Geoscience Frontiers 11 (2020) 1219–1229

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Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

The westward lithospheric drift, its role on the subduction and transform zones surrounding Americas: Andean to cordilleran orogenic types cyclicity

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A R T I C L E I N F O

Handling Editor: Christopher J Spencer

Keywords:
Lithospheric drift
Converging hinge
Diverging hinge
Slab rollbakc
Terranes

A B S T R A C T

We investigate the effect of the westerly rotation of the lithosphere on the active margins that surround the Americas and find good correlations between the inferred easterly-directed mantle counterflow and the main structural grain and kinematics of the Andes and Sandwich arc slabs. In the Andes, the subduction zone is shallow and with low dip, because the mantle flow sustains the slab; the subduction hinge converges relative to the upper plate and generates an uplifting doubly verging orogen. The Sandwich Arc is generated by a westerly-directed SAM (South American) plate subduction where the eastward mantle flow is steepening and retreating the subduction zone. In this context, the slab hinge is retreating relative to the upper plate, generating the backarc basin and a low bathymetry single-verging accretionary prism. In Central America, the Caribbean plate presents a more complex scenario: (a) To the East, the Antilles Arc is generated by westerly directed subduction of the SAM plate, where the eastward mantle flow is steepening and retreating the subduction zone. (b) To the West, the Middle America Trench and Arc are generated by the easterly-directed subduction of the Cocos plate, where the shallow subduction caused by eastward mantle flow in its northern segment gradually steepens to the southern segment as it is infered by the preexisting westerly-directed subduction of the Caribbean Plateau.

In the frame of the westerly lithospheric flow, the subduction of a divergent active ridge plays the role of introducing a change in the oceanic/continental plate's convergence angle, such as in NAM (North American) plate with the collision with the Pacific/Farallon active ridge in the Neogene (Cordilleran orogenic type scenario). The easterly mantle drift sustains strong plate coupling along NAM, showing at Juan de Fuca easterly subducting microplate that the subduction hinge advances relative to the upper plate. This lower/upper plate convergence coupling also applies along strike to the neighbor continental strike slip fault systems where subduction was terminated (San Andreas and Queen Charlotte). The lower/upper plate convergence coupling enables the capture of the continental plate ribbons of Baja California and Yakutat terrane by the Pacific oceanic plate, transporting them along the strike slip fault systems as para-autochthonous terranes. This Cordilleran orogenic type scenario, is also recorded in SAM following the collision with the Aluk/Farallon active ridge in the Paleogene, segmenting SAM margin into the eastwardly subducting Tupac Amaru microplate intercalated between the proto-Liquiñe-Ofqui and Atacama strike slip fault systems, where subduction was terminated and para-autochthonous terranes transported. In the Neogene, the convergence of Nazca plate with respect to SAM reinstalls subduction and the present Andean orogenic type scenario.

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Peer-review under responsibility of China University of Geosciences (Beijing).

https://doi.org/10.1016/j.gsf.2019.11.002
Received 17 July 2019; Received in revised form 24 September 2019; Accepted 16 November 2019
Available online 18 December 2019

1. Introduction

The westward drift of the lithosphere relative to the asthenosphere is an ingredient of plate tectonics that has not been well understood so far, both in terms of origin, duration and speed (e.g., Scoppola et al., 2006; Crespi et al., 2007; Carcaterra and Doglioni, 2018 and references therein). However, all reference frames relative to the mantle exhibit a “westerly” directed component of the lithosphere with respect to the asthenosphere. In this research we test the consequences of this phenomenon on the structure and evolution of the subduction and transform zones developed around the Americas (Fig. 1). We discuss the influence of the subduction hinge as a key for interpreting the geometry of the geodynamic setting. The subduction hinge can in fact either converge or diverge relative to the upper plate (Doglioni et al., 2007), producing different slab dips (Fig. 1C and D). Furthermore, we discuss North America active margin low angle convergence, introduced by the subduction of a divergent active ridge producing a complex segmented margin with microplates intercalated between strike slip fault systems, where subduction is terminated.

Westward lithospheric drift is a phenomenon that could be related to the Earth’s rotation mechanics, because the lithosphere rotates slightly slower and eccentric with respect to the underlying convecting mantle (Fig. 1A). The net “westerly” directed rotation of the lithosphere relative to the underlying mantle is a constraint that needs to be considered when evaluating a lithospheric plate subducting into the eastward moving mantle. In other words, whether the subduction of the plate is counter flow or along flow with the mantle. This westward net rotation is indicated by plate kinematics (Gripp and Gordon, 2002) with a value that may span from 0.2°/Ma to 0.4°/Ma to 1°/Ma–1.2°/Ma, as a function of the used hotspot reference frame (Crespi et al., 2007; Cuffaro and Doglioni, 2007). Some models of subduction angle consider the age/-thickness, convergence rate to explain the geometry of subduction, but these parameters have been shown to have negligible influence because slab dip may occur with any lithospheric age or convergence rate (Cruciani et al., 2005). The trenchward motion of thick cratonic lithosphere with trench retreat had also been proposed to promote slab flattening (Manea et al., 2013). The asymmetry of slab dip, i.e., the steeper westerly directed slabs, can rather be interpreted to be related to the westerly net rotation of the lithosphere triggered by solid Earth tidal effects.

In this scenario, the western and eastern boundaries of the Pacific ocean show respectively two end member cases of subduction styles; roll-back Vs, normal to flat slab (Fig. 2), with single and double vergence orogens respectively, that are directly related to the westward lithospheric drift (Doglioni et al., 1999a, b, 2009). Thus considering Americas continental plates (Figs. 1B and 3A), westward subduction dip generates roll back (Caribbean and Sandwich arcs), and eastward subduction dip generates high plate coupling and explains its shallow if not flat subduction dip (Cruciani et al., 2005; Ficini et al., 2017; Juan da Fuca, Cocos and Nazca plates). Besides this subduction asymmetrie, the western and eastern Pacific boundaries show transform plate margins segments (New

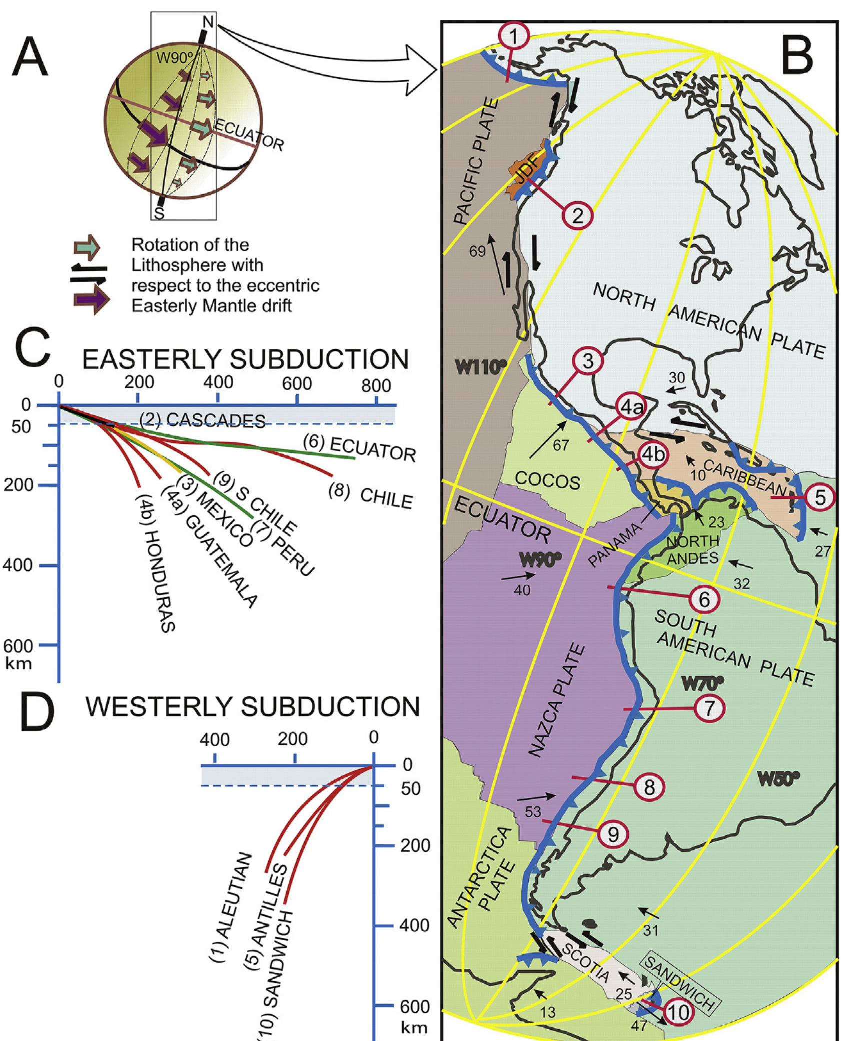


Fig. 1. Simplified global view of the eastern Pacific plates. (A) Global view showing the eccentricity of the easterly mantle drifts with respect to the lithosphere rotation. Notice that for this Longitude; the differences in rotation from the equator to the north diminish, and increase from the equator to the south. (B) Global view of major plate’s arrangements along W90° Longitude. Showing the location of the subduction profiles of the next figure. Based on data from the database SubMap Tool 4.2 (Heuret and Lallemand, 2005, http://submap.gm.univ-montp2.fr/index.php). (C) Easterly subduction zones. (D) Westerly subduction zones.

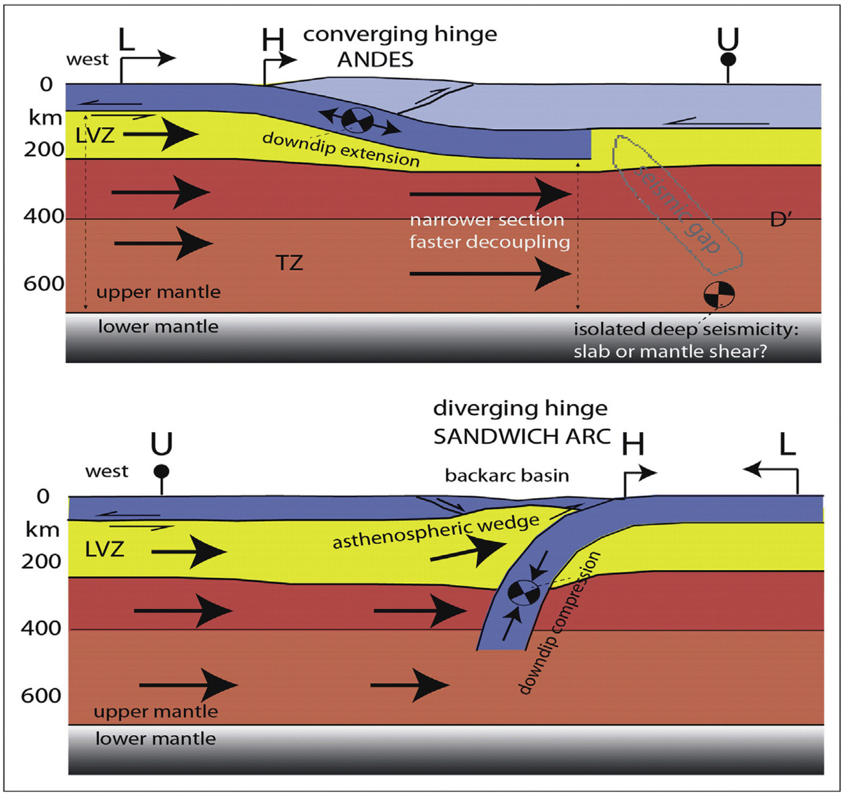


Fig. 2. The westerly directed rotation of the lithosphere implies an easterly directed mantle counterflow and a detachment zone at the low viscosity zone (LVZ). Therefore easterly directed subducted slab is shallower because it is sustained by the mantle flow (upper panel), whereas the westerly directed subducted slab is steeper and deeper where it opposes the mantle flow (lower panel). When assuming a converging lower plate (L) relative to a fixed upper plate (U), the subduction hinge (H) may either converge as in the Andes or diverge as in the Sandwich Arc. Two very different geodynamic settings occur: in the Andes it forms a contracting, upward growing and doubly verging orogen; in the Sandwich Arc it forms a shallow single verging accretionary prism, a deep foredeep and the backarc basin. Deep upper mantle seismicity (550–670 km) beneath the Andes can be inferred as the shear between upper and lower mantle where the flow should be faster, due to the thinner upper mantle section.

Zealand vs. Western North America types) and the subduction of active ridges (Izanagi-Pacific vs. Farallon-Pacific). The western margin of the North America plate (NAM) shows since the Miocene the development of transform segments (San Andreas and Queen Charlotte strike slip fault systems), microplates (Juan da Fuca), and para-autochthonous terranes (Baja California Peninsula, Yakutat), as a consequence of the collision of the Farallon/Pacific active ridge with NAM plate (Plafker et al., 1994; Atwater and Stock, 1998) and the change to a low convergence angle, introduced by the Pacific plate with respect to NAM (Fig. 3B and C). Both transform fault systems are related to extensional settings (Plafker et al., 1994; Atwater and Stock, 1998). Instead, at the western Pacific counterpart, the Pacific and Australian plates show also a transform segment in New Zealand southern island (the Alpes Fault system), that developed in the early Miocene. Along the Alpine Fault, the plates are not only moving past each other, they are also moving towards each other. Here, the main part of South Island is being thrust over the Australian plate. This compressive movement is causing the Southern Alps to be uplifted forming a high elongate mountain range parallel to the Alpine Fault (Wellman, 1979; Norris et al., 1990).

Two major differences are recognized between the Pacific/Australian with respect to Pacific/NAM plate margin transform systems. The first is that the New Zealand transform segment is transpresive and did not originate by the subduction of an active ocean ridge. The second is the change in subduction geometry along strike: To the northeast of New Zealand transform fault, and underneath North Island, the Pacific Plate is being subducted below the Australian Plate. By contrast, to the south of New Zealand transform fault, and underneath Fiordland, the two plates are also moving toward each other but here the Australian Plate is being subducted under the Pacific Plate.

The western margin of the South America plate (SAM) has been active since the early Jurassic to the present time. There is agreement on the subduction relationship along strike SAM for the Aluk plate in the Cretaceous, and for the Nazca plate in the Neogene, but in the Paleogene, the collision with the Aluk-Farallon active ridge segmented the margin. Reconstructions for the Aluk-Farallon-SAM triple junction suggest that it migrated from southern Peru-northern Chile to the Patagonian Andes within the 72–47 Ma time interval, and reconstructions of the Farallon-SAM plates for the Paleogene agree in the occurrence of northward obliquity of the convergence angle and negligible to moderate convergence rates (Cande and Leslie, 1986; Pardo Casas and Molnar, 1987; Somoza and Ghidella, 2005). The Farallon-Aluk ridge collision with SAM introduced low convergence angle episodes between Farallon/SAM Plates in the Paleogene, and the segmentation into subducting microplates intercalated with strike slip plate margin transform segments (Aragon et al., 2011; Giani et al., 2018).

The strike slip plate margin transform segments show extension, uplift and bimodal volcanism in the foreland, such as San Andreas fault system with Basin and Range province in the foreland (Hakesworth et al., 1995). In plate margin dynamics of the past, extension in the foreland is usually attributed to roll back, without checking if the slab subduction direction with respect to the mantle flow is capable of generating roll back, or whether the extension is related to subsidence or uplift.

This paper considers the influence of the westward lithospheric drift (relative to the convecting mantle) on the eastern pacific active margin and examines how a change to low angle convergence introduced by the Paleogene collision of an active ocean ridge can result in the termination of the Cretaceous continuous subduction system of the Andes and develop the Paleogene segmentation of the active margin into microplates, para-autochthonous terranes, as well as coeval transform and subduction segments. The western Pacific subduction style and the New Zealand transform type will not be considered here. We propose a model of Plate margin segmentation in times of low angle convergence introduced by a triple junction. To achieve this we use present day major constraints from NAM western active margin, and compare them with those from the SAM Paleogene western active margin.

2. Easterly dipping subduction zones of America

Easterly dipping subduction zones with the North American plate result from interactions with the Pacific, Cocos and Juan de Fuca Plates.

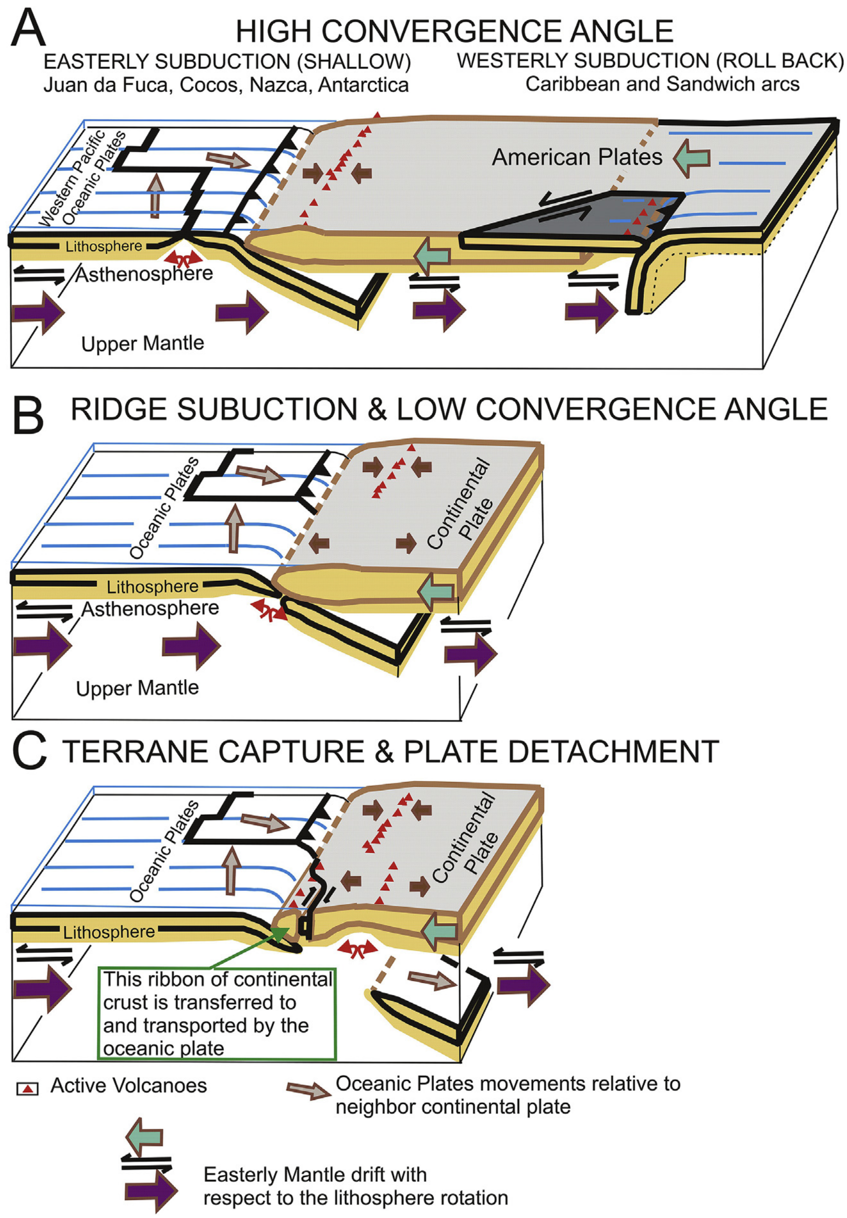


Fig. 3. Schematic in short representation of the American plates, Pacific/Atlantic oceanic plates and active ridges scenarios with respect to the westward lithospheric drift: (A) The South American plate show both easterly and westerly directed subduction. The easterly directed subducted slab is shallower because it is sustained by the mantle flow, whereas the westerly directed slab is steeper and deeper where it opposes the mantle flow. (B) The west margin of the American continental plates subducting systems have been subject to several arrivals and subduction of active ridges. The collision with a ridge segment causes relaxation and extension in the continental counterpart, and the detachment of the subducted plate. (C) Because of the high coupling between the underlying and overlying plates (sustained by the mantle flow), and partitioning of oblique convergence, the subducted rim of the new plate moving parallel to the continent can capture a ribbon of continental margin and transport it, as a para-authochtonous terrane.

In addition, the Pacific/NAM interaction is a strike and slip fault relationship (Queen Charlotte and San Andreas strike slip fault systems), due to the low convergence angle between them (Figs. 1B and 7A). In these strike slip fault segments the subduction was terminated and part of the subducted plate is detached (slab window). In North America, the only remnant of easterly subduction is restricted to the Cascades arc promoted by the subduction of the Juan de Fuca microplate, bounded by the Queen Charlotte and San Andreas fault systems where subduction terminated at ca. 30 Ma. In Juan de Fuca microplate, the subduction hinge advances relative to the upper plate (Fig. 1C, Cascades cross-section; Fig. 2A) causing strong coupling between underlying/overlaying plates. This coupling between plates continues in the neighbor strike slip segments of San Andreas and Queen Charlotte fault systems, allowing the underlying Pacific plate to capture ribbons of the continental margin and transport them along the strike slip faults (Baja California and Yakutat terrane respectively, Fig. 7A).

Towards the south of NAM and the Central America strip, the subducting plate is the Cocos Plate, and the overriding plates are the NAM, Caribbean plates and part of Panama micro-plate. Subduction beneath the NAM plate shows high coupling and the shallow subduction angle is similar to that in South America (Fig. 1C, Mexico cross-section), but to the south, as subduction interacts with the Caribbean plate, the subduction angle increases (Fig. 1C, Guatemala and Honduras cross-sections), and plate coupling gradual decreases (Scholz and Campos, 1995). This subduction angle increase is solely restricted to the Caribbean Plate segment, Thus, the subducting parameters of Cocos plate; age, convergence angle and rate, are the same as in the subduction beneath the neighbor Mexico's NAM plate segment. Then, the factor controlling the Cocos plate subduction angle beneath the Caribbean plate can be interpreted to be restricted to the relationship between the Caribbean lithosphere and asthenosphere. From Fig. 1C, it is suggested that a recognizable subduction angle change between Mexico and Honduras cross sections occurs at depths in excess of 50 km, suggesting that it occurs at or beyond the lithosphere/asthenosphere boundary. If so, it could be interpreted as confronting subduction plates in the Caribbean asthenosphere. An argument supporting this conclusion comes from Costa Rica and the southern neighbor (Panama microplate: Astorga et al., 1991) that interacts with the southern end of Cocos plate (in early and mid Mionene) and the northern end of Nazca plate (since late Miocene). In this scenario, the narrow Panama and Costa Rica are subject to the

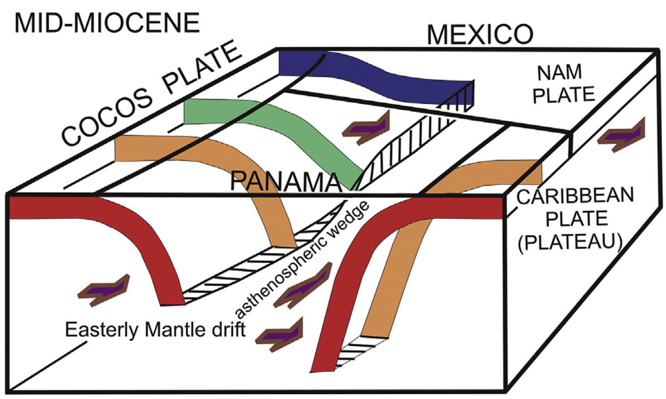


Fig. 4. Schematic block diagram of the coeval just opposite subduction of Cocos and Caribbean plates beneath Central America in the mid Miocene. The westward subduction of the Caribbean plateau (20 km thick) beneath Panama and Costa Rica began 33 Ma ago (Pindell, and Kennan, 2009) and predates the beginning of the just opposite eastward directed subduction of Cocos plate since 19 Ma (Mescua et al., 2017). The Cocos plate is a young plate with no age; or convergence rate; or angle differences along the trench that may justify any change in the subduction geometries, from shallow in the north to steep in the south (Fig. 1C). This suggests the pre-existence of an opposite thick lithosphere counterflow subduction that controlled the subduction angle of the Cocos plate at its southern end.

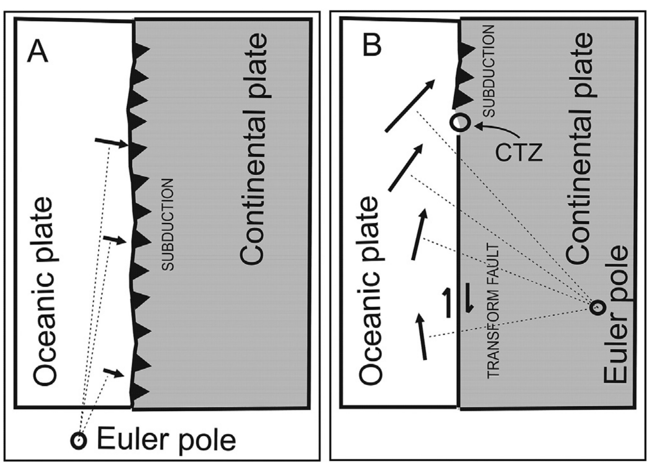


Fig. 5. Main end member oceanic-continental plate Euler pole geometries considered for this model. (A) The oceanic plate motion projections from the Euler Pole are quite parallel to the oceanic-continental plate boundary. As the distance from the Euler pole increase, the perpendicular convergence angle changes are small, but convergence rates increase. (B) The oceanic plate motion projections from the Euler pole are perpendicular to the oceanic-continental plate boundary. But as the distance from the Euler pole increase along the oceanic-continental boundary the convergence angle changes from parallel to highly oblique with a notorious increase in the convergence rates. References: CTZ = critical Transition Zone; Arrows = vectors showing oceanic plate convergence angle and rate with respect to continental plate.

coeval just opposite easterly and westerly subduction of the Cocos and Caribbean plates respectively in the mid Miocene (Figs. 1A and 4). The Caribbean plate started to subduct the thick Caribbean plateau beneath Panama and Costa Rica in the early Oligocene ~33 Ma (Pindell and Kennan, 2009). But on the Pacific side, Farallon plate split into Nazca and Cocos plates at ~23 Ma, had oblique convergence until ~18 Ma that changed to orthogonal convergence between the Cocos plate and the Middle America trench (Mescua et al., 2017) causing subduction and contractional deformation along Costa Rica and Nicaragua (Weinberg, 1992; Kumpulainen, 1995; Ranero et al., 2000; Mescua et al., 2017), with the arc having its maximum migration toward the foreland (Alvarado and Gans, 2012; Saginor et al., 2013). The extensional configuration of the Nicaragua subduction zone (e.g., Burkart and Self, 1985; Ramos, 2010) with the migration of the arc towards the trench starting in the latest Miocene ~11 Ma, after the contraction event (Alvarado and Gans, 2012; Saginor et al., 2013). The arrival of the Cocos Ridge at the trench at 5–4 Ma (Meschede et al., 1999) further modified the geodynamic setting, leading to the present configuration in which contraction is predominant only in southern Costa Rica (Marshall et al., 2000; Manea et al., 2013). The mid Miocene compression event caused by the coeval opposite eastwardly subduction of Cocos plate and the westward subduction of the Caribbean plate, suggest that the pre-existence of the subducted thick plateau of the Caribbean plate at the southern end of Cocos plate controls the gradual steepening of Cocos plate subduction angle (Fig. 4).

The Andes are located above the easterly-directed subduction (high convergence angle) of the Nazca oceanic lower plate slab (Fig. 1). In the northern side, the lower plate was the Cocos Plate, whereas south of the Chile triple junction it is the Antarctica plate. Along the Sandwich Arc, the SAM subducted slab is westerly directed and as the upper plate is located the Scotia backarc basin. Based on the dataset of Heuret and Lallemand (2005) few cross-sections of the slab seismicity representing the projection of a 200 km wide volume are presented (Fig. 1C and D), that show normal to flat subduction segments all along the Andean orogen. These subduction geometries, are explained by a high trenchward absolute velocity of the upper plate (overriding of the trench by the upper plate) (Forsyth and Uyeda, 1975; Heuret and Lallemand, 2005; Somoza and Zaffarana, 2008). Or in other words, the mantle flow sustains the slab; the subduction hinge converges relative to the upper plate and generates an uplifting doubly verging orogen (Doglioni et al., 2007). Other processes proposed to influence the subduction are: subduction of an oceanic ridge (Cloos, 1993; Ramos and Folguera, 2009); age of the subducted oceanic lithosphere (Protti et al., 1994; Yáñez and Cembrano, 2004); and sediment supply to the trench (arid climates) (Lamb and Davis, 2003).

The thickness of the continental South America lithosphere varies moving along the strike of the subduction zone (Artemieva, 2009; Hamza and Vieira, 2012), being thicker where the slab dip increases (Cruciani et al., 2005).

South America is moving westerly relative to the mantle, but it also undergoes a clockwise rotation (Cuffaro et al., 2008). This second order rotation with respect to the first order one can account for the strike-slip component at the South America-Nazca plate boundary.

3. Westerly subduction zones of America

Two westerly subduction zones are recognized within the SAM plate, the South Sandwich and the Lesser Antilles arcs. A third westerly subduction zone is localized in NAM plate at the Aleutian arc.

The South Sandwich active volcanic arc is built largely on oceanic crust of the small Sandwich plate which formed about 10 Ma at the back-arc East Scotia ridge spreading centre (Larter et al., 2003). The arc is forming in response to steeply inclined subduction of the South American plate beneath the Sandwich plate at the rate of 67–79 mm/Ma (Thomas et al., 2003). Models for South Sandwich arc evolution have a westward-dipping subduction zone active at 34 Ma or earlier for the ancestral South Sandwith volcanic arc, and 4–5 Ma for the active South Sandwich volcanic arc. (e.g. Barker, 1995, 2001; Larter et al., 2003; Pearce et al., 2014). The South Sandwich volcanic arc has a steep subduction front (Figs. 1D and 2) and the volcanism shows a typical western Pacific geochemical signature of Volcanic Island arcs (Pearce et al., 2014).

The Lesser Antilles Cenozoic volcanic arc is related to subduction of the SAM plate under the Caribbean plate. The rate of subduction is low, 20–40 mm/yr (Macdonald and Holcombe, 1978; Jarrard, 1986). The steeply inclined subduction of the Atlantic plate beneath the Caribean plate is segmented; in the northern segment the subducted plate dips at

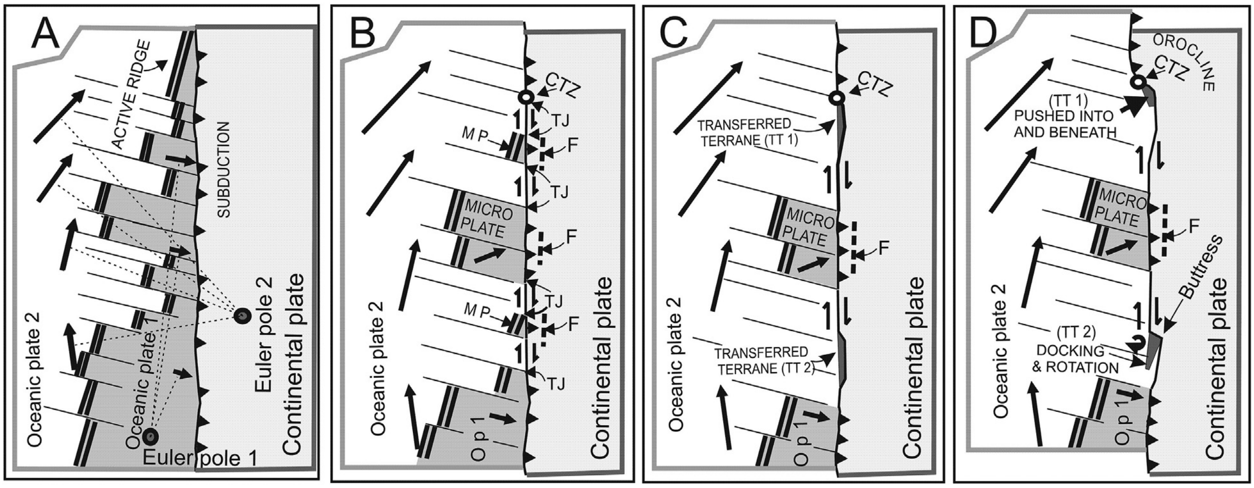


Fig. 6. Schematic representation for the development of a complex segmented plate margin. (A) Arrival of an active ridge with a subducting plate where the newly arriving plate changes convergence to very low angle. (B) As the active ridge segments reach scattered along different places of the trench, triple junctions (TJ), and transform oceanic-continental plate segments are developed, leaving scattered remnants of not-subducted oceanic ridge that feed microplates. In the fore-arc important fault systems (F) are activated parallel to the trench. (C) The high coupling caused by both, the lithospheric drift and the westward push of the Atlantic ridge on the continental plate, causes that the underlying oceanic plate may capture a ribbon of the continental crust, creating para-autochthonous terranes of continental crust that move along with the ocean plate. (D) The transform movement transport the terranes TT 1 and TT 2 to two different situations; The TT 1 case reaches the critical Transition Zone (CTZ) and is "pushed into and beneath" the continental plate (duplicating the crust), and the orogenic belt bends (orocline). Instead the TT 2 case moves until it reaches a buttress and "docks" against the continental plate showing shortening by rearrangement of blocks by vertical axis block rotation. References: CTZ = critical Transition Zone; TJ = Triple Junction; F = Transtensional fault system; Op 1 = Oceanic plate 1; TT 1 and 2 = Transferred Terranes as continental ribbons are captured by the oceanic plate; M P = Microplate.

50°–60°, whilst the southern segment the dip varies from 45° to 50° in the north to vertical in the south. Activity in the eastern arc was mainly from Eocene to mid-Oligocene, whereas the western arc has been active from early Miocene to present. Although there is evidence, that the arc north of Dominica may be underlain by a Cretaceous arc (Bouysse, 1984; Macdonald et al., 2000).

4. The lithospheric westward drift and the segmentation of the American plate margin caused by the subduction of an active ridge

Since oceanic and continental plates move along the surface of a sphere (geoid), the motion, rates and type of plates interaction depends on the relative location of the Euler Pole of the oceanic plate with respect to the continental plate margin (Fig. 5A and B). The two possible end-member cases are: (a) the active plate margin may have the oceanic plate's Euler pole located in a position in which rotation only allows convergence (Fig. 5A), and the only change is an increase of convergence rate as the distance to the Euler pole increases. (b) The oceanic plate's Euler pole may be located in a position where rotation allows a parallel movement of the oceanic plate with respect to the continental plate (Fig. 5B) and along-strike plate interaction may change from a transform plate margin, to a subduction plate margin as the lateral distance to the Euler pole increases.

NAM and SAM have been subject to the collision of active ridges in the Cenozoic (Fig. 7A and B). These events have introduced major changes in the geological features of the continental margins.

The coeval collision of a ridge at different latitudinal sites of the continental plate, promotes the segmentation of the continental/oceanic plates boundary into a complex of along strike alternation of subduction with strike slip transform segments such as in NAM the collision with the Pacific/Farallon active ridge in the Neogene (Fig. 7A). Here, the eastwardly subducting Juan da Fuca microplate is intercalated between the San Andreas and Queen Charlotte strike slip fault systems, where subduction is cancelled.

The development of an active margin segmentation as defined here, has four main constraints: (1) the collision of an active oceanic ridge (divergent sea-floor spreading centre) with a continental plate (Fig. 6A and B). (2) The newly incoming ocean plate has an Euler Pole configuration (Fig. 6A) that terminates subduction by introducing parallel displacement along a significant length of the active plate margin. (3) Since the active ocean ridges are segmented they may produce a coeval scattered collision of the active ridge, leaving isolated remnants of unsubducted ridge segments that become oceanic microplates (Fig. 6B, C and D). (4) The westward lithospheric drift sustains a strong coupling between oceanic/continental plates, allowing the capture of continental plate ribbons by the oceanic plate (Fig. 3C). These conditions were met in the NAM/Farallon/Pacific plate boundary (Plafker et al., 1994; Atwater and Stock, 1998), and in the Paleogene with the SAM/Aluk/Farallon plate boundary (Fig. 7B) (Cande and Leslie, 1986; Pardo Casas and Molnar, 1987; Somoza and Ghidella, 2005; Aragón et al., 2011).

The role of the collision for the active ocean ridge is twofold; it provides the possibility that the next incoming ocean plate can produce an instantaneous major change in the ocean-continental plate convergence angle, and it provides a major discontinuity to facilitate a new type of oceanic/continental plate interaction. This implies that the previous subduction geometry has little or no influence on the overriding plate segment as the subducted plate detaches and sinks into the mantle. The main remaining forces active are; the westward lithospheric drift and the westward push of the SAM and NAM plates growth.

The next major question to consider in the model is the critical Transition Zone (CTZ) from transform to subduction active margin (CTZ in Fig. 5B). From the mechanical point of view, it should be controlled mainly by six major constraints; the critical convergence angle in which the transform finally evolves to subduction, the convergence rate, the shape and rheology of the continental plate margin, and the partitioning of the convergence angle.

An estimate value of the critical angle and the convergence rate, combined with the continental plate margin/subduction shape, rheology and partitioning can be obtained from the present day Pacific/NAM example. In southern Alaska/Canada as the Pacific plate moves northward, it shifts from the Queen Charlotte transform margin to that of subduction in the Aleutian trench (with a drastic change in convergence angle). The convergence angle of the Pacific plate with the Queen

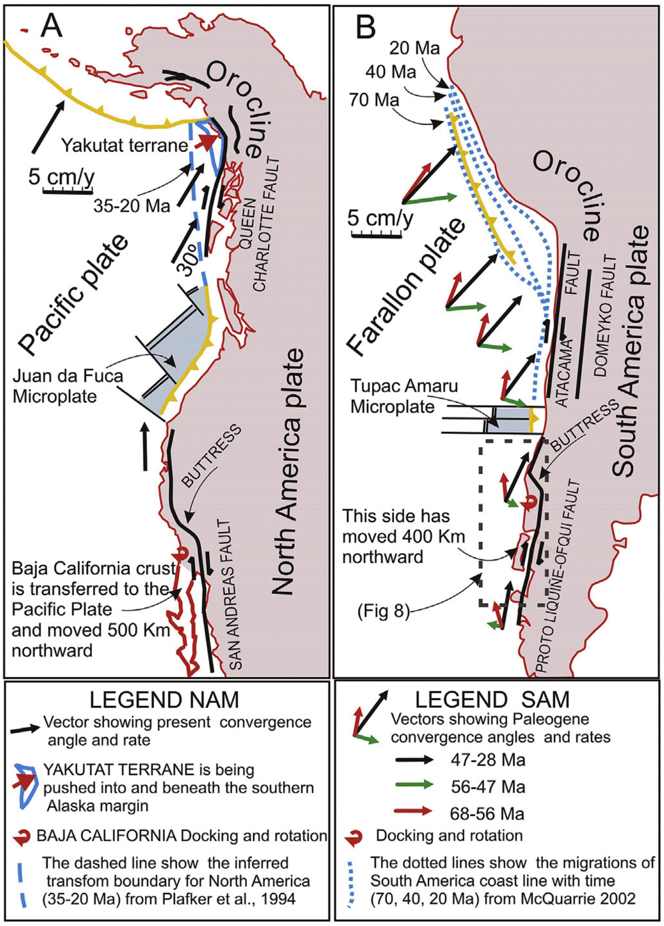


Fig. 7. Schematic representation of Ocean-Continental plate segmented plates margins: (A) The Neogene Pacific-NAM plates segmented system is developed by the Farallon-Pacific-NAM triple junctions. (B) The Paleogene Farallon-SAM plates Transform segmented system is developed by the Aluk-Farallon-SAM triple junctions.

Charlotte transform system is about 30° with an average convergence rate of 6 cm/yr for the last 5 Ma (Engebretsen et al., 1985). Thus, a 30° convergence angle could be considered a reference value for the critical Transition Zone for low convergence rates in the order of 6 cm/yr. On the other hand, to consider the influence of shape, rheology and the partitioning of effort into the continental margin, the reconstruction must be based on the paleogeographic reconstruction at the time when the Queen Charlotte transform began. Plafker et al. (1994) reconstruct the early (35–20 Ma) position of the transform fault boundary (stippled line Fig. 7A). At about 30 Ma the transform fault boundary jumped inland from the early transform fault boundary system to the Queen Charlotte-Fairweather fault system to form the Yakutat terrane. The continuous subduction of the Yakutat terrane in the last 20 Ma has increased the bend of the Alaska gulf and resulted in the uplift of the Chugach Mountains and Fairweather Range. This suggests that the strong northeastward deformation is closely related to partitioning in the critical Transition Zone from the Queen Charlotte transform to the bend of the Aleutian subduction. Oblique convergence zones have partitioned plate boundaries, with the shortening component being taken up on the subduction zone and the major portion of the strike-slip component being taken up by strike-slip faults inland, in the overriding plate.

Another orogenic feature present close to the critical Transition Zone is the Alaska orocline. Although it is not established to which extent the subduction of the Yakutat terrane has influenced the deformation of the Alaska orocline (Johnston, 2001), it must also be considered that to some extent, there was a continental bend before the Yakutat terrane started to push beneath southern Alaska.

4.1. The oceanic/continental boundary jumps inland with a strike slip fault at the boundary: the oceanic plate captures a continental ribbon

As the low convergence angle plate motions are sustained over time, partitioning develops in the overriding continental plate margin major strike slip fault systems (Fig. 6B) close and parallel to the coast. The easterly mantle drift sustains strong coupling along NAM, and at Juan de Fuca subducting microplate that the subduction hinge converges relative to the upper plate. This upper/lower plates coupling also applies to the neighbor continental plate margin with the strike slip fault systems (San Andreas and Queen Charlotte) where subduction has stopped, and extension developer in the foreland (Basin & Range). These crustal strike slip fault segments have strong coupling with the underlying plate. Thus, the remaining subducted Pacific plate, will eventually capture the overlying continental plate ribbon (Baja California and Yakutat terrane), transporting them along strike as para-autochthonous terranes (Fig. 6C).

Two major different fates are observed for these para-autochthonous terranes transferred to, or captured by the oceanic plate (Fig. 6D): (a) If the para-authochtonous terrane arrives at the critical Transition Zone (see TT 1 in Fig. 6D), then that terrane will be pushed into and beneath the continental crust as exemplified by the Yakutat terrane in southern Alaska (Queen Charlott/Aleutian arc transition zone) in the last 6 Ma (Plafker et al., 1994). (b) Instead, if the terrane is stopped by a continental margin buttress (see TT 2 in Fig. 6D), such as the Baja California peninsula, it docks along the continental margin, as its northwestward motion is hindered at the San Andreas Fault restraining bend (buttress). It shows in the collision end some internal deformation such as shortening (clockwise imbrication) by vertical axis block rotations, and by the deformation along the transverse range. The transport of the Baja California peninsula began around 6 Ma when Magdalena and Guadalupe microplates were captured by the Pacific plate and the plate boundary had fully jumped eastward and formed the Gulf of California transtensional fault system (Lonsdale, 1991; Atwater and Stock, 1998; Plattner et al., 2009). Further on, as the Baja California northwestward motion was impeded at the San Andreas Fault restraining bend (buttress), the whole Baja California terrane rotates clockwise opening the Gulf of California sea floor.

5. The south America paleogene transform margin segmentation

With the perspective of a complex continental-oceanic plate segmentation system (Figs. 6D and 7A), an analogy can be made with the Aluk-Farallon-SAM triple junction for the Paleogene (Fig. 7B). The Farallon-SAM reconstructions for the 68–28 Ma interval (after Somoza and Ghidella, 2005), show that by that time, the Aluk-Farallon-SAM triple junction had interacted along the southern South America margin and that the Farallon plate had two episodes of Euler pole rotation (one in the Paleocene and the other in the Oligocene), that promoted a Farallon/SAM plates low convergence angle relative motion, similar to that which occurred between the Pacific/NAM plates in the Neogene (Fig. 7A and B). A significant difference with NAM, is the episode of a higher convergence angle during the Eocene.

5.1. The Paleocene and oligocene transform segmentation episodes

Partitioning caused by the plates low convergence angle during these Paleocene and Oligocene episodes of transform faulting have used first-order, continental-scale, trench-parallel strike-slip fault systems in northern and Southern Chile (Atacama, and Liquiñe-Ofqui fault systems respectively, Fig. 7B). But the Atacama (northern Chile) and Liquiñe-Ofqui (southern Chile) fault systems are not connected. As a result, a broad zone in central Chile area is free of trench-parallel strike-slip fault systems. The central Chile Paleogene deformation is a fold-and-thrust belt (west-east convergence) with a complete absence of the southern and northern Chile coastal strike-slip fault systems (north-south). In this scenario, the coeval existence of a west-east convergent deformation bounded by two major continental margin (north-south) strike-slip fault systems negates a simple two plates shallow convergence partitioning. If so, a few remnants of the Aluk-Farallon active ridge could have remained unsubducted at the central Chile latitude, preserving a hypothetical oceanic microplate "*Tupac Amaru*", and retaining subduction (throughout the Cenozoic) in the central Chile segment of the Andes as is also suggested by the continuous presence of calc-alkaline arc magmatism including the Paleocene to Miocene batholiths (e.g., Cogotí Super unit, 67–35 Ma; Río Grande Super unit 26–24 Ma; Río Chicharra Super unit 17–9 Ma; Rivano et al., 1985) and volcanic formations (e.g., Doña Ana Group, Las Tórtolas, Tambo, Vallecito and further south Abanico and Farellones covering from ~34 Ma to 5 Ma; Charrier et al., 2007) limited mostly to this segment.

To the south of the Tupac Amaru microplate (Fig. 7B), the Patagonia-Farallon transform system was well developed along the Proto-Liquiñe-Ofqui fault (Aragón et al., 2011), transporting and docking the fore-arc more than 400 km to the north (Garcia et al., 1988). During the Paleocene, Patagonia was subjected to extension (Aragón et al., 2011), plutonic magmatic arc activity shows nearly total quiescence (Pankhurst et al., 1999), with volcanic activity having migrated to the former back-arc characterized by bimodal rhyolite-basalt magmatism (tholeiitic and alkalic basalts), having rhyolites and basalts with low Ba/Nb ratios.

The Oligocene–early Miocene Farallon/SAM plates low angle convergence episode was accompanied by magmatic activity with intraplate affinities in the former fore and back arc with the Coastal belt (Muñoz et al., 2000) and the El Maiten belt (Aragón et al., 2011) respectively.

It is suggested (Fig. 8) that the northward motion of the terranes to the west of the proto-Liquiñe-Ofqui fault system may have been restrained by a buttress (present Lananhue fault system Aragón et al. (2011), an interpretation supported by shortening by vertical axis block rotations (clock and counter clock) in los Lagos area (Beck et al., 1993).

To the west of the proto-Liquiñe-Ofqui fault system, the northwestward displacement and docking of the Chonos terrane develops results in extension and opening of a gulf with thin continental or oceanic floor as suggested by the pillow basalts and dykes (the Traiguén Formation, Fig. 8) with geochemical MORB/volcanic arc affinities (Herve et al., 1995).

In the Miocene, the Traiguén Formation with pillow basalts is tectonically inverted caused by a nearly orthogonal plate convergence, after the breakup of Farallon plate to give birth to Nazca plate at about 23 Ma (Lonsdale, 2005). These pillow basalts are intruded by the Miocene plutons of the North Patagonian batholith (Pankhurst et al., 1999). This major convergence change introduced by the new Nazca plate ends with the Paleogene transform plate margin Complex (Cordilleran type orogen), and starts a new subduction episode with the Neogene arc magmatism and the Andean type orogen building.

To the north of the Tupac Amaru microplate (northern Chile), the Atacama and Domeyko fault systems were active in the Paleogene. Extension dominated the Paleocene and the Oligocene; convergence characterizes the Eocene with the Domeyko fault system associated with the Incaic orogeny (Charrier et al., 2009). The Atacama fault system is located very close to the edge of the continental plate, and it has been active since lower Cretaceous time (Scheuber and Adriessen, 1990; Niemayer et al., 1996) suggesting earlier episodes of oblique convergence with a highly partitioned strain system at this latitude (Mpodozis et al., 2005). The Paleocene syn-extensional magmatism of northern Chile includes at the former fore-arc bi-modal potassic-calcalkaline with associated development of nested caldera complexes (Cornejo et al., 1994), porphyry copper deposits and episodic within-plate-like magmatism (Cornejo and Matthews, 2000; Rabbia et al., 2013). The Coastal Batholith of Peru also shows episodic quiescence of magmatic activity (e.g., Arequipa segment), or caldera complexes development (e.g., Lima segment) for this time (Cobbing and Pitcher, 1983). The syn-extensional bi-modal magmatism, porphyry copper deposits and with within-plate-like basalts strongly supports a transform plate margin setting, much like that of Queen Charlotte transform margin in western Canada for the northern Chile segment along the Paleocene.

Finally, the Andean orogen forms the Bolivian orocline in the Eocene-Oligocene (McQuarrie, 2002; Arriagada et al., 2008). Reconstructions of the Bolivian orocline find that east-west shortening is too low to explain the thick Andean crust and propose significant material transfer from the south toward the center of the orocline. Hindle et al. (2005) and Arriagada et al. (2008) estimate 30%–40% and 10%–15% (respectively) of material displaced with along-trend component compared to the material that moved normal to the trend of the mountain range. This excess of material required for the orocline thick crust can be provided by the terranes that moved along the transform margin and where pushed into and beneath the continental crust as they reached the critical Transition Zone. In present time the Atacama fault system is adjacent and parallel to the trench and is devoid of Paleogene terranes. The good fit between the age of deformation of the Bolivian Orocline, and the location of the critical Transition Zone for the Farallon-SAM complex segmented system is considered analogous to the Yakutat terrrane subduction and the Alaskan Orocline, implying that the Bolivian Orocline could be related to the critical Transition Zone where the continent-ocean plate transform system along the Atacama fault evolved (to the northeast) into subduction and the fore-arc terranes could be pushed into and beneath the continental plate providing the excess of mass transfer needed to build the Bolivian orocline.

5.2. *The eocene convergence angle increase episode*

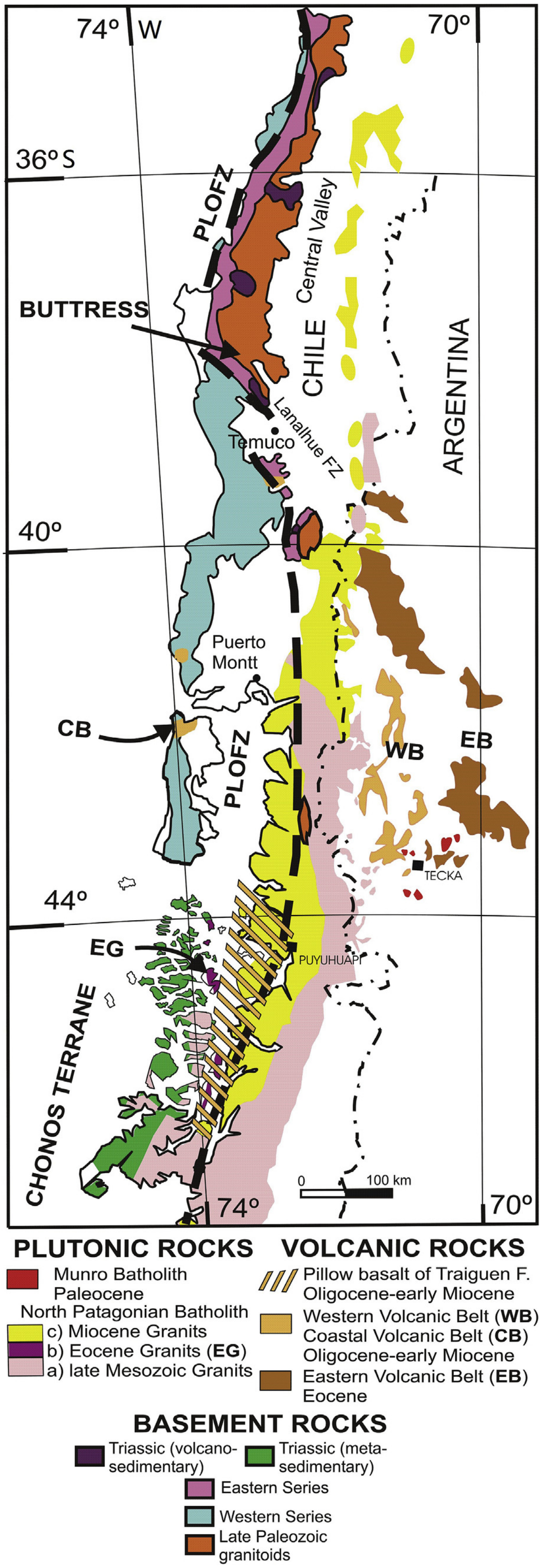
The change of the Euler pole position in the Eocene (Somoza and Ghidella, 2005) for the Farallon plate with respect to SAM increased the convergence angle along SAM active margin, but with a strong decrease in convergence rate from northern to southern Chile (Fig. 7B). The north-south differences of convergence rate has caused; in northern Chile the Eocene Incaic Orogen along the Domeyko transpresive fault system, with the emplacement of super-giant porphyry copper deposits at the end of this orogeny (Charrier et al., 2009). The convergence capable of building the Incaic orogeny suggests that the transform plate margin developed in the Paleocene in northern Chile may have evolved into subduction during the Eocene. Instead, in southern Chile, the Eocene convergence rate is so minor that there is a total absence of any evidence of horizontal shortening, to the extent that it has been proposed that the Paleocene transform margin continued as a transform margin until late Oligoene/early Miocene (Aragón et al., 2011) when the new Nazca plate rearrangement re-installed subduction all-along the western SAM margin.

6. Final remarks

Subduction zones in NAM, SAM Caribbean and Scotia plates show easterly and westerly directed subduction zones. The westerly directed subduction zones have steep subduction angles. The eastward mantle flow results in the steepening and retreating of the subduction zone (Fig. 2). In this context, the subduction hinge is diverging relative to the upper plate, generating the backarc basin and a low bathymetry single-verging accretionary prism. On the other hand, the observed westerly directed subduction zones have shallow to low dip because the eastward mantle flow sustains the eastward dip of the slab (Fig. 2); the subduction hinge converges relative to the upper plate and generates an uplifting doubly verging orogen. But, there is one exception to this scenario and that is the segment of Cocos plate subduction beneath the Caribbean plate.

6.1. *Constraints for steep eastward subduction*

The Cocos plate is a young plate with no age or convergence-rate-



(caption on next column)

Fig. 8. Schematic Geological map of South Central Chile (basement rocks modified from Hervé et al., 2007), showing: (1) docking of the para-autochthonous Chonos terrane and the Peninsular block (thickened Western Series) at Temuco buttress area, along the Proto Liquiñe-Ofqui Fault Zone (PLOFZ); (2) the Paleogene magmatic gap between the Cretaceous and Miocene Patagonian batholith; (3) migration of Paleogene magmatism to the fore arc and the foreland; (4) the Paleogene extensional maximum with Oligo-Miocene pillow basalts along the Proto Liquiñe-Ofqui Fault Zone having MORB and arc affinities showing the formation of a proto-ocean floor as the Chonos terrane rotated (Hervé et al., 1995).

angle differences along the trench that may justify any change in subduction geometries. Nevertheless, the eastwardly directed subduction of Cocos plate has a normal to shallow dip beneath NAM plate and gradually steepens beneath the Caribbean plate (from Guatemala to El Salvador). The opposite westward subduction of the Caribbean plateau (since 33 Ma), to that of the confronting eastward directed subduction of Cocos plate (since 19 Ma) (Fig. 4) suggests that the main constraint for the existence of steep eastward subduction is the existence of an opposite counter-subduction system that controls the subduction angle of the new subducting plate, similar to the example of Cocos plate at its southern end (Fig. 4).

6.2. *High angle convergence*

In times of high angle convergence, the easterly-directed subduction beneath the Andes is characterized by high coupling caused by shallow dip. The subduction hinge is converging relative to the upper plate, sustained by the easterly-directed mantle flow (Figs. 2 and 3). The intraslab seismicity shows down-dip extension and the orogen is thick and doubly verging. The opposite westerly-directed Sandwich Arc subduction shows opposite characters; the slab is steeper and deeper, the intraslab seismicity shows downdip compression; there is a backarc basin and the accretionary wedge has low volume and elevation. Moreover is single verging and has a deep trench.

6.3. *Low angle convergence*

In times of low angle convergence, the easterly-directed subduction is still characterized by high coupling, of the lower with respect to the upper plate but subduction may stop and be replaced by a strike slip (transform) plate margin due to the partitioning of convergence vector. In this scenario, if low angle convergence is introduced by subduction of an active ridge where the new incoming oceanic plate has an Euler pole geometry that causes the development of a strike slip oceanic-continental plate boundary. The first observation is that the strike slip margin will inevitably evolve into subduction as lateral distance from the Euler pole increases or the continental plate margin bends with respect oceanic plate motion increasing convergence angle between plates (Fig. 5B). The second observation is as the active ridge is segmented, the collision with the continental plate will be scattered (in space) leaving remnants of unsubducted ridge that will continue as oceanic microplates (Fig. 6D). The third observation is that since the easterly-directed subduction is characterized by high coupling of the lower with respect to the upper plate, the partitioning of the low angle convergence vector generates strike slip fault systems along the continental plates boundary, allowing the capture of continental crust ribbons by the underlying oceanic plate, and thus to be transported along the margin as terranes (Fig. 7A and B). The final fates for these transported terranes have two end member situations: (1) they are stopped by a buttress and dock along the margin (Figs. 7 and 8), or (2) they are pushed into and beneath the continental crust as they reach the critical Transition Zone where a transform system evolves into subduction (Fig. 7A and B).

These complex interacting tectonic features such as several transform margin segments with oceanic microplates, terranes and subduction segments, can be grouped as a "Segmented Complex" since all are a consequence of the movement of a major oceanic plate with respect to a continental plate as an active ocean ridge is subducted.

Another coincidence between NAM and SAM Segmented Complexes is the presence of an orocline closely related in time and space to the critical Transition Zone from strike slip fault plate boundary to subduction conditions (Fig. 7A and B). The critical Transition Zone of NAM provides a good example for mass transfer to thicken continental crust as the Yakutat terrane is being pushed into and beneath south-eastern Alaska (Fig. 7A).

The development of oceanic microplates allows the coeval existence of a segment of continental active plate margin with a continuous subduction and its arc magmatism history, bounded by segments with strike slip plates boundary arrangements and subducted slab detachments (the Cascades is bounded by San Andreas and Queen Charlotte fault systems in NAM, and in central Chile Andes in the Paleogene, Tupac Amaru microplate was bounded by Liquiñe-Ofqui and Atacama fault systems in SAM). This oceanic microplate and strike and slip fault systems survived at Chile plate margin area at least to the early Miocene time, when the breakup of Farallon Plate into Cocos and Nazca plates resulted in renewed subduction all along SAM western margin and subducted Tupac Amaru microplate remnants.

With respect to the differences between NAM and SAM active margins, a major difference of the SAM Paleogene with respect to NAM Neogene Segmented Complexes is that SAM in the northern Chile segment has an interruption caused by an Eocene convergent event (with the probable re-establishment of a short subduction episode), leading to the development of the Incaic orogeny along the Domeyko fault system, and with the emplacement of super-giant porphyry copper deposits developed at the end of the Incaic orogenic episode (Fig. 7B).

Cyclicity of Andean to Cordilleran orogenic types:

In this work, we show that NAM and SAM western continental margin show episodes of subduction that later are replaced by segmented transform episodes (Andean vs. Cordilleran orogenic types respectively), in which the arrival and subduction in succession of active ridges (Phoenix/Farallon first and Farallon/Pacific later), controlled the cyclicity of Andean/Cordilleran orogenic types changes. These ridges arrive segmented and oblique (low angle) with respect to NAM and SAM. Thus, the subduction of the ridge is diachronous, generating a segmented plate margin that has transform segments of varying age, growing at the expenses of the subducting microplate remnants. The cycle starts when an active ridge arrives and segments de plate margin; as Farallon/Pacific in NAM, or Phoenix/Farallon in SAM. The cycle ends when plate reorganization renews subduction along the plate margin, as the reorganization of the Nazca plate along SAM in the Neogene.

6.4. Extension in the back arc and foreland

When modeling subduction settings of the past that show extension in the back arc and foreland there are two end cases that can account for such extension: (A) In roll back the lower plate is diverging relative to the upper plate, generating the backarc basin and a low bathymetry single-verging accretionary prism. (B) In a Segmented Complex, even though the lower plate is convergent relative to the upper plate, the strike slip plate margin transform segments show extension, uplift and bimodal volcanism in the back arc-foreland, such as the San Andreas fault system with Basin and Range province in the foreland (Fig. 3C), and new ocean floor at the forearc (Baja California Gulf). Thus, extension in the back arc and foreland is a feature common to both; roll back (diverging hinge) and complex transform segments (converging hinge) (Figs. 2 and 3C). So, to assess the role of the subduction geometry to the extension in the foreland, the first step should check the constraint of eastward or westward dip of the subducting slab with respect to the mantle flow. And in case of eastward dip subduction, the second step should check if the extension is related to regional uplift and major strike slip fault systems along the plate margin (Fig. 3C).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The paper benefited from critical reviews of Brendan Murphy and another referee that greatly improved the quality and science of this work.

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