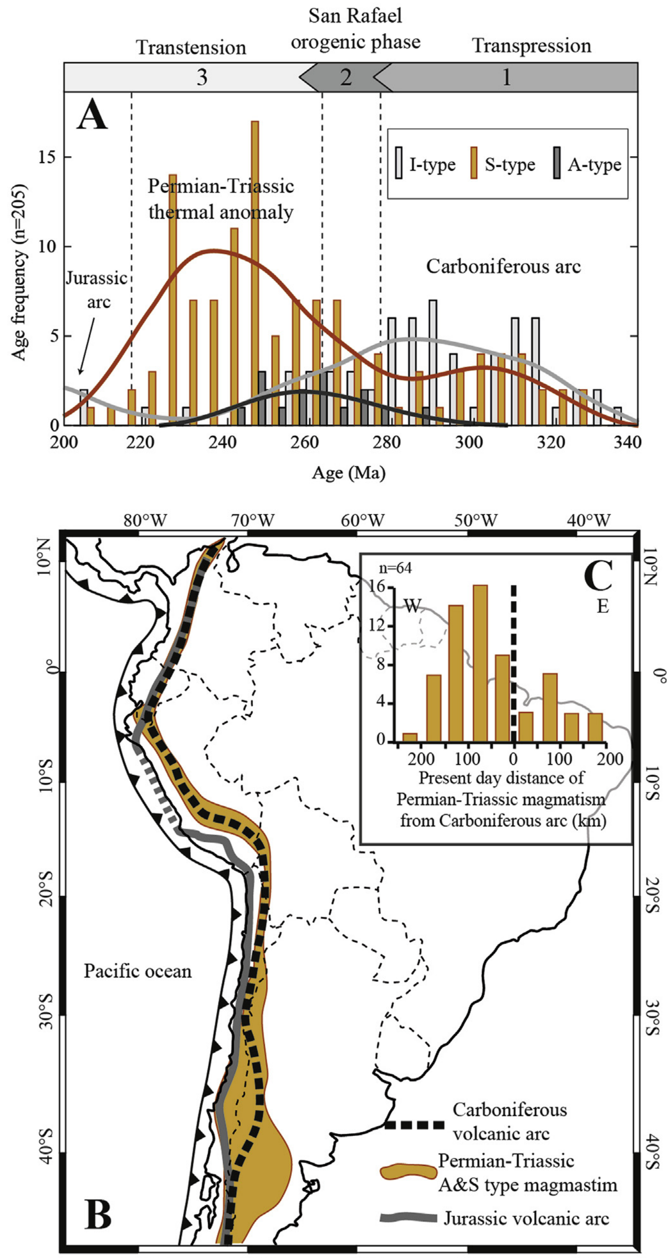

Fig. 3. Present–day position of the Carboniferous to early Jurassic magmatic belt. A: Positions of magmatic arcs are compiled from the literature (see Supporting Information); Jurassic arc in northern Peru is indicated in grey dashed line and is likely offshore. B: Present day absolute distance of the Permian–Triassic magmatism from the Carboniferous arc axis (integrated on the entire South America and binned at 50 km intervals).

Patagonia (Fig. 3). Subsequently, S/A–type magmatism vanished along the South American margin at 205 Ma (Fig. 2A), and was progressively replaced by subduction related magmatism in early Jurassic times (Jaillard et al., 2000; Rapela et al., 2005).

According to the regions, distinct models have been proposed to explain the Permian-Triassic thermal anomaly: (1) rifting in northern south America (Aspden et al., 1995; Villagómez et al., 2011; Cochrane et al., 2014; Spikings et al., 2016), (2) strong plate coupling followed by slab steepening in Peru and Chile (Franzese and Spalletti, 2001; Mišković et al., 2009; Rocher et al., 2015), slab roll-back (del Rey et al., 2016), or (3) late Paleozoic collage of exotic terranes in Chile and Patagonia (e.g., Llambías and Sato, 1995; Cardona et al., 2010). However, no evidence of such widespread and synchronous collisional events have been observed all along the South American margin. In Colombia and Ecuador, evidence of terranes of oceanic affinity tectonically juxtaposed with Triassic migmatites and granulites during a Late Triassic subduction event (Bustamante et al., 2011; Riel et al., 2015) argue against a rifting model. The thermal anomaly and the coeval tectonic events along the South American margin could also reflect the subduction of an oceanic ridge. Such an event would trigger protraction of the margin with subsequent extensional setting in the arc and back-arc regions (e.g., Whittaker et al., 2011). In this interpretation, an eastward migration of the volcanic arc should also be observed. However, it is unlikely that ridge subduction can occur simultaneously along a more than 10 000 km margin segment, from Colombia to Antarctica. Therefore an improved geodynamic model has to be proposed in order to explain this long-lived period of bimodal magmatic and volcanic activity.

Although tectonic and magmatic data are scarce in Antarctica, detrital (Millar et al., 2002) and *in situ* zircon U-Pb geochronology (Riley et al., 2012) shows that magmatic and metamorphic activity associated with anatexis occurred in the Antarctic Peninsula at 275-265 Ma, 260-255 Ma and 240-225 Ma, in a possible extensional tectonic setting (Millar et al., 2002, Fig. 2). This evolution is compatible with that observed in western South America at the same time (Kay et al., 1989). In spite of their scarcity, these data are consistent with an extension of the Permian-Triassic thermal anomaly to Antarctica.

2.3. The eastern Gondwana segment (eastern Australia, New Guinea)

In eastern Australia, from 320 to 270 Ma, I-type arc magmatic was related to west dipping subduction in an extensional regime (Glen, 2005; Cawood et al., 2011) (Fig. 2). At 270-265 Ma, a magmatic gap followed a change in the tectonic setting from extensive to compressive. This period is interpreted as the result of a change in convergence direction between Gondwana and the Panthalassa slab, from orthogonal to oblique (Cawood et al., 2011), and marks the onset of the Hunter Bowen, transpressive orogen (Fig. 2). Subsequently, from the Mid–Late Permian to the Late Triassic (ca. 260-230 Ma), the Hunter Bowen Orogen recorded transpressive deformation and widespread I-type calc-alkaline magmatism related to west-dipping subduction (Li et al., 2012, Fig. 2). Finally, between 230 and 215 Ma, the axis of the magmatic arc rotated from NNE-SSW to N-S and the tectonic regime changed from compressive to extensive (Fig. 2). Similar tectono-magmatic events are also described farther North in New Guinea (Crowhurst et al., 2004).

3. Discussion

3.1. Main Permian-Triassic geodynamic events along the outward Pangea margin

From Late Paleozoic to Early Mesozoic, the geodynamic evolution of the Panthalassa margin is marked by strikingly synchronous changes in tectonic and magmatic setting and by the development of orogenic phases that occurred all along the margin.

Three main periods can be distinguished: (1) Early Permian times (280-260 Ma), (2) Late Permian to Middle Triassic times (260-230 Ma) and (3) Late Triassic times (230-200 Ma) (Fig. 2). (1) In Early Permian (275-260 Ma), the subduction flipped from east to west-directed in northwestern Laurentia. In western Gondwana, subduction-related magmatism exhibit increasing crustal contamination during synchronous contractional orogenic phases recorded all along the margin (López Gamundi, 2006; Mišković et al., 2009; Cochrane et al., 2014). In eastern Gondwana, the tectonic setting of the margin switched from extensive to compressive during a magmatic gap at 270-265 Ma and the subduction direction changed (Fig. 2). (2) In Late Permian to Middle Triassic times (260-230 Ma), the western Laurentia margin was characterized by the closure of a marginal sea and the following synchronous Klondike and Sonoman orogenes, which developed between 260 and 250 Ma (Beranek and Mortensen, 2011). From 250 to 230 Ma, the margin was uplifted and recorded a moderate felsic magmatic activity. In western Gondwana, the margin underwent widespread S/A-type magmatic and volcanic activity under extensive tectonic setting between 260 and 230 Ma (e.g., del Rey et al., 2016; Spikings et al., 2016). At the same time, in eastern Gondwana, the margin was marked by the transpressive Hunter Bowen Orogen and by subduction-related magmatic activity. (3) In Late Triassic times, between 230 and 210 Ma, arc magmatism related to the cordilleran east-direct subduction resumed in most of the Laurentia margin (e.g. Beranek and Mortensen, 2011). In western Gondwana, the same period (230-220 Ma) was marked by the waning of A/S-type magmatic activity and by underplating of high pressure and low temperature rocks in Colombia (Bustamante et al., 2011) and Ecuador (Riel et al., 2013, 2015). In eastern Gondwana, between 230 and 215 Ma, the direction of the magmatic arc rotated and the tectonic setting changed from compressive/transpressive to extensive.

3.2. Pangean-scale event

Although the Permian-Triassic geodynamic evolution of western Laurentia, western Gondwana and eastern Gondwana are different, the major changes of tectonic and magmatic setting occurred simultaneously along these large segments of the whole Panthalassa margin (>5000 km each). Moreover, in Early Permian times, available data show that western Laurentia and the whole Gondwana recorded inversion in their tectonic regime (Fig. 4). These events can be related to either three large-scale geodynamic events during Panthalassa subduction, which would have affected independently but synchronously the three segments of the margin, or by global variations of the state of stress, which affected both the outward margin of the Pangea supercontinent and the surrounding Panthalassa subduction.

Local perturbations in the subduction forces, such as ridge subduction, block accretion or slab breakoff have been proposed in South America in order to explain the Permian-Triassic thermal anomaly. However, these processes would only affect the margin locally (e.g. Guillot et al., 2009) and would likely exhibit evidence of diachronism if multiple events occurred at the scale of the Laurentia-Gondwana margin. Moreover, it is very unlikely that three regional perturbations would occur simultaneously, and this, three times during Permian-Triassic times. By contrast, during Permian-Triassic times, Pangea was amalgamated and was covering 70% of a hemisphere as a quasi-rigid plate (Marcano et al., 1999), which could propagate forces across its whole extent. Consequently, global and synchronous changes in the state of stress of the margin are most likely to be achieved by variations in the motion of Pangea supercontinent itself.

3.3. Correlation with the Tethyan realm reorganization

During the early stages of Pangaea break-up, the Tethyan realm was enclosed in the crescent shape of the Pangea supercontinent (Fig. 1). The Late Paleozoic-Early Mesozoic plate reorganization occurred because of the subduction of the Paleotethys ridge at 310-280 Ma (Stampfli and Borel, 2002), which triggered a general change of the stress-strain regime within Pangea (Gutiérrez-Alonso et al., 2008), the opening of the Neotethys ocean in early Permian times (280-260 Ma, Stampfli and Borel, 2002; Golonka, 2007; Torsvik et al., 2012) related to the northward drift of the Cimmerian blocks between 260 and 230 Ma, and the subsequent closure of the Paleotethys ocean in Late Triassic times, leading to the accretion of the Cimmerians blocks against the Asian margin at 230-220 Ma (Pullen et al., 2008). On the other hand, palinspastic reconstructions based on paleomagnetic reconstructions (Marcano et al., 1999; Stampfli and Borel, 2002; Torsvik et al., 2012) and on global hotspot reference frame (Golonka, 2007), indicate that during the Permian (280-260 Ma), Pangea underwent a slowdown of its westward motion, followed by a counter−clockwise motion from Late Permian to Triassic times (260−220 Ma), around an Euler Pole roughly located at the triple point between North America, South America and Africa (Marcano et al., 1999; Golonka, 2007; Torsvik et al., 2012, Fig. 4c). The inferred period of counterclockwise rotation ceased at ca. 230 Ma and the westward motion of Pangea resumed.

Thus, the available data on the geodynamic evolution of the Pangea-Tethyan system clearly indicate that the three step reorganization of the Tethyan realm at 280−260, 260−230 and 230-220 Ma is coeval with the main changes in tectonic and magmatic settings along the whole Laurentia and Gondwana margin and also with changes in drifting direction of Pangea (Figs. 2 and 4).

3.4. Interpretative evolutionary model

At the plate tectonic scale, the most efficient physical process that can propagate vertical motion to horizontal motion is subduction. In this view, the opening of the Neotethys (280-260 Ma) and the closing of the Paleotethys (230-220 Ma) are likely the triggering events that modified the drift motion of Pangea. Moreover, the fact that subduction-related magmatism was active all along the Laurentia-Gondwana margin (North America, South America, Australia) without any major recognized gaps from Carboniferous to at least mid-Permian times indicate that the Panthalassa subduction system was extending on more than 20 000 km (Fig. 1). Schellart et al. (2007)) showed that large slabs (>4000 km) are nearly stationary in the center. This implies that even a limited motion of Pangea with respect to the surrounding Panthalassa will have strong implications on the tectonic setting of the margin. As a consequence, we propose that the motion of Pangea from late Carboniferous to early Jurassic times (Marcano et al., 1999; Stampfli and Borel, 2002; Golonka, 2007; Torsvik et al., 2012) (Fig. 4A), triggered changes in both the tectonic and magmatic settings observed along the Laurentia-Gondwana margin. Since the Permian-Triassic Euler Pole of Pangea was roughly located in the Equatorial plane in northernmost South America (Marcano et al., 1999; Golonka, 2007; Torsvik et al., 2012), we expect synchronous and opposite changes in tectonic/magmatic settings north and south of the Euler pole, in the Laurentia and Gondwana margin, respectively (Fig. 5A). We also expect limited changes of the margin geodynamic setting near the Euler pole (Central America and Eastern Australia) (Fig. 5).

3.4.1. The western Laurentia margin

During Permian-Triassic times, the global apparent pole wandering path of Pangea indicates that the Laurentia margin was moving eastward. Based on available paleomagnetic and geological data along the Laurentia margin, Marcano et al. (1999) discussed the Permian-Triassic counterclockwise rotation of Pangea either as an apparent pole wandering path or as true pole wandering. These authors showed that if apparent pole wandering path occurred,

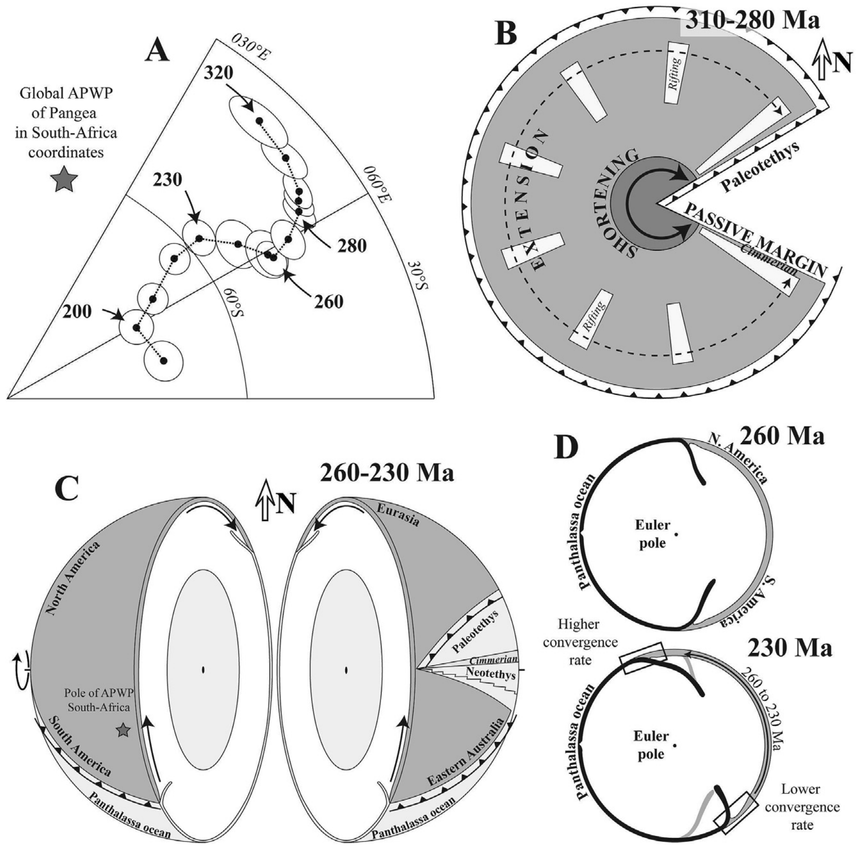

Fig. 4. Geodynamic evolution of Pangea from 320 to 200 Ma. A: Global Apparent Pole Wandering Path of Pangea (APWP), projected in South African coordinates (Torsvik et al., 2012). B: Schematic self-subduction of Pangean global plate: model of Gutiérrez-Alonso et al. (2008) during subduction of the Paleotethys ridge at 290-270 Ma. C: Rotation of Pangea between 260 and 230 M, coevally with the northward drifting period of the Cimmerian blocks. D: Schematic section normal to the Euler pole of rotation of C, showing rotation of Pangea and resulting changes in convergence velocities.

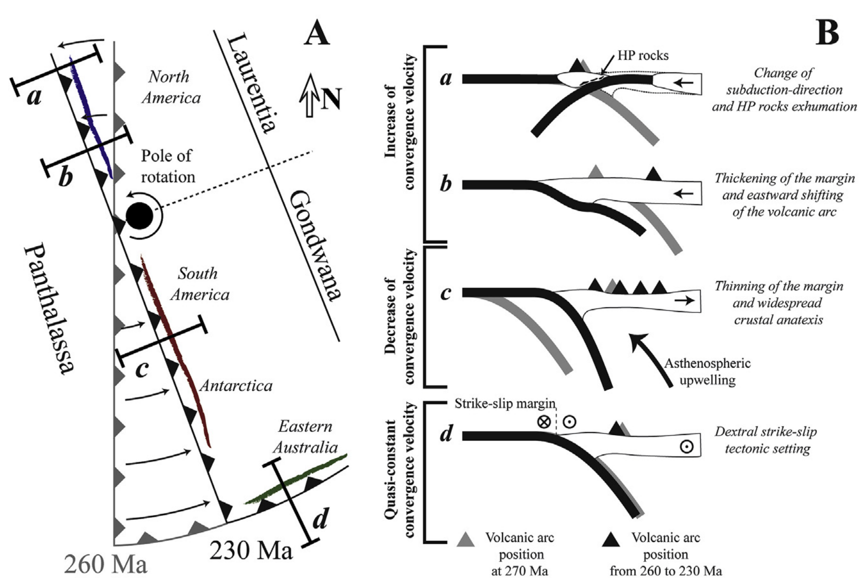

Fig. 5. Interpretative models of the Permian-Triassic evolution of western Laurentia and Gondwana margins. A: Idealized representation of the Pangea rotation from 260 to 230 Ma with respect to the Euler pole of rotation located in northernmost South America (Marcano et al., 1999; Golonka, 2007; Torsvik et al., 2012). The color brushes are identical to those of Fig. 1. B: Schematic cross-sections of the margins at different locations reported in A. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

large part of oceanic lithosphere would have been subducted at the leading edge of Laurussia. Because at that time available geological data of North America were limited, Marcano et al. (1999) concluded that true pole wandering likely occurred during Permian-Triassic times. However, more recent studies show that the subduction-direction reversed at 275-270 Ma (Early Permian) and that the asymmetric 1200–2400 km wide, Blue Mountains marginal sea closed synchronously at 260-250 Ma (early Late Permian) in a dextral strike-slip tectonic regime (Nelson and Colpron, 2007; Beranek and Mortensen, 2011). This supports our model in which higher convergence velocity is expected northward, i.e. at greater distance from the Euler pole (Figs. 4 and 5).

3.4.2. The western Gondwana margin

In South America, available geological, geochronological and geochemical data indicate synchronous plate-scale events between late Carboniferous to early Jurassic times. Since the Gondwana margin was located south of the Euler pole of rotation of Pangea (Figs. 1 and 5A), we expect a decrease in convergence velocity between the Panthalassa ocean and Gondwana between 280 and 260 Ma and an west-ward motion of Gondwana between 260 and 230 Ma (Figs. 4A and 5A). During subduction, changes plate velocities are known to lead to slab-dip readjustment as the force balance of the system has to equilibrate (e.g., Jaillard and Soler, 1996; Capitanio et al., 2009). In this scenario, we postulate that the decrease of convergence velocity due to Pangea rotation between 280 and 260 Ma (Fig. 4A) resulted in increased coupling forces between the panthalassan slab and the South American margin. This led to the formation of the transient San Rafael orogenic phase along the South American margin (e.g., Mišković et al., 2009) (Fig. 6B). Subsequently, we propose that the counter-clockwise rotation of Pangea between 260 and 230 Ma triggered extensional tectonic conditions along the Gondwana margin. Schellart et al., 2007 showed that large slabs are stable and nearly stationary in their central part. This implies that the lithospheric deformation related to eastward motion of Gondwana was accommodated in the weakest part of the continent i.e. in back-arc region were the lithospheric mantle is metasomatized (e.g., Pankhurst et al., 1988). As a consequence, we postulate that trench advance due to eastward motion of Gondwana resulted in the steepening of the Panthalassa slab, triggering relative opening of the mantle wedge and hot asthenosphere upwelling (Fig. 6C). Associated high heat fluxes along the margin led to partial melting of the mantle, underplating of mafic magma and widespread crustal melting with voluminous S/A-type magmatic and volcanic activity (Fig. 6C), as predicted by modeling of slab steepening (Zhu et al., 2011). At the first order our model is in good agreement with recent studies attributing the Permian change from compressive to extensional setting along the Gondwana margin to slab steepening (Ramos et al., 2011; Rocher et al., 2015; del Rey et al., 2016; Oliveros et al., in press). This model is also supported by the southward widening of the margin area affected by the Permian-Triassic thermal anomaly, since a southward location with respect to the Euler pole of rotation increased the absolute retreat velocity, and thus the effects of the slab steepening (Figs. 4c and 5a). Moreover, the progressive waning of S-type magmatic activity from 230 Ma to 205 Ma along the South America margin (Fig. 3c) was coeval with the end of the Pangea rotation (Figs. 2, 4A and 6D).

3.4.3. The eastern Gondwana margin

During Permian-Triassic times, the eastern Gondwana, including eastern Australia and New-Guinea, was facing the Panthalassa ocean with a trench roughly striking NNW-SSE (Cawood et al., 2011). This implies that, with respect to the Permian-Triassic Euler pole rotation of Pangea, strike-slip movements controlled the tectonic regime of eastern Gondwana during Pangea rotation (Fig. 5a). However, because the trench orientation was roughly parallel to the drifting direction of the margin it is difficult to assess how the rotation of Pangea affected the convergence velocity and the stress-strain conditions in these areas. Nevertheless, the rapid changes in the strain regime from transtensive to transpressive at 270-260 Ma and from transpressive to transtensive at 235-230 Ma (Cawood et al., 2011) are, at the first order, consistent with our model.

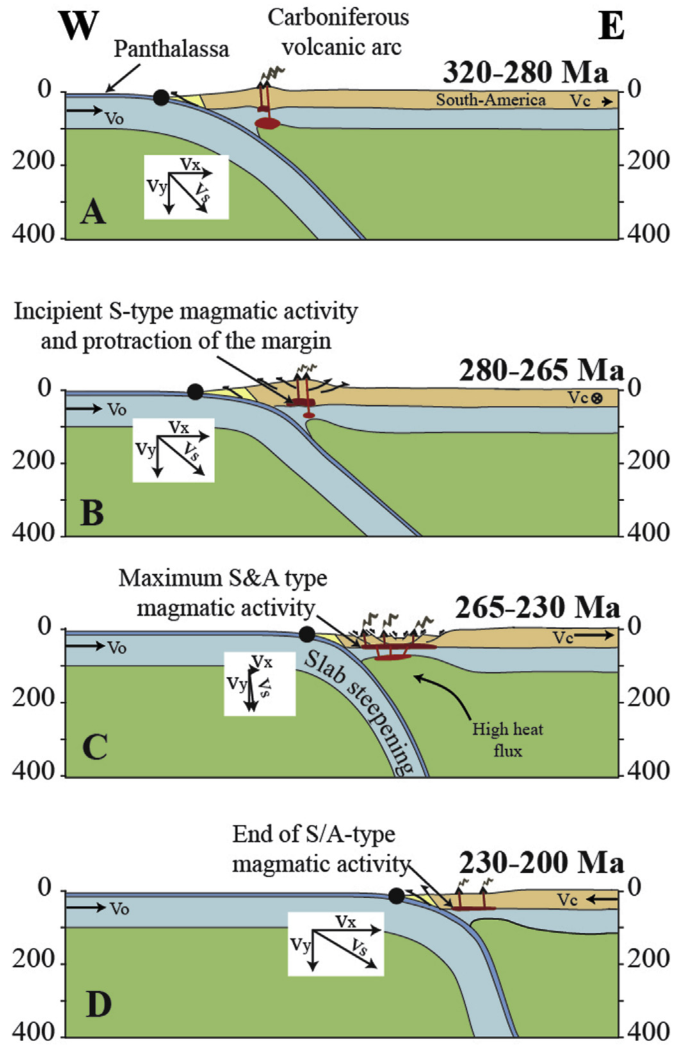

Fig. 6. Schematic evolution model of western South America from 300 to 225 Ma. A: Carboniferous subduction at 300 Ma. B: The widely recorded San Rafael orogenic phase between 275 and 260 Ma related to an increase in coupling forces between the slab and the margin. C: The decrease of the convergence velocity between South America and Panthalassa due to Pangea rotation triggered steepening of the slab and high heat flow in the mantle wedge, producing bimodal magmatism, crust melting and S–type magmatic and volcanic activity. D: End of the Permian-Triassic rotation of Pangea, associated in south America with vanishing of the S-type magmatic activity. In northern Andes (Ecuador, Colombia) this period is associated with strong plate coupling and underplating of blueschists units. Vx, Vy and Vs represent the convergence, the vertical and the subduction velocities vectors, respectively. They are given for visual purpose only, to present the first order changes in force balances between each diagram. Note that Vx = Vo - Vc and that the velocity of the Panthalassa ocean (V_0) cannot be constrained in any way. Consequently we consider only the relative changes in convergence velocity related to the motion of Pangea.

3.4.4. Limitations and perspectives

Although, the reorganization of the Tethyan realm and associated motion of Pangea can explain the first order the geodynamic evolution of the Panthalassan margin from Carboniferous to early Jurassic times, we emphasis that regional variations played an important role in controlling the local tectono-magmatic evolution of the system. This is for instance well expressed in the South American margin where along-trench variations in the slab geometry have been proposed by del Rey et al. (2016) to explain inland shift of the magmatism in southern Chile while it is not recorded in northern Chile. In this light, our model offers a general geodynamic framework allowing to unify the first order tectono-magmatic evolution of the panthalassan margin, while regional second order feature are controlled by local variations.

Another limitation of our conceptual model is that only few data are available about the Permian-Triassic evolution of the northern Laurussia margin. However, this part of the margin accounts for less than 15% of the overall length of the outward Pangea margin (see Fig. 1). Moreover, east of the Laurussia margin, Asia underwent multiple episodes of accretion between 275 Ma and 225 Ma (de Jong et al., 2008). Even though these terranes were not part of the Pangea supercontinent itself, these numerous episodes of marginal sea closure leading to the amalgamation of eastern Asia are consistent with a period of high convergence rate in the northern hemisphere (Fig. 4c,d).

Furthermore, LIPs were emplaced in Siberia at 300–275, 270–240 and 230-197 Ma (Yarmolyuk and Kuzmin, 2011) with a climax at the Permian-Triassic boundary, triggering the well-known major biologic extinction (Ganino and Arndt, 2009). We tentatively propose that these large episodes of magmatic and volcanic activity were geodynamically linked with the reorganization of the Tethyan realm and with the related changes in global apparent pole wandering path of Pangea. Whereas the Permian-Triassic evolution of the outward Pangea margin can be seen from the relatively shallow lithospheric point of view, the emplacement of large igneous province are related to hotspot activity and therefore to the mobilization of deeper part of the mantle. Mantle avalanche have been proposed to explain the episodic and important formation of continental crust during the Archean (van Hunen and Moyen, 2012). As voluminous magmatic and volcanic bodies were emplaced along the whole South America margin during Permian-Triassic times, we speculate that a similar slab fall event could have occurred at that time. Steepening of the slab along the western Pangea margin may have led to an overpressure on the 660 km discontinuity exerted by the slabs resting on this surface, and to the eventual avalanche of these oceanic slabs into the lower mantle, triggering mantle upwelling and widespread melting at the margin, as well as large scale reorganization of the mantle cells. In this light and in order to better understand the global system and the complex Permian-Triassic interactions between the reorganization of the Tethyan realm, Pangea motion, LIP magmatism and mantle activity, the use of advanced tools such as large-scale 3D numerical modeling may be crucial.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jsames.2017.11.007.

References

Aspden, J.A., Bonilla, W., Duque, P., 1995. The El Oro metamorphic complex, Ecuador: geology and economic mineral deposits. Overseas Geol. Miner. Resour. 67, 63.

Beranek, L.P., 2009. Provenance and Paleotectonic Setting of North American Triassic Strata in Yukon: the Sedimentary Record of Pericratonic Terrane Accretion in the Northern Canadian Cordillera. Ph.D. thesis. University of British Columbia, p. 324.

Beranek, L.P., Mortensen, J.K., 2011. The timing and provenance record of the Late Permian klondike orogeny in northwestern Canada and arc–continent collision along western North America. Tectonics 30, TC5017. https://doi.org/10.1029/2010TC002849.

Bustamante, A., Juliani, C., Hall, C.M., Essene, E.J., 2011. 40Ar/39Ar ages from blueschists of the Jambaló region, Central Cordillera of Colombia: implications on the styles of accretion in the Northern Andes. Geol. Acta 9, 351–362.

Caminos, A., 1979. Cordilera frontal. In: Leanza, A.F. (Ed.), Geología Regional Argentina. Academia Nacional de Ciencias de Córdoba, pp. 237–262.

Capitanio, F.A., Morra, G., Goes, S., 2009. Dynamics of plate bending at the trench and slab-plate coupling. Geochem. Geophys. Geosyst. 10, Q04002. https://doi.org/10.1029/2008GC002348.

Cardona, A., Chew, D., Valencia, V.A., Bayona, G., Miskovic, A., Ibanez-Mejia, M., 2010. Grenvillian remnants in the northern Andes: rodinian and phanerozoic paleogeographic perspectives. J. S. Am. Earth Sci. 29, 92–104.

Cawood, P.A., Leitch, E.C., Merle, R., Nemchin, A.A., 2011. Orogenesis without collision: stabilizing the Terra Australis accretionary orogen, eastern Australia. Geol. Soc. Am. Bull. 123, 2240–2255.

Charrier, R., Ramos, V.A., Tapia, F., Sagripanti, L., 2014. Tectono-stratigraphic evolution of the andean orogen between 31° and 37° S (Chile and western Argentina). Geol. Soc. Lond. Special Publ. 399, 13–61. https://doi.org/10.1144/SP399.20.

Clark, A.H., Farrar, E., Kontak, D.J., Langridge, R.J., Arenas, M.J., France, L.J., McBride, S.L., Woodman, P.L., Wasteneys, H.A., Sandeman, H.A., Douglas, D.A., 1990. Geologic and geochronologic constraints on the metallogenic evolution of the Andes of southeastern Peru. Econ. Geol. 85, 1520–1583.

Cochrane, R., Spikings, R.A., Gerdes, A., Winkler, W., Ulianov, A., Mora, A., Chiaradia, M., 2014. Distinguishing between in-situ and accretionary growth of continents along active margins. Lithos 202–203, 382–394.

Coloma, F., Valin, X., Oliveros, V., Vásquez, P., Creixell, C., Salazar, E., Ducea, M., 2017. Geochemistry of Permian to Triassic igneous rocks from northern Chile (28º-30º15′S): implications on the dynamics of the proto-Andean margin. Andean Geology 44, 147–178. https://doi.org/10.5027/andgeoV44n2-a03.

Creixell, C., Oliveros, V., Vásquez, P., Navarro, J., Vallejos, D., Valin, X., Godoy, E., Ducea, M.N., 2016. Geodynamics of late carboniferous–early permian forearc in north Chile (28°30′–29°30′S). J. Geol. Soc. https://doi.org/10.1144/jgs2016-010.

Crowhurst, P.V., Maas, R., Hill, K.C., Forster, D.A., Fanning, C.M., 2004. Isotopic constraints on crustal architecture and Permo-Triassic tectonics in New Guinea: possible links with eastern Australia. Aust. J. Earth Sci. 51, 107–122.

de Jong, K., Kurimoto, C., Ruffet, G., 2008. Triassic $^{40}Ar/^{39}Ar$ ages from the sakaigawa unit, Kii Peninsula, Japan: implications for possible merger of the central Asian orogenic belt with large-scale tectonic systems of the east Asian margin. Int. J. Earth Sci. 98, 1529–1556. https://doi.org/10.1007/s00531-008-0340-1.

Deckart, K., Hervé, F., Fanning, M., Ramírez, V., Calderón, M., Godoy, 2014. U–Pb geochronology and Hf–O isotopes of zircons from the pennsylvanian coastal Batholith, South-Central Chile. Andean Geol. 41, 49–82. https://doi.org/10.5027/andgeoV41n1-a03.

del Rey, A., Deckart, K., Arriagada, C., Martínez, F., 2016. Resolving the paradigm of the late paleozoic–triassic chilean magmatism: isotopic approach. Gondwana Res. 37, 172–181. https://doi.org/10.1016/j.gr.2016.06.008.

Dusel-Bacon, C., Hopkins, M.J., Mortensen, J.K., Dashevsky, S.S., Bressler, J.R., Day, W.C., 2006. Paleozoic tectonic and metallogenic evolution of the pericratonic rocks of east-central Alaska and adjacent Yukon. In: Colpron, M., Nelson, J.L. (Eds.), Paleozoic Evolution and Metallogeny of Pericratonic Terranes at the Ancient Pacific Margin of North America, Canadian and Alaskan Cordillera. Geol. Assoc. Can. Spec. Pap., 45, 25–74.

Farrar, E., Clark, A., Heinrich, S., 1990. The age of the zongo pluton and the tectonothermal evolution of the zongo san Gaban zone in the cordiellera real. Boliv. Int. Symp. Andean Geodyn. Grenoble 171–174.

Franzese, J.R., Spalletti, L.A., 2001. Late Triassic–Early Jurassic continental extension in southwestern Gondwana: tectonic segmentation and pre-break-up rifting. J. S. Am. Earth Sci. 14, 257–270.

Ganino, C., Arndt, N.T., 2009. Climate changes caused by degassing of sediments during the emplacement of large igneous provinces. Geology 37, 323–326.

Glen, R.A., 2005. The Tasmanides of eastern Australia. In: Vaughan, A.P.M., Leat, P.T., Pankhurst, R.J. (Eds.), Terrane Processes at the Margins of Gondwana, vol. 246. Geological Society Special Publication, pp. 23–96.

Golonka, J., 2007. Phanerozoic Paleoenvironment and Paleolithofacies Maps. Late Paleozoic. Mapy paleosrodowiska i paleolitofacje fanerozoiku. Pózny paleozoik. kwartalnik AGH. Geologia 33, 145–209.

Golonka, J., Bocharova, N.Y., 2000. Hot spot activity and the break-up of Pangea. In: Stemmerik, L.S., Trappe, J. (Eds.), Pangea: the Late Carboniferous to Late Triassic Interval, Palaeogeography, Palaeoclimatology, Palaeoecology, vol. 161, pp. 49–69.

Guillot, S., Hattori, K., Agard, P., Schwartz, S., Vidal, O., 2009. Exhumation processes

in oceanic and continental subduction contexts: a review. In: Lallemand, S., Funiciello, F. (Eds.), Subduction Zone Dynamics. Springer–Verlag Berlin, Heidelberg, pp. 175–204.
Gutiérrez-Alonso, G., Fernández-Suárez, J., Weil, A.B., Murphy, J.B., Nance, R.D., Corfu, F., Johnston, S.T., 2008. Self-subduction of the Pangaean global plate. Nat. Geosci. 1, 549–553. https://doi.org/10.1038/ngeo250.
Hervé, F., Fanning, C.M., Calderón, M., Mpodozis, C., 2014. Early permian to late triassic batholiths of the chilean frontal cordillera (28°–31°S): SHRIMP U–Pb zircon ages and Lu–Hf and O isotope systematics. Lithos 184–187, 436–446. https://doi.org/10.1016/j.lithos.2013.10.018.
Jaillard, E., Soler, P., 1996. Cretaceous to early Paleogene tectonic evolution of the northern Central Andes (0-18's) and its relations to geodynamics, 259, 41–53.
Jaillard, E., Hérail, G., Monfret, T., Díaz Martínez, E., Baby, P., Lavenu, A., Dumont, J.–F., 2000. Tectonic evolution of the Andes of Ecuador, Peru, Bolivia and nothernmost Chile. In: Cordani, U.G., et al. (Eds.), , Tectonic evolution of South America, Publ. 31st International Geological Congress, Rio de Janeiro, 481–559.
Jaillard, E., Lapierre, H., Ordoñez, M., Álava, J.T., Amórtegui, A., Vanmelle, J., 2009. Accreted oceanic terranes in Ecuador: southern edge of the caribbean plate ?. In: James, K., Lorente, M.A., Pindell, J. (Eds.), The Origin and Evolution of the Caribbean Plate, vol. 328. Geol. Soc. Spec. Publ., London, pp. 467–483.
Kay, S.M., Ramos, V.A., Mpodozis, C., Sruoga, P., 1989. Late paleozoic to Jurassic silicic magmatism at the Gondwana margin: analogy to the Middle proterozoic in north America? Geology 17, 324–328.
Kleiman, L.E., Japas, M.S., 2009. The Choiyoi volcanic province at 34-36S (San Rafael, Mendoza, Argentina): implications for the late Palaeozoic evolution of the southwestern margin of Gondwana. Tectonophysics 473, 283–299.
Kurz, G.A., Schmitz, M.D., Northrup, C.J., Vallier, T.L., 2012. U-Pb geochronology and geochemistry of intrusive rocks from the cougar Creek complex, Wallowa arc terrane, Blue Mountains province, Oregon-Idaho. Geol. Soc. Am. Bull. 124, 578–595.
Li, P.F., Rosenbaum, G., Rubatto, D., 2012. Triassic asymmetric subduction rollback in the southern New England Orogen (eastern Australia): the end of the Hunter-Bowen Orogeny. Aust. J. Earth Sci. 59, 965–981.
Llambías, E.J., Sato, A.M., 1995. El batolito de Colangüil: transición entre orogénesis y anorogénesis. Rev. la Asoc. Geol. Argent. 50, 111–131.
López Gamundi, O., 2006. Permian plate margin volcanism and tuffs in adjacent basins of west Gondwana: age constraints and common characteristics. J. S. Am. Earth Sci. 22, 227–238.
Maksaev, V., Munizaga, F., Tassinari, C., 2014. Timing of the magmatism of the paleo-pacific border of Gondwana: U-Pb geochronology of late paleozoic to early mesozoic igneous rocks of the north chilean Andes between 20° and 31°S. Andean Geol. 41, 447–506. https://doi.org/10.5027/andgeoV41n3-a01.
Marcano, M.C., Van der Voo, R., Mac Niocaill, C., 1999. True polar wander during the Permo-Triassic. J. Geodyn. 28, 75–95.
Martin, M.W., Kato, T.T., Rodriguez, C., Godoy, E., Duhart, P., McDonough, M., Campos, A., 1999. Evolution of Late Paleozoic accretionary complex and overlying forearc–magmatic arc south–central Chile (38–41°S): constraints for the tectonic setting along the southwestern margin of Gondwana. Tectonics 12, 582–605.
Millar, I.L., Pankhurst, R.J., Fanning, C.M., 2002. Basement chronology and the Antarctic Peninsula: recurrent magmatism and anatexis in the Palaeozoic Gondwana margin. J. Geol. Soc. Lond. 159, 145–158.
Mišković, A., Schaltegger, U., Spikings, R.A., Chew, D.M., Košler, J., 2009. Tectono–magmatic evolution of Western Amazonia: geochemical characterization and zircon U–Pb geochronologic constraints from the Peruvian Eastern Cordilleran granitoids. Geol. Soc. Am. Bull. 121, 1289–1324.
Munizaga, F., Maksaev, V., Fanning, C.M., Giglio, S., Yaxley, G., Tassarini, C.C.G., 2008. Late paleozoic–early triassic magmatism on the western margin of Gondwana: collahuasi area, northern Chile. Gondwana Res. 13, 407–427.
Nelson, J.L., Colpron, M., 2007. Tectonics and metallogeny of the British columbia, Yukon, and Alaskan cordillera, 1.8 Ga to the present. In: Goodfellow, W.D. (Ed.), Mineral Deposits of Canada: a Synthesis of Major Deposit-Types, District Metallogeny, and Evolution of Geological Provinces, and Exploration Methods. Geol. Assoc. Can. Spec. Publ., 5, 755–701.
Oliveros, V., González, J., Espinoza, M., Vásquez, P., Rossel, P., Creixell, C., Sepúlveda, F., Bastías, F., in press. The early stages of the magmatic arc in the Southern Central Andes, in Folguera et al. (eds.): The Evolution of the Chilean-Argentinean Andes. Springer. Berlín.
Pankhurst, R., Hole, M., Brook, M., 1988. Isotope evidence for the origin of Andean granites. Trans. R. Soc. Edinb. Earth Sci. 79, 123–133.
Pichowiak, S., Buchelt, M., Damm, K.-W., 1990. Magmatic activity and tectonic setting of the early stages of the Andean cycle in Northern Chile. In: Kay, S.M., Rapela, C.W. (Eds.), Plutonism from Antarctica to Alaska. Geological Society of America Bulletin, Secial Paper, vol. 241, pp. 127–144.
Poma, S., Zappettini, E.O., Quenardelle, S., Santos, J.O., Koukharsky, M., Belousova, E., McNaughton, N., 2014. Geochemistry, U-Pb SHRIMP zircon dating and Hf isotopes of the Gondwanan magmatism in NW Argentina: petrogenesis and geodynamic implications. Andean Geol. 41, 267–292. https://doi.org/10.5027/andgeoV41n2-a01.
Pullen, A., Kapp, P., Gehrels, G.E., Vervoort, J.D., Ding, L., 2008. Triassic continental subduction in central tibet and mediterranean–style closure of the Paleo–Tethys Ocean. Geology 36, 351–354.
Ramos, V.A., Kay, S.M., 1991. Triassic rifting and associated basalts in the Cuyo basin, central Argentina. In: Harmon, R.S., Rapela, C.W. (Eds.), Andean Magmatism and its Tectonic Setting, Geological Society of America, Special Paper, vol. 265, pp. 79–91.
Ramos, V., Mosquera, A., Folguera, A., Garcia Morabito, E., 2011. Evolución tectónica de los Andes y del engolfamiento neuquino adyacente, Relatorio de la Provincia de Neuquén. Asoc. Geol. Argent. 335–348.
Rapela, C.W., Pankhurst, R.J., Fanning, C.M., Hervé, F., 2005. Pacific subduction coeval with the Karoo mantle plume: the Early Jurassic Sub cordilleran belt of northwestern Patagonia. In: Vaughan, A.P.M., Leat, P.T., Pankhurst, R.J. (Eds.), Terrane Processes at the Margins of Gondwana, vol. 246. Geological Society of London, pp. 217–240.
Reitsma, M., Schaltegger, U., Spikings, R., Winkler, W., Carlotto, V., 2010. Constraining the Age of the Mitu Group, South-east Peru: U-Pb Ages of Detrital and Igneous Zircons. EGU Assembly, Vienna.
Restrepo, J.J., Ordóñez–Carmona, O., Armstrong, R., Pimentel, M.M., 2011. Triassic metamorphism in the northern part of the Tahamí Terrane of the central cordillera of Colombia. S. Am. Earth Sci. 32, 497–507.
Riel, N., Guillot, S., Jaillard, E., Martelat, J.-E., Paquette, J.-L., Schwartz, S., Goncalves, P., Duclaux, G., Thebaud, N., Lanari, P., Janots, E., Yuquilema, J., 2013. A metamorphic and geochronogical study of the Triassic El Oro metamorphic Complex in Ecuador: implications for high–temperature metamorphism in a forearc zone. Lithos 156–159, 41–68. https://doi.org/10.1016/j.lithos. 2012. 10.005.
Riel, N., Martelat, J.-E., Guillot, S., Jaillard, E., Monié, P., Yuquilema, J., Duclaux, G., Mercier, J., 2015. Forearc tectonothermal evolution of the El Oro metamorphic province (Ecuador) during the Mesozoic. Tectonics 680, 174–191. https://doi.org/10.1002/2014TC003618.
Riley, T.R., Flowerdew, M.J., Whitehouse, M.J., 2012. U-Pb ion-microprobe zircon geochronology from the basement inliers of eastern Graham Land, Antarctic Peninsula. J. Geol. Soc. Lond. 169, 381–393.
Rocha–Campos, A.C., Basei, M.A., Nutman, A.P., Kleiman, L.E., Varela, R., Llambias, E., Canile, F.M., da Rosa, O.de C.R., 2011. 30 million years of Permian volcanism recorded in the Choiyoi igneous province (W Argentina) and their source for younger ash fall deposits in the Parana Basin: SHRIMP U–Pb zircon geochronology evidence. Gondwana Res. 19, 509–523.
Rocher, S., Vallecillo, G., Castro de Machuca, B., Alasino, P., 2015. El Grupo Choiyoi (Pérmico temprano-medio) en la Cordillera Frontal de Calingasta, San Juan, Argentina: volcanismo de arco asociado a extensión. Rev. Mex. Cien. Geol. 32, 415–432.
Ruks, T.W., Piercy, S.J., Ryan, J.J., Villeneuve, M.E., Creaser, R.A., 2006. Mid to late Paleozoic K-feldspar augen granitoids of the Yukon-Tanana terrane, Yukon, Canada: implications for crustal growth and tectonic evolution of the northern Cordillera. Geol. Soc. Am. Bull. 118, 1212–1231.
Sato, A.M., Llambías, E.J., Basei, M.A.S., Castro, C.E., 2015. Three stages in the Late Paleozoic to Triassic magmatism of southwestern Gondwana, and the relationships with the volcanogenic events in coeval basins. J. South Am. Earth Sci. 63, 48–69. https://doi.org/10.1016/j.jsames.2015.07.005.
Schellart, W.P., Freeman, J., Stegman, D.R., Moresi, L., May, D., 2007. Evolution and diversity of subduction zones controlled by slab width. Nature 446, 308–311.
Spalleti, L.A., Fanning, C.M., Rapela, C.W., 2008. Dating the triassic continental rift in the southern Andes: the potrerillos formation, cuyo basin, Argentina. Geol. Acta 6, 267–283.
Spikings, R., Reitsma, M.J., Boekhout, F., Mišković, A., Ulianov, A., Chiaradia, M., Gerdes, A., Schaltegger, U., 2016. Characterisation of Triassic rifting in Peru and implications for the early disassembly of western Pangaea. Gondawna Res. 35, 124–143. https://doi.org/10.1016/j.gr.2016.02.008.
Stampfli, G.M., Borel, G.D., 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. Phys. Earth Planet. In. 196, 17–33.
Torsvik, T.H., van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P.V., van Hinsbergen, D.J.J., Domeier, M., Gaina, C., Tohver, E., Meert, J.G., McCausland, P.J.A., Cocks, L.R.M., 2012. Phanerozoic polar wander, paleogeography and dynamics. Earth-Sci. Rev. 114, 325–368.
van Hunen, J., Moyen, J.-F., 2012. Archean subduction: fact or fiction? Annu. Rev. Earth Planet. Sci. 40, 195.
Vásquez, P., Glodny, J., Franz, G., Frei, D., Romer, R.L., 2011. Early Mesozoic Plutonism of the Cordillera de la Costa (34°–37°S), Chile: constraints on the Onset of the Andean Orogeny. J. Geol. 119, 159–184.
Villagómez, D., Spikings, R., Magna, T., Kammer, A., Winkler, W., Beltrán, A., 2011. Geochronology, geochemistry and tectonic evolution of the Western and Central cordilleras of Colombia. Lithos 125, 875–896.
Whittaker, J.M., Müller, R.D., Sdrolias, M., and C., Heine, 2007. Sunda-Java trench kinematics, slab window formation and overriding plate deformation since the Cretaceous, Earth Planet. Sci. Lett., 25,5 445-457, doi.org/10.1016/j.epsl.2006.12.031.
Yarmolyuk, V.V., Kuzmin, M.I., 2011. Rifting and silicic large igneous provinces of the late paleozoic – early mesozoic in the central Asia. Large igneous provinces commission. http://www.largeigneousprovinces.org/11dec.
Zhu, G., Taras, G., Yuen, D.A., 2011. Melt evolution above a spontaneously retreating subducting slab in a three–dimensional model. J. Earth Sci. 22, 137–142.