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Synorogenic foreland rifts and transtensional basins: A review of Andean imprints on the evolution of the San Jorge Gulf, Salta Group and Taubaté Basins

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ABSTRACT

Orogenic-induced foreland rifting/transtension or reactivations of preexisting basins have been documented mostly in collisional settings. However, recent works assessed the possibility that Andean-type margins could also induce this mechanism. In order to analyze the potential of subduction orogenesis in nucleating and/or reactivating extensional basins, we review the evolution of the San Jorge Gulf, Salta Group and Taubaté Basins and the uplift history of the Andes. This revision highlights the strong linkage between Andean constructional stages and rifting at the foreland zone.

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1. Introduction

Foreland lithosphere is sensitive to a wide variety of processes directly to indirectly related to orogenesis: lithospheric flexure, where the continental plate is forced to bend under the weight of the orogen (creating a foreland basin system), lithospheric fragmentation, where the plate breaks in response to orogenic compression (giving place to a broken foreland basin system) (DeCelles and Giles, 1996; Strecker et al., 2011) and dynamic subsidence (e.g. Mitrovica, Beaumont, & Jarvis, 1989).

A less common but lengthily acknowledged process is that orogenesis may lead to foreland rifting or transtension. Molnar and Tapponnier (1975) and Sengör (1976) proposed that in a collisional context, continental indentation could transmit far-field stresses that could in turn drive foreland extension or transtension at a high angle to the orogenic front. Sengör et al. (1978) defined these intraplate rift basins, induced by collisional processes, as *impactogenes*. This peculiar rifting mechanism has been identified in active

systems as well as in ancient basins around the world (Molnar and Tapponnier, 1975; Sengör, 1976; Burke et al., 1985; Burke and Lytwyn, 1993; Gordon and Hempton, 1986; Visser and Praekelt, 1998; Liu et al., 2013, among others). Even though, orogenic-induced foreland rifting has been mainly associated with continent–continent collisions, where horizontal stresses are particularly strong, little attention has been paid to similar processes on Andean-type margins. In these systems, orogenic build-up takes place during continued oceanic subduction under continental plates. In particular, the Andes are the most important mountain system in an active subduction setting and currently hold the largest non-collisional orogenic plateau on earth (Barnes and Ehlers, 2009). In the past, Andean far-field stresses have effectively propagated throughout the foreland area, locally upthrusting basement blocks and inverting rift basins located on- and offshore of eastern Brazil, Central Andes and Patagonia (Homoc et al., 1995; Birmes et al., 2013; Cobbold et al., 2001, 2007; Marques et al., 2014; Nogueira et al., 2015). Moreover, focal plane mechanisms of thrust faulting on the Brazilian margin occurs hundreds of kilometers off the Andean deformational zone, showing that the foreland area is sensitive to the plate interactions occurring at the Pacific margin (Assumpção, 1998). Recently, Pedoja et al. (2011) proposed that ongoing compression would be responsible for Quaternary uplift of

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marine terraces in SE Brazil, where the World Stress Map (Heidbach et al., 2008) provides concrete evidence for ongoing E–W compression far from the Andean front.

In order to analyze the potential of the Andean orogenesis to induce nucleation or extensional/transensional reactivation of basins located in the foreland area, we review the most recent works of two basins of southern South America, where a causal relation between Andean contraction and foreland extension has been proposed (San Jorge Gulf and Taubaté Basins) (Fig. 1) (Cobbold et al., 2001; Cogné et al., 2011, 2012, 2013; Gianni et al., 2014, 2015; Ramos, 2014) (Fig. 1). Additionally, we review and compare recent advances in the evolution of the Andes of northern Chile (e.g. Mpodozis et al., 2005; Arriagada et al., 2006a,b; Jordan et al., 2007; Somoza et al., 2012 among others) and the tectonic evolution of the Salta Group Basin (e.g. Bianucci, 1999; Cominquez and Ramos, 1995; Starck et al., 2011).

Thus, it is established a potential relation between contraction

and induced rifting focalized in the transversal arm of the Salta Group Basin (Olmedo Sub-basin).

Finally, based on these reviewed Andean examples of contraction-induced rifting, we discuss the limitations of the impactogene definition and the need of a more general concept that could include ocean-continent subduction settings.

In the following section we briefly introduced the collision-rift or impactogene concept in order to contrast this with the South American examples revised latter.

1.1. Collision-related rifts: the impactogene concept

Sengör (1995) defined three main types of collision-related rifts, i) rifts that formed along intracontinental convergent belts ii) impactogenes iii) and Pack-ice rifts. In this section we will focus on type ii) (impactogenes) and the reader is referred to the work of Sengör (1995) for further details on the other rift types.

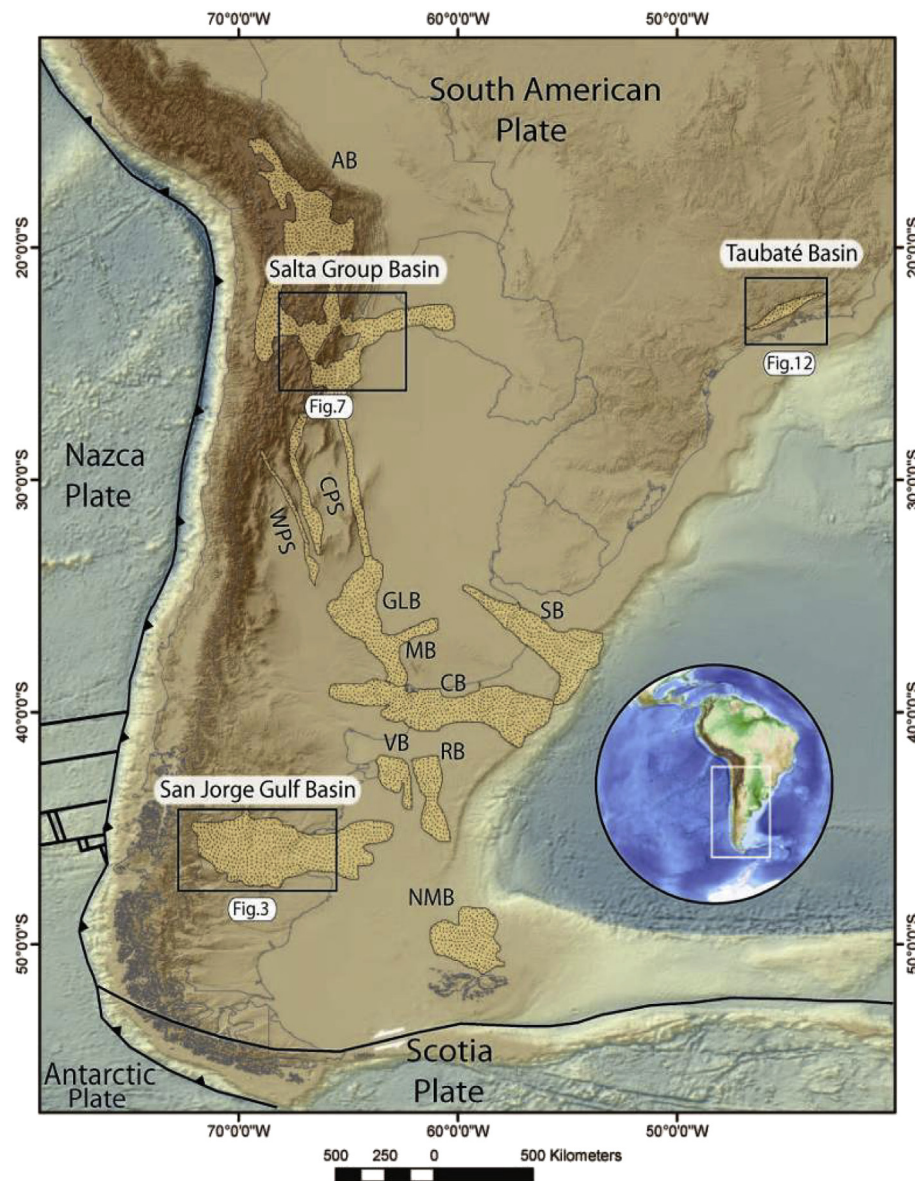


Fig. 1. Map showing the location of Cretaceous and Paleocene rift basins of southern South America. As a reference, the reconstruction of the paleo Pacific-margin of the Central Andes during oroclinal bending is indicated (taken from Barnes and Ehlers, 2009). Abbreviations mean NMB: Malvinas Basin, VB: Valdéz Basin, RB: Rawson Basin, CB: Colorado Basin, SB: Salado Basin, MB: Mascachin Basin, GLB: General Lavalle Basin, WPS: Western Pampean System, CPS: Central Pampean System, AB: Andean Basin.

Even though, the recognition of a causal relationship between collisional orogenic belts and the development of far-field extensional structures was made in the beginning of the past century; the term impactogene was first coined by Sengör et al. (1978). Specifically, this concept refers to passive rifting in a foreland (or hinterland) position induced by collisional stresses propagating through the lithosphere. This type of rifting is produced by secondary tension set up at high angles of a zone of compression (collisional front) (Fig. 1). Sengör (1976), exploring the implications of continental collision, concluded that localized compression, produced by indentation of a continental promontory (e.g. collision of an irregular continental margin), could lead to the development of orogen perpendicular fractures, mafic dikes, alkaline volcanism and transversal extensional/transtensional basins far from the orogenic front.

The development of intraplate collision-related rift or impactogenes depends on a variety of factors. Some of these factors have been analyzed in natural examples as well as in analog experiments (Sengör, 1995; Davy and Cobbold, 1988), among which the more relevant are:

- 1) Magnitude of induced foreland deformation will be governed by the rate of convergence and the angle of collision. In this sense, a high convergence rate between colliding plates will favor rifting in the foreland area.
- 2) As in many other rift systems, Intraplate weaknesses may control nucleation as well as the extent and orientation of an impactogen (e.g. Schumacher, 2002).
- 3) The presence of crustal and/or lithospheric domes in the foreland or hinterland zones may help to localize impactogenes either by stored potential energy that makes them prone to rifting or by plate weakening related to lithospheric thinning.
- 4) Formation of impactogenes depends on the general thermal state of the involved plates and the rate of strain. These factors control the capacity of stress transmission through the foreland lithosphere and in turn whether a collision rift will develop synchronously to collision or at a time after initial contraction. Particularly, the existence of an Andean-type margin previous to a continental collision may delay impactogene development, since long-lived subduction thermally weakens the margin through magmatic arc activity as well as mechanically through construction of accretionary complexes, taking up much of the convergent strain through absorption of the impact during collision (see examples in Sengör, 1995).
- 5) This type of rifting may be hinder if the foreland area is laterally confined. Intraplate splitting caused by orogen compression produces different degrees of lateral escape of foreland pieces. When, laterally confined these are not allowed to spread (escape) inhibiting foreland rifting/transtension (e.g. Davy and Cobbold, 1988).

A key diagnosis for several impactogene proposals has been the recognition of i) transversal rifting/transtension in close spatial and temporal relation to orogen evolution, and ii) when present, migration of the locus of maximum subsidence and syn-extensional magmatism away from the orogenic front (e.g. Sengör, 1976; Burke et al., 1985; Gordon and Hempton, 1986; Ziegler and Van Hoorn, 1989; Burke and Lytwyn, 1993; Visser and Praekelt, 1998; Liu et al., 2013).

A paradigmatic case of this type of rifting mechanism is the Upper Rhine Graben (Sengör, 1976) (Fig. 2A). This basin is part of a group of collision-related rifts known as the European Cenozoic Rift system (ECRS) that involved reactivation of Late Paleozoic shear systems, directly caused by contractional intraplate stresses exerted by the Alpine and Pyrenean orogens in the Paleogene (Dèzes et al.,

2004; Ziegler and Dèzes, 2006) (Fig. 2A). Noteworthy, is that collisional events, may also reactivate previous extensional basins when oriented parallel to the imposed main contractional stress field. It was first conceptually outlined by Sengör et al. (1978) who proposed that aulacogens onboard a continental margin may reactivate during collision in an extensional or transtensional way, depending on their orientation respect to the contractional stress field.

A natural example of this is the Baikal Rift, where a Late Cretaceous to early Oligocene rifting stage took place before India–Asia collision (Fig. 2B and C). This basin was later reactivated and its subsidence accelerated during the late Oligocene due to the far-field effects of India–Asia interaction that reached the Baikal area by this time (Mats and Perelepova, 2011; Mats, 2013; Jolivet et al., 2013) (Fig. 2B and C).

2. Methodology

We made a review of the latest advances in the San Jorge Gulf and Taubaté Basins that highlighted the important role of Andean far-field stress on their evolution (Cobbold et al., 2001; Cogné et al., 2012, 2013; Gianni et al., 2014, 2015; Ramos, 2014). For the case of the Salta Group Basin, we revised and compared the main Andean orogenic stages of Northern Chile with the evolutionary stages of the transversal Olmedo Sub-basin of the Salta Group Basin. A similar approach has been used by several authors to diagnose contraction-induced extensional/transtensional reactivations in South America (Cobbold et al., 2001; Cogné et al., 2012, 2013; Gianni et al., 2014, 2015; Ramos, 2014) as well as in Asia (Mats and Perelepova, 2011).

Particularly, in order to analyze a problematic sector of the San Jorge Gulf Basin we present 3-D seismic information from the Perales Anticline (provided by Y.P.F.). We used borehole data as constraint to adjust the main reflectors of the Chubut Group units. To identify deeper units (basement and Neocomian deposits) we were based on seismic character following the work of Homocv et al. (1995) in this area.

Then, the revision is used to compare these basins and analyze the main intervening factors that could have favored rifting or transtension as well as those that may have inhibited and consequently ended this process. Finally, this analysis is used to establish a framework to contrast the Andean examples of contraction-induced foreland rifts and transtensional basins with collision-related rifts (impactogenes).

3. San Jorge Gulf Basin

During the latest stages of Western Gondwana break-up (Late Jurassic–Early Cretaceous), widespread extension led to the development of several rift basins in the Patagonian region of southern South America (Fig. 1). During Early Cretaceous times a series of extensional depocenters filled with marine and continental deposits developed in Central Patagonia in relation to South Atlantic opening (informally referred to as Neocomian depocenters). These events led to the initial development (Neocomian stage) of the San Jorge Gulf Basin (Figs. 3 and 4). This basin stage was characterized by a complex structural mosaic outlined by normal faults with different orientations (Ramos, 1981; Fitzgerald, 1990; Figari, 1999) (Figs. 4 and 5A).

The westernmost part of the basin opened in relation to W–NW structures that interfered to the east with a trend of NNW structures (Figari, 1999) (Figs. 3 and 5A). Further west, extensional NW-trending half grabens gave place to the opening of the Rio Mayo Embayment/Aysen Basin (Figs. 3 and 5A) (Ramos, 1981; Suárez et al., 2010). In this context, NNW-trending structures were

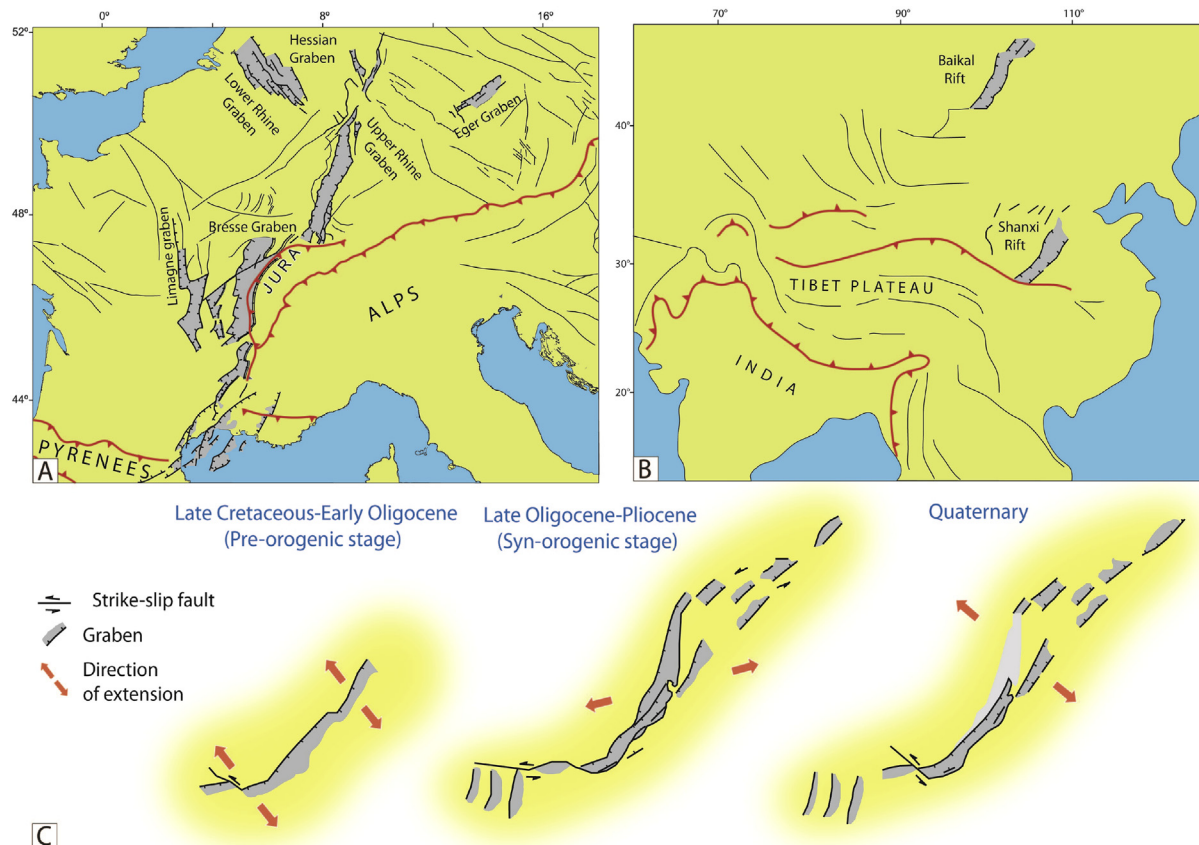


Fig. 2. A) Example of collisional rifts in Europe after [Dèzes et al. \(2004\)](#). Location map of the European Cenozoic Rift system (ECRIS) in the Alpine and Pyrenean foreland. B) Location map of the Baikal Rift in the Asian foreland. C) Example of collisional-reactivation from [Mats and Pereleppova \(2011\)](#). These authors postulated a three step evolution of the Baikal rift, showing its initial subsidence in the Late Cretaceous (previous to India–Asia collision) and the contractional induced reactivation in late Oligocene, related to far-field effects of India–Asia interaction.

preferentially reactivated during Andean orogenesis in Late Early Cretaceous and Cenozoic times to form the Bernardides (Patagonian broken foreland) ([Homocv et al., 1995](#); [Peroni et al., 1995](#); [Gianni et al., 2015](#)) (Fig. 3). To the east, the San Jorge Gulf Basin opened through a series of E–W and minor W–NW extensional trending structures (Figs. 3 and 5A). Early Cretaceous extension ceased between 130 and 120 Ma when the first Atlantic oceanic lithosphere was created ([Fitzgerald et al., 1990](#)). Subsequently, a substantial change in the geodynamic context of the basin was achieved in Late Early Cretaceous, known as the Chubutian stage of the San Jorge Gulf Basin ([Hechem and Strelkov, 2002](#)). At this time the magmatic activity increased at the western zone and the arc front represented by volcanic rocks of the Divisadero Group migrated eastwards presumably in response to a slab shallowing event ([Suárez et al., 2009](#)) (Figs. 4 and 5C). Subsequently, the arc front remained at a retroarc position in Late Cretaceous times and finally turned off during the Paleocene ([Suárez and De La Cruz, 2001](#); [Gianni et al., 2015](#)) (Figs. 4 and 5C). Synchronously, early Andean orogenesis led to uplift and exhumation of the Rio Mayo embayment as recorded from a regional angular unconformity between Neocomian deposits and the Divisadero Group, as well as thick- and thin-skinned deformation in the retroarc sector of the Andes ([Folguera and Iannizzotto, 2004](#); [Suarez et al., 2009](#)) (Figs. 4 and 5B). To the east, broken foreland development took place though inversion of Neocomian NNW-trending faults, associated with synorogenic deposition of fluvial and lacustrine beds of the Chubut Group ([Gianni et al., 2015](#); [Navarrete et al., this issue](#)) (Figs. 4 and 5B).

Paradoxically, synchronic to Andean orogenesis and foreland fragmentation, a sudden extensional reactivation took place in the San Jorge Gulf Basin ([Figari et al., 1999](#); [Paredes et al., 2013](#)) (Figs. 4 and 5B).

A rotation in the extensional axis, in relation to Neocomian rift system, to a roughly N–S extension turned this basin into a dominantly E–W rift system, with the main subsiding area located to the east ([Uliana et al., 1989](#); [Chelotti et al., 1997](#); [Figari et al., 1999](#); [Paredes et al., 2013](#)) (Figs. 4 and 5B). Thus, the Chubutian stage of the San Jorge Gulf Basin responded to a contractional stress field related to Andean orogenesis to the west and to extensional-transtensional tectonics mainly in the eastern sector ([Hechem and Strelkov, 2002](#)). To the west, the Chubut Group deposited in a broken foreland basin in response to the Andean contractional uplift, as revealed by subsurface (seismic) and surface recognition of syn-contractional growth strata in all units belonging to this group ([Homocv et al., 2011](#); [Gianni et al., 2015](#); [Navarrete et al., this issue](#)) (Figs. 4 and 5B). Contrastingly, to the east, seismic surveys have showed a general E–W-trending extensional control on its deposition ([Figari et al., 1999](#); [Paredes et al., 2013](#)) (Figs. 4 and 5B). Recently, [Gianni et al. \(2014, 2015\)](#) proposed a causal relationship between compression in the Patagonian Andes-broken foreland area (Bernardides) and the synchronous extensional-transtensional tectonics at the Golfo de San Jorge Basin. [Gianni et al. \(2014, 2015\)](#) proposed that the San Jorge Gulf Basin would have mimicked at a smaller scale, the mechanics of collision-related rifts. As hypothetically envisaged by [Sengör \(1978\)](#), in these cases a preexistent rift basin oriented parallel to the maximum horizontal stress (σ_1)

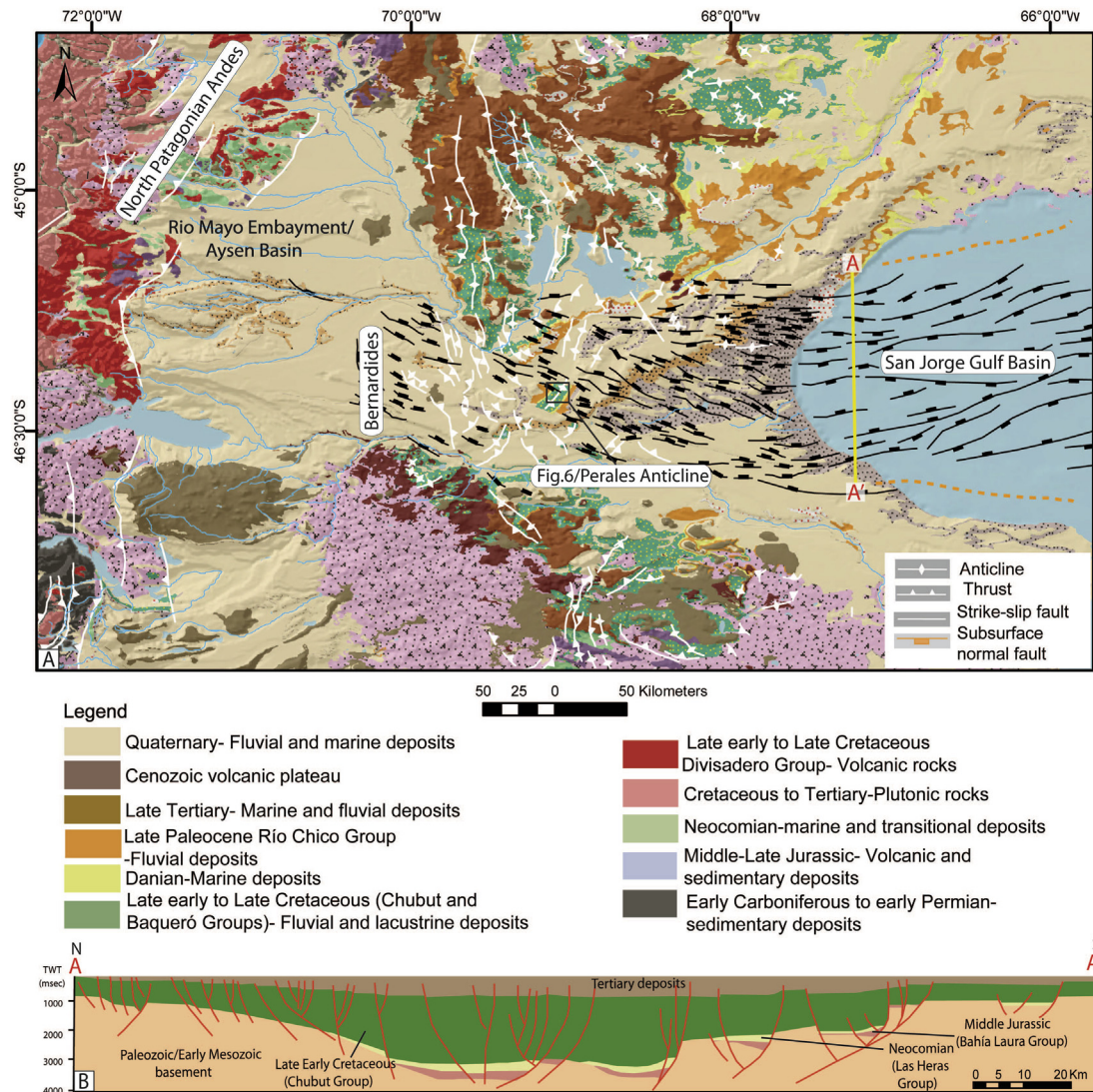


Fig. 3. A) Geological sketch map of the Central Patagonia showing the San Jorge Gulf Basin, the Patagonian broken foreland (Bernardides), Río Mayo Embayment/Aysén Basin and the North Patagonian Andes. Note the area where the extensional system of the San Jorge Gulf Basin interferes with the Bernardides (Interference zone). B) Cross section in the offshore area of the San Jorge Gulf Basin (modified from Figari et al., 1999).

could be reactivated in an extensional/transtensional mode. Gianni et al. (2015) argued that the source of a strong contractional stress-field during Cretaceous times was associated to a slab swallowing event, instead of a micro-continent collision needed to induce impactogenesis (Fig. 5C). This subduction geometry would have produced intense deformation far inland Central Patagonia typical of other shallow subduction examples in South America. Ramos (2014) noted that the general N-S extension in the basin is compatible with the roughly E-W main stress field inferred at these latitudes. Hence, Andean contraction would have selectively induced extensional reactivation using the most favorable E-W and minor W-NW structures, as well as nucleating new faults at the eastern San Jorge Gulf Basin (Fig. 5B). This process may have continued with a marked decrease in intensity up to the Late Paleocene as suggested by subsurface evidence of synorogenic deposition of the Río Chico Gr. to the west and the synextensional deposition of the same unit in the eastern sector of the San Jorge Gulf Basin (Foix et al., 2013; Gianni et al., 2015; Navarrete et al., this issue).

Simultaneous activity of both tectonic mechanisms (contraction

and extension) has been documented in the subsurface area of the San Bernardo fold belt, where this system is cross-cut by W-NW and E-W extensional structures of the Eastern San Jorge Gulf Basin (Pérez et al., 2011) (Fig. 3). In order to illustrate this interaction we reinterpreted two vertical slices of a 3D seismic line across the Perales anticline in the southernmost San Bernardo fold belt previously released by Homoc et al. (1995) and a new slice immediately to the south (Figs. 3 and 6). In seismic line B crossing the Perales anticline in an N-S direction, W-NW-trending extensional structures can be outlined affecting the complete sedimentary section of Neocomian and Chubut Group deposits. Particularly, across this section, the Castillo Fm. shows synextensional fault activity during its deposition (See also Fig. 13, Homoc et al., 1995) (Fig. 6C and A). On seismic line C that crosses the Perales anticline in an E-W sense, an inverted half-graben of Neocomian age has been previously described by Homoc et al. (1995). In strong contrast to line B, overlying the synextensional Neocomian deposits, a different sedimentary pattern in the Chubut Group deposits suggests a different control on subsidence (Fig. 6C).

The D-129, Castillo and lower member of Bajo Barreal Fms. show

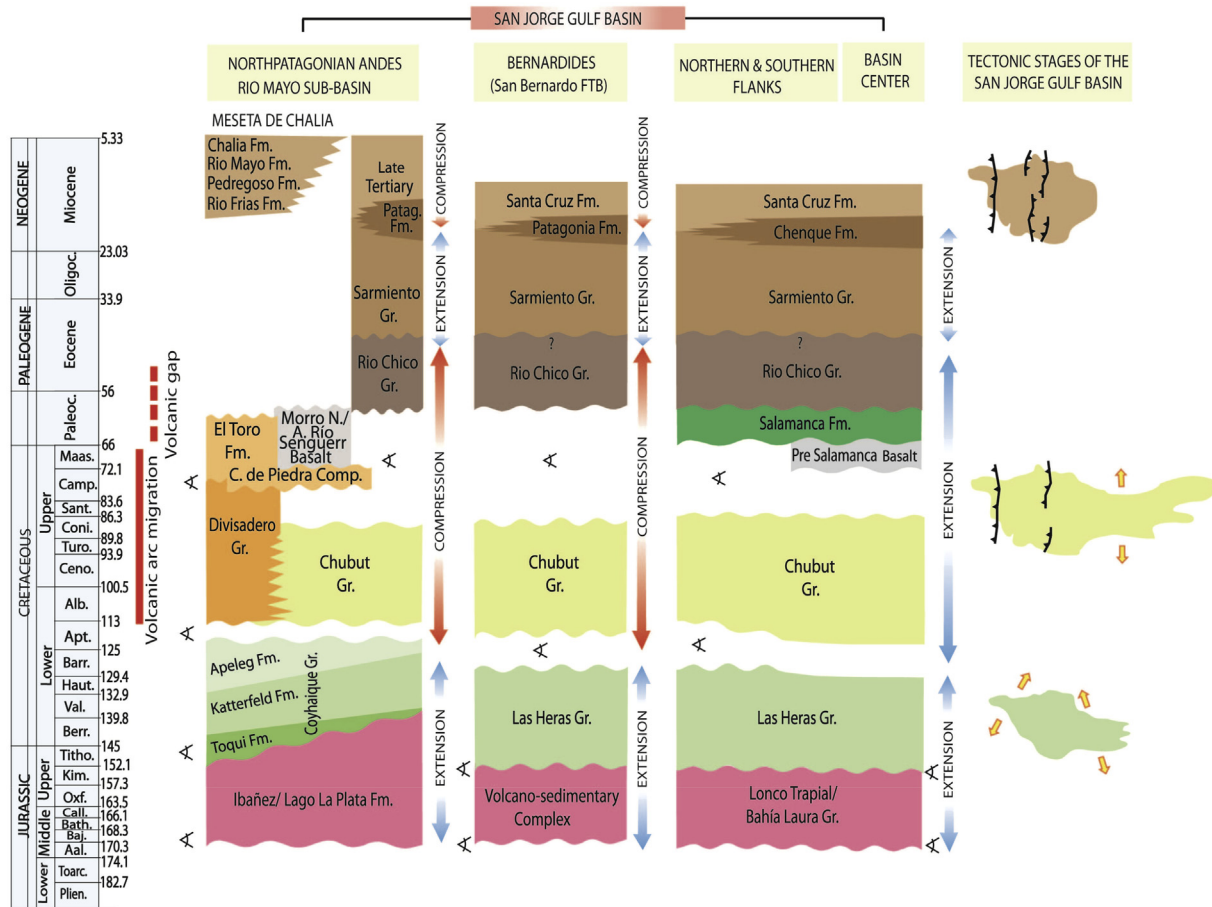


Fig. 4. Stratigraphic correlation among different units of the Patagonian Andes, Bernardides (broken foreland) and the eastern San Jorge Gulf Basin (based on [Clavijo, 1986](#), [Barcat et al., 1989](#); [Bruni et al., 2008](#); [Suarez et al., 2009b](#); [Sylwan, 2001](#); [Suarez et al., 2014](#)).

thickening of strata at both flanks of the Perales anticline away from the hinge ([Fig. 6C](#)). This has been interpreted as synorogenic strata associated with the early uplift of this structure ([Barcat et al., 1989](#); [Jalfin et al., 2005](#); [Gianni et al., 2015](#)). In line C, extensional structures are also seen affecting the Chubut Group. Particularly, a normal fault close to the anticline hinge shows syn-extensional deposition of the Castillo Fm. Finally, seismic line D crosses the Perales anticline in a WNW sense, in an area unaffected by WNW extensional structures ([Fig. 6D](#)). Here, units thickening away from the anticline hinge depict clear syncontractional deposition of the Chubut Group ([Fig. 6D](#)). Hence, the area where extensional structures interfere with the San Bernardo fold belt seems to record at least at times, coetaneous contractional and extensional activity. This kind of interaction has been described in collisional systems such as in the southern sector of the Rhine impactogene where the Alpine orogenic front coexists with normal faulting, which has been suggested by geomorphic, seismic (focal mechanisms) and in-situ stress studies ([Giamboni et al., 2004](#)).

For the San Jorge Gulf Basin, [Ramos \(2014\)](#) proposed that contraction-induced N–S extensional/transensional reactivation was favored by a laterally unconfined state in this basin. Thus, rifting developed through discrete pulses of N and S motion of crustal domains bounding the San Jorge Gulf Basin (see [Davy and Cobbold, 1988](#)). However, this situation may have changed during Paleogene times, when the progressive NE migration of the subduction zone, in the south closed the Rocas Verdes Basin (RVB) and ended up developing a northward propagating fold and thrust Belt

in Paleogene times ([Maffione et al., 2010](#) and references therein) ([Fig. 5D](#)).

Thus, the build-up of the Fueguian fold and thrust belt to the south would have produced a natural buttress that could have raised a lateral confinement impeding effective spreading of the San Jorge Gulf Basin and consequently N–S extension. This could explain the marked shut down in rifting activity during the Paleocene recorded in the San Jorge Gulf Basin and the end of further synorogenic rifting from then onwards.

4. Grupo Salta Basin

The Salta Group Basin corresponds to the southernmost sector of the Cretaceous to Paleogene Andean Basin of Perú, Bolivia and northern Argentina ([Fig. 1](#)). This has been interpreted as a typical intracontinental rift basin associated with the opening of Atlantic Ocean ([Viramonte et al., 1999](#)) ([Fig. 1](#)). Throughout the evolution of the Salta Group Basin different magmatic episodes have been identified: A pre-rift stage (130–120 Ma) characterized by anorogenic magmatism; a syn-rift volcanic episode which started with a mainly alkaline volcanic activity (110–100); a more voluminous volcanic episode (80–75 Ma) characterized by an alkaline suite; and a last volcanic episode (65–60 Ma) ([Fig. 8](#)) ([Viramonte et al., 1999](#)). This extensional system was affected from the Eocene onwards by Andean deformation that distorted its original geometry giving place to a series of morphostructural units known as the Puna, Cordillera Oriental, Subandean Zone and Santa Barbara

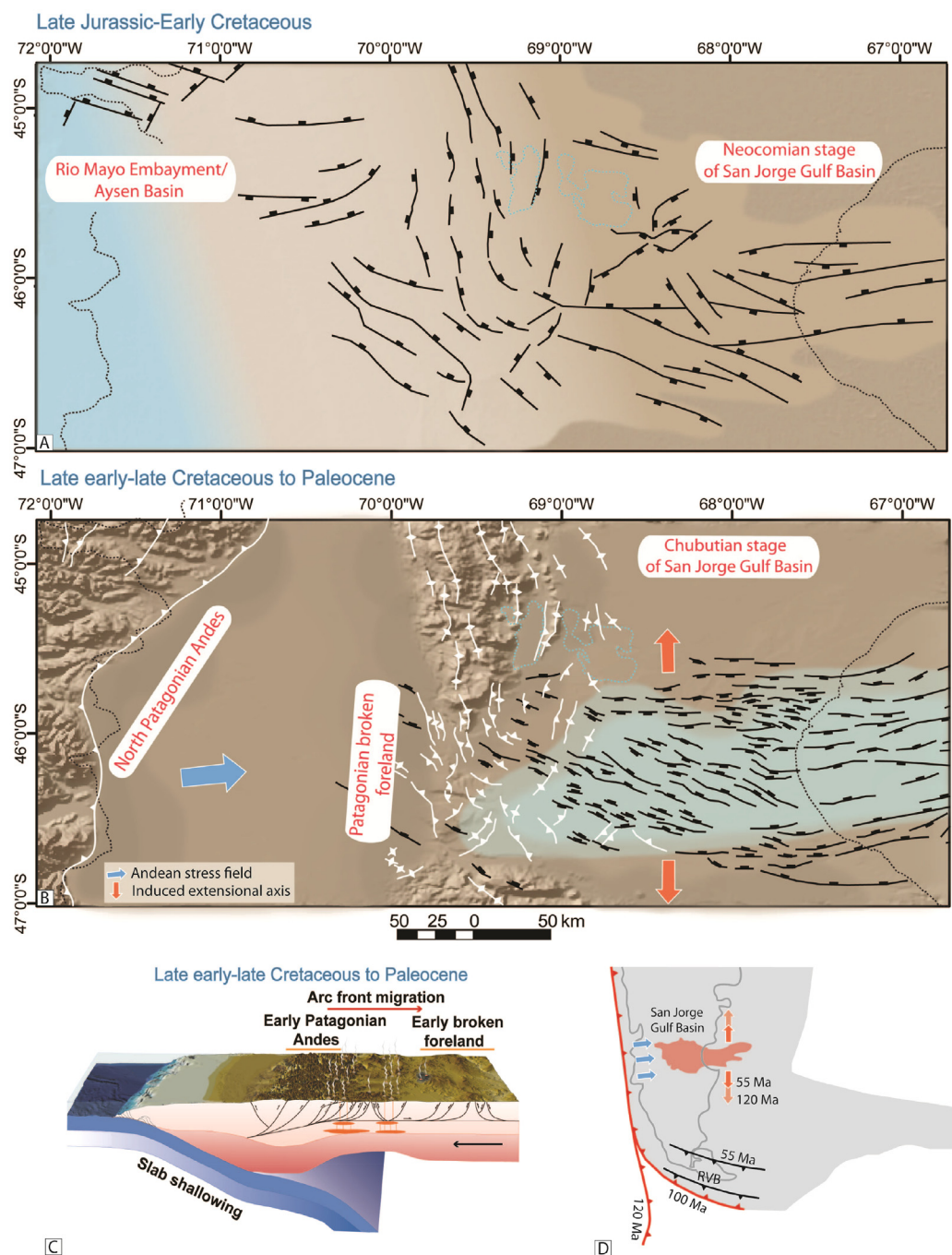


Fig. 5. A) Extensional mosaic outlined in Late Jurassic to Early Cretaceous, constructed with data from Fitzgerald et al. (1990), Folguera and Iannizzotto (2004), and Figari et al. (2014). B) Synorogenic foreland rifting stage of the San Jorge Gulf Basin in Late Early Cretaceous, when the Patagonian Andes began to develop and the foreland area was deformed mainly through inversion of previous NNW-trending faults. Synchronously in the foreland area, E–W and minor W–NW structures were reactivated, while others nucleated extensionally (data taken from Folguera and Iannizzotto, 2004; Figari et al., 1999 and Gianni et al., 2015). C) Proposed Late Early Cretaceous to Paleocene shallow subduction event and related Andean uplift and deformation of the foreland area to the west of the San Jorge Gulf Basin (modified after Gianni et al., 2015). D) Building of lateral confinement during Meso-Cenozoic evolution of the Fueguian Andes in southern Patagonia. The progressive NE migration of the subduction zone closed the Rocas Verdes Basin (RVB) and ended up developing an N-vergent Fold and thrust Belt in Paleocene times. The build-up of this belt would have raised a lateral confinement that could have progressively inhibited the effective escape of southern Patagonia. This could explain the deceleration in rifting subsidence during the Paleocene recorded in the San Jorge Gulf Basin and the end of further synorogenic rifting from then onwards (modified after Maffione et al., 2010).

System (Fig. 7A). In the Salta Group Basin, three main depocenters can be recognized: The Tres Cruces Sub-basin to the NW, Metán-Alemanía Sub-basin to the SW and Lomas de Olmedo Sub-basin located to the NE (Fig. 7B). The latter depocenter is characterized by a more oblique disposition (NE) respect to the Pacific margin than the rest of the sub-basins and an outstanding rift asymmetry

(Comínguez and Ramos, 1995) (Figs. 1 and 9A).

The Salta Group Basin has a characteristic homogeneous stratigraphy described since the early works of Moreno (1970), Reyes and Salfity (1973) and Reyes et al. (1976). Tectonic conditions in the basin from Cretaceous to Paleogene times have changed as inferred from the study of the Salta Group stratigraphy (Gómez

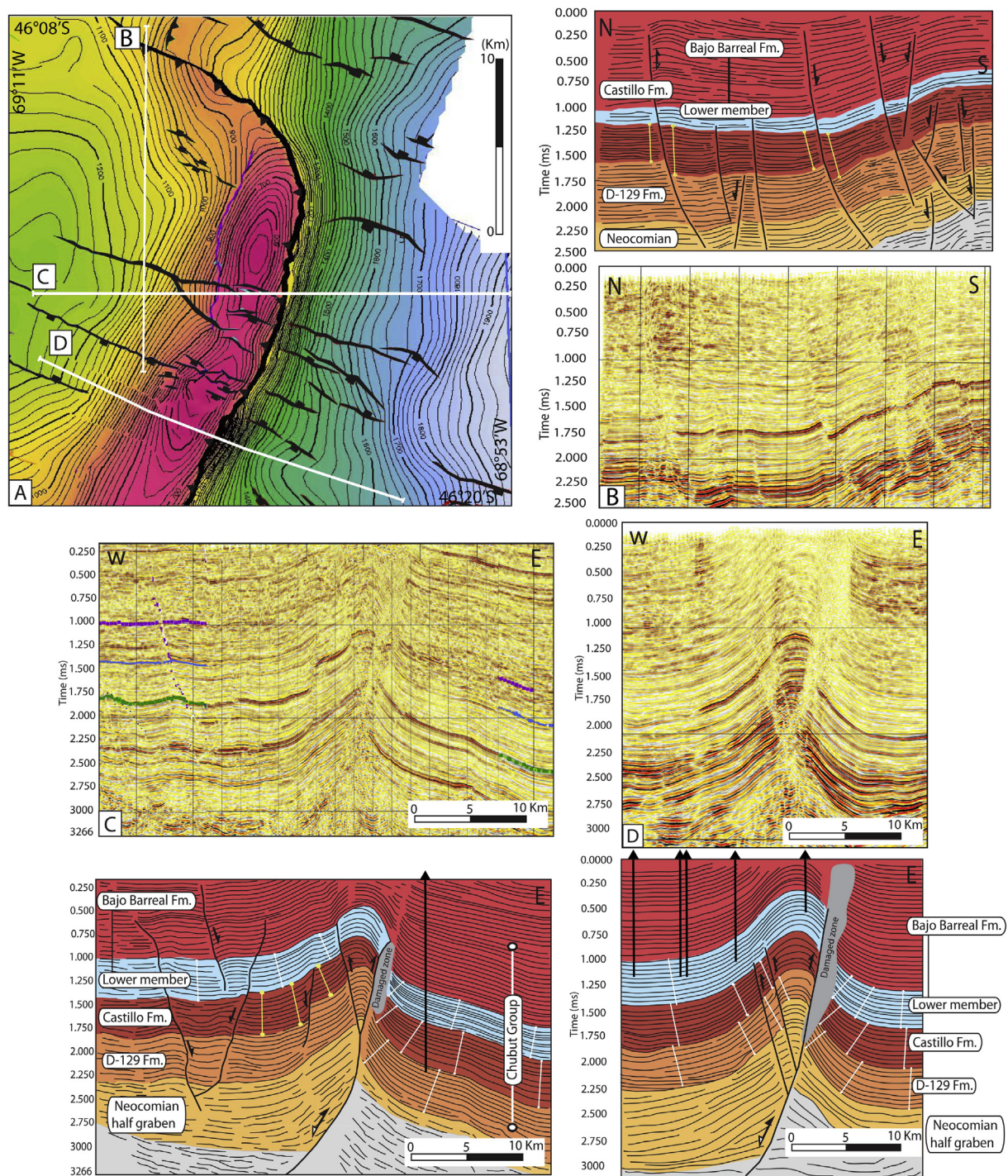


Fig. 6. Seismic lines crossing the Perales anticline that show simultaneous syn-contractional deposition of the Chubut Group and syn-extensional deposition of its mid section (Castillo Fm.) (see Fig. 3 for location). A) Isopauc map at the top of the Bajo Barreal Fm. showing the NNE-trending Perales anticline and the transversal WNW extensional trend. B) North-south seismic line crossing the WNW extensional structures cutting through Neocomian deposits and the Chubut Group. Note that some faults were active during deposition of the Castillo Fm., as revealed by thickness changes in this unit across the contractional structure. C) East-west seismic line showing an inverted Neocomian half graben and related growth strata in different units of the Chubut Group. Note that seismic line C crosses W-NW extensional structures at the western sector, where one of these faults shows syn-sedimentary activity during deposition of the Castillo Fm. D) WNW-seismic line showing the Perales anticline and related syn-contractional deposition of the Chubut Group in an area unaffected by normal faulting. Thin lines perpendicular to beds indicate relative thickness changes in synorogenic (white) and synextensional (yellow) deposits of the Chubut Group. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Omil and Boll, 1989; Marquillas et al., 2003; Starck, 2011).

While, the basal units have been linked to the initial rifting stage (Pirgua Subgroup), the more tabular upper units (Balbuena and Santa Bárbara Subgroups) represent most likely a post-rift stage

related to thermal subsidence trespassing and expanding from the original troughs (Gallisky and Viramonte, 1988; Salfity and Marquillas, 1994; Cominquez and Ramos, 1995) (Figs. 7B and 8). However, the thermal subsidence stage hypothesis has been

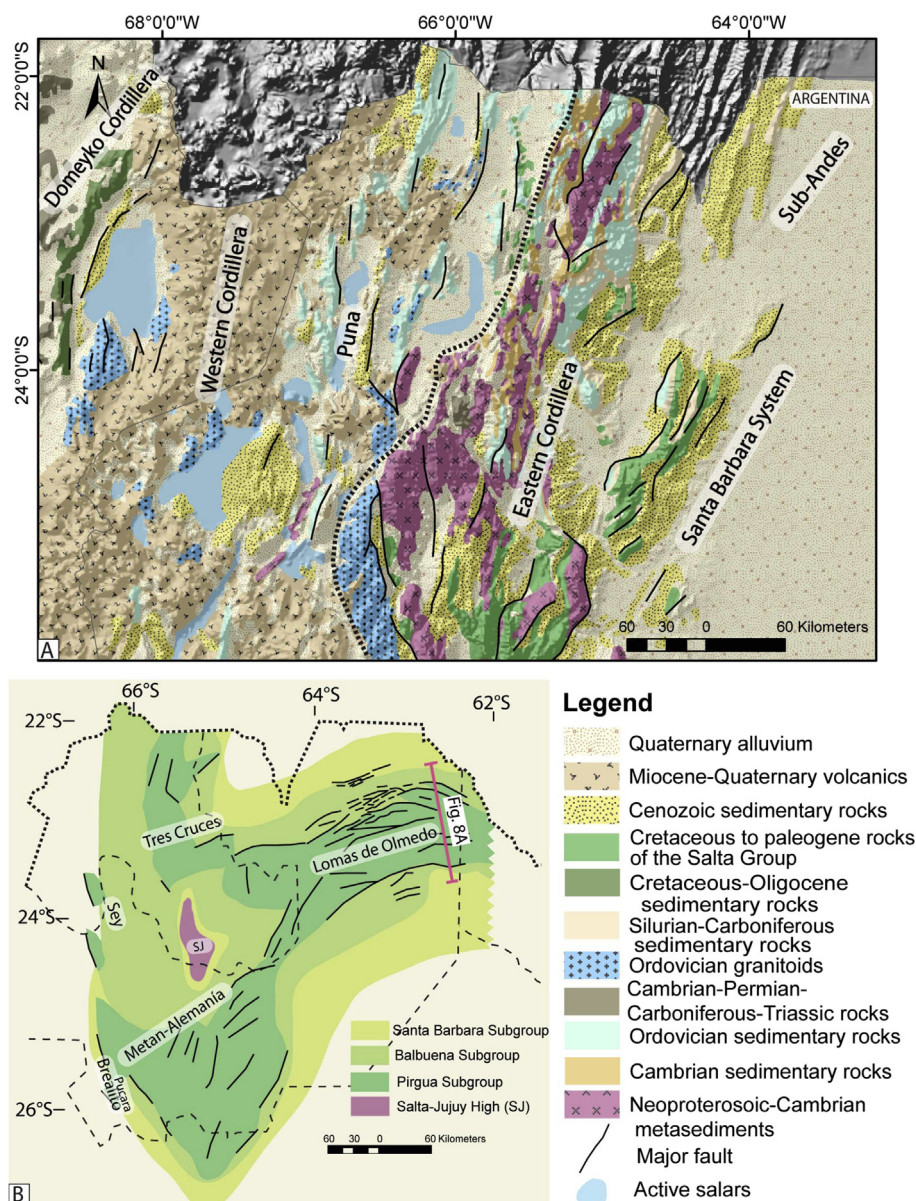


Fig. 7. A) Geological sketch map of the Southern Bolivian and Northern Argentina fold and thrust belt showing main morphostructural units (modified from DeCelles et al., 2011). B) Map showing the general distribution of subunits in the Salta Group (in worn eye view) and the location of the Sub-basins (modified after Starck, 2011).

recently questioned by DeCelles et al. (2011) working on the western Andean sector, proposing that these sections could be most likely related to distal foreland deposits. On the other hand, a late extensional reactivation event, well documented through seismic surveys, was associated with normal faulting affecting post-rift units mostly in Lomas de Olmedo Sub-basin (Bianucci et al., 1981, 1999; Comínguez and Ramos, 1995; Monaldi et al., 2008) (Fig. 9A). This poorly understood late extensional event was responsible for base level fall, variations in sedimentary thicknesses and facial changes in post-rift units (Bianucci, 1981, 1999; Gómez Omil and Boll, 1989, 2005; Di Persia et al., 1991; Monaldi et al., 2008; Starck, 2011) (Figs. 8, 9B and 9C). Particularly, the Pre-Olmedo event, that took place between the Yacoraite and Olmedo Fms. has been related to a strong break in the subsidence velocity curve of the Lomas de Olmedo Sub-basin, totally absent in the Metan-Alemania and Tres Cruces Sub-basins (Starck, 2011) (Fig. 9C). Since this stage was related to fault-controlled rapid

basin subsidence, alkaline magmatism (65–60 Ma) and sudden paleogeographic modifications (Salfity and Marquillas, 1994; Comínguez and Ramos, 1995; Gomez Omil and Boll, 1989, 2005; Bianucci, 1981, 1999), tectonic controls were considered as the most plausible (Starck, 2011).

4.1. Early growth of the Central Andes of northern Chile and the evolution of the Salta Group Basin

During the latest stages of the Salta Group Basin, the Andes started to rise producing a thick- and thin-skinned belt as a consequence of basin inversion to the west in the Atacama Basin (Muñoz et al., 2002; Mpodozis et al., 2005; Arriagada et al., 2006a,b) (Fig. 8). The synrift stage of the Salta Group Basin in the Early to Late Cretaceous (128–80 Ma) was associated with the deposition of continental successions of the Pirgua Subgroup (Gallisky and Viramonte, 1988) (Figs. 8 and 10A).

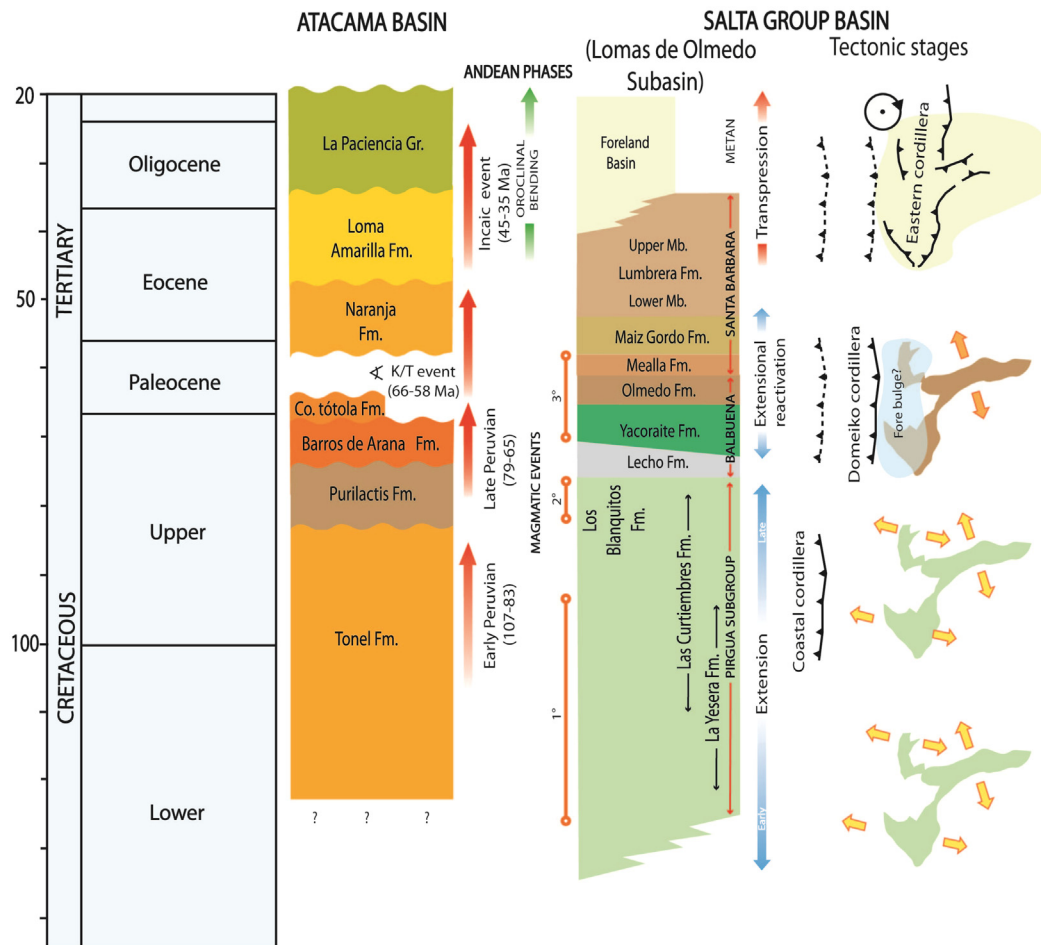


Fig. 8. A) Correlation between the stratigraphy and tectonic events that affected the Atacama and Salta Group Basins (based on Mpodozis et al., 2005; Arriagada et al., 2006a,b and Marquillas et al., 2011).

To the west next to the current South American Pacific margin, the Cordillera de la Costa was incipiently uplifted in Late Early Cretaceous times, in response to the early Peruvian phase (107–80 Ma) (Bascuñán et al., 2015). This event is coincident with progressive crustal thickening in the volcanic arc and retroarc regions as indicated by La/Yb ratios and the synorogenic deposition of the basal fluvio-lacustrine section of the Purilactis Group (Tonel Fm.) (Haschke et al., 2006; Mpodozis et al., 2005; Arriagada et al., 2006a,b) (Fig. 8). During the Late Cretaceous the orogenic front suddenly jumped eastwardly through the Chilean Andean slope, uplifting the Domeiko Cordillera as a result of the late Peruvian phase (79–65 Ma), of larger magnitude than the previous tectonic event (Bascuñán et al., 2015) (Figs. 8 and 10B). In this context, synorogenic fluvial deposits, belonging to the upper section of the Purilactis and Barros de Arana Fms. deposited in the Atacama Basin in a foredeep depozone (Arriagada et al., 2006a,b; Bascuñán et al., 2015 (Fig. 8). Coetaneously, in the Coastal Cordillera, rapid cooling took place between 80 and 60 Ma due to a resumption of compression and arc uplift (Juez-Larré et al., 2010). At the western sector of the Salta Group Basin, thermochronological data show a rapid cooling event in Late Cretaceous to early Paleocene interpreted as either a sag stage or uplift related to a shortening-related flexural peripheral bulge (Insel et al., 2012 and references therein, Carrapa and DeCelles, 2015) (Fig. 10B). However, at the eastern Puna margin apatite fission track data indicate active tectonic deformation and exhumation at that time (Coughlin et al., 1998; Coutand

et al., 2001, 2006; Mortimer et al., 2007, Carrapa et al., 2008) (Fig. 10B). Coevally to active uplift in the Domeiko Cordillera associated with the Late Peruvian phase, the Lomas de Olmedo Sub-basin reactivated during deposition of the lower section of the Balbuena Sub-Group (Yacoraite Fm. transgression) as revealed by subsurface evidences of syn-tectonic deposition of this unit and the presence of interfingered alkaline basalts (Di Persia, 1991; Comínguez and Ramos, 1995) (Figs. 8 and 10B). Equivalent deposits in Bolivia (El Molino Fm.) have been interpreted as a post-rift thermal sag and/or foreland basin back-bulge deposits based on provenance data and the absence of syn-sedimentary faulting (Fink, 2002). During the earliest Paleocene in the Andes of northern Chile, a regional angular unconformity attributed to a renewed orogenic reactivation constrained between approx. 66 to 58 Ma has been broadly documented (see Somoza et al., 2012 and references therein) (Figs. 8 and 10B). In the Atacama Basin area, this mountain building stage is recorded as a strong angular unconformity between the Co. Tótola Fm. and the Paleocene Naranja Fm., and by coetaneous rapid cooling (65–50 Ma) of neighboring igneous bodies (Andriessen and Reuter, 1994; Mpodozis et al., 2005; Jordan et al., 2007) (Fig. 10B).

Moreover, geochemical data indicate that the Andean crust thickened coetaneous to this event as Paleocene to Eocene magmas initially evolved at higher pressures than during the Late Cretaceous (Cornejo et al., 1999; Cornejo and Mathews, 2001; Haschke et al., 2006). Paradoxically, to the east the strongest late rift

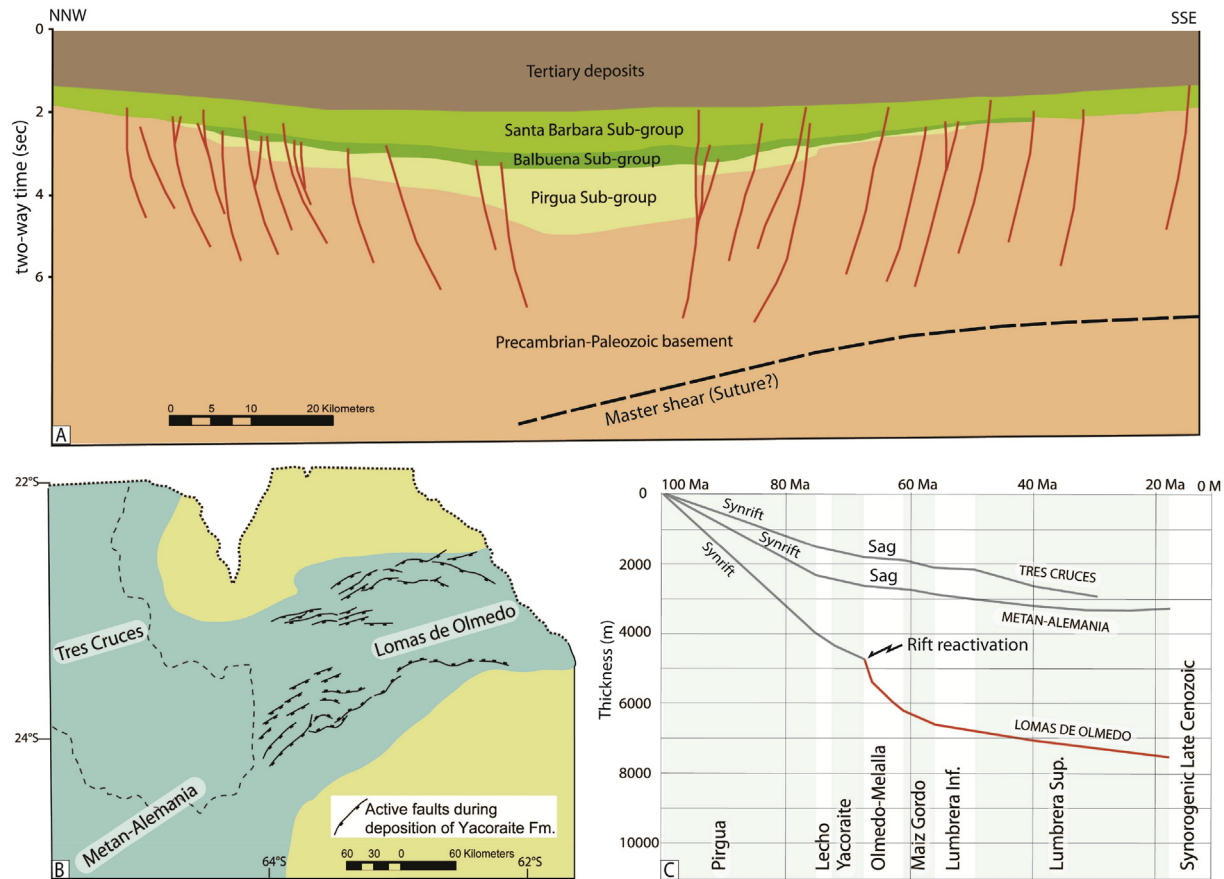


Fig. 9. A) Interpretation of a seismic line across the Lomas de Olmedo Sub-basin. Modified from Fig. 7 of Comínguez and Ramos (1995). B) Map showing faults that recorded syndimentary activity during deposition of the Yacoraite Fm. in the Lomas de Olmedo Sub-basin (data taken from Di Persia et al., 1991). C) Subsidence curves from the Tres Cruces, Metán-Alemania and Lomas de Olmedo Sub-basins taken from Starck (2011). The figure depicts a break on the subsidence curve of the NE-trending Lomas de Olmedo Sub-basin between the deposition of the Yacoraite and Olmedo Fms. evidencing a strong and late subsidence event. Note that this break is absent in the other neighbor Sub-basins trending roughly parallel to the Pacific margin.

reactivation (Pre-Olmedo event) took place almost exclusively at the NE to ENE Lomas de Olmedo Sub-basin (Fig. 10B). The extensional reactivation produced an accentuated acceleration in the subsidence rate of this depocenter that continued mainly during deposition of the Olmedo-Mealla Fms. (Bianucci et al., 1981; Gómez Omil and Boll, 2005; Starck, 2011) (Figs. 8 and 9C).

Furthermore, main magmatic activity during this period (65–60 Ma) expanded eastwards respect to the first and second volcanic cycle, concentrating in the Lomas de Olmedo Sub-basin and the northern border of the Salta-Jujuy High (Fig. 10B) (Comínguez and Ramos, 1995). According to Bianucci et al. (1981, 1999), late post rift reactivation beginning in earliest Paleocene may have extended with a marked decrease in intensity until the Eocene (lower Lumbreira Fm. member). To the west, contractional deformation propagated rapidly from the Cordillera de Domeyko during late Paleocene-early Eocene times (where the Naranja Fm. deposited synorogenically), into the western part of the Cordillera Oriental by about 40 Ma during the Incaic phase (45–35 Ma) (Arriagada et al., 2006a,b; DeCelles et al., 2011) (Fig. 11B and C). As compression proceeded from Early to Late Cenozoic during the Quechua phase (20 Ma), different sectors of the Group Salta Basin fill were progressively incorporated into the orogenic wedge as it expanded eastwards (Monaldi et al., 2008; DeCelles et al., 2011, among others) (Fig. 11C). Thus, the Lomas Olmedo Sub-basin turned transpressively deformed with different degrees of inversion (Chiarenza and Ponzone, 1989; Comínguez and Ramos, 1995;

Bianucci et al., 1999).

4.2. Early Andean compression and late rifting in the Lomas de Olmedo Sub-basin: A causal effect?

As summarized above the Andes built progressively from west to east from Late Early Cretaceous times onwards (Figs. 8, 10 and 11). During the latest synrift stage of the intraplate Salta Group Basin, the early Peruvian phase affected the western Andean slope and was associated with the raise of the Coastal Cordillera (Fig. 8). Noteworthy, as the orogenic wedge expanded eastwards, from the Coastal Cordillera to the Domeyko Cordillera during the Late Peruvian and K/T phases, the NE arm of the Salta Group Basin (Lomas de Olmedo Sub-basin) underwent extensional reactivation (Figs. 9B–C and 10). Thus, at least for this depocenter the rift/thermal sag model currently used to explain the Salta Group Basin evolution does not seem to apply readily. Particularly, the selective character of this reactivation remains unexplained. We speculate that uplift of the Domeyko Cordillera and extension in the Lomas de Olmedo Sub-basin could be causally related. Although, in a totally different scale and intensity, the Lomas the Olmedo Sub-basin may have responded to Andean compression in a similar way to orogenic-induced rift reactivations on preexisting basins (Mats and Pereleпова, 2011; Gianni et al., 2015).

According to the oblique angle of convergence that results from plate-kinematic reconstructions and structural studies, during

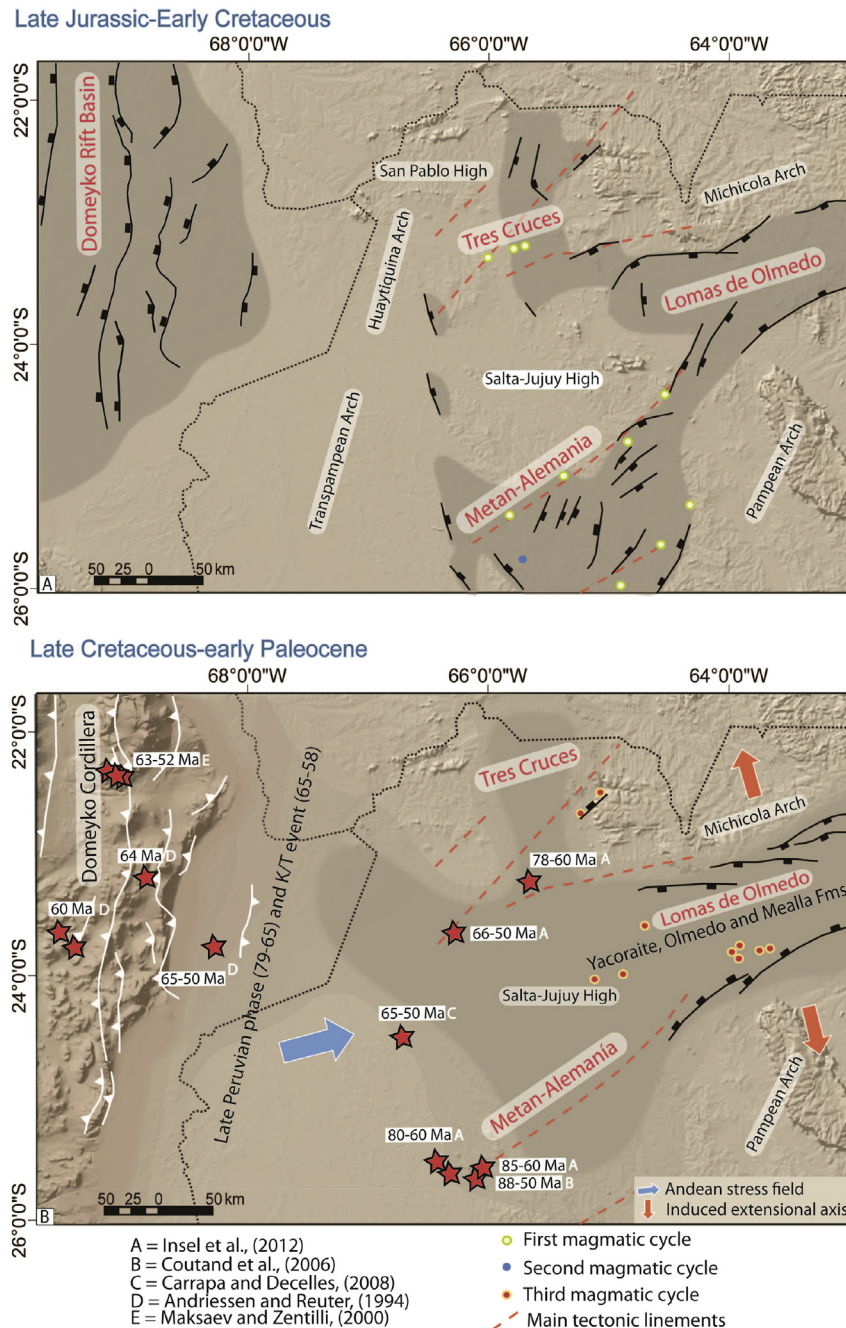


Fig. 10. Evolution of the Atacama and Grupo Salta Basin A) Late Jurassic to Early Cretaceous rifting stage in the Atacama and Salta Group Basins. B) Late Cretaceous to Early Paleocene uplift of the Domeyko Cordillera and foreland rifting stage at the Lomas de Olmedo Sub-basin (modified from DeCelles et al., 2011 and Bascuñán et al., 2015). Note the concentration of magmatism and tectonic activity in the Lomas de Olmedo Sub-basin since the Late Cretaceous. Magmatic cycles taken from Viramonte et al. (1999) and Marquillas et al. (2011). The stars indicate the timings of enhanced cooling associated with exhumation, shortening and deformation from thermochronological data taken from different works (Maksaeve and Zentilli, 2000).

Latest Cretaceous to Paleogene, an NE-directed compressional stress-field has been inferred (e.g. Somoza and Ghidella, 2005; Cobbold and Rosello, 2003).

Hence, synorogenic foreland rift reactivation from Latest Cretaceous to Paleocene would have occurred preferentially in this sub-basin where a most favorable NE to ENE-trending structural strike, roughly parallel to the imposed contractional stress-field would have facilitated extensional reactivation (Fig. 10B). This process may have continued with decreasing intensity in Late Paleocene times (Fig. 11). Also, similarly oriented release faults in

the Tres Cruces Sub-basin were also slightly reactivated during this stage (Monaldi et al., 2008). This process could have been progressively inhibited since the late Eocene when intense orogenesis inverted most of the Salta Group Basin filling (Fig. 11B). At this time, while the basin incorporated progressively into the orogenic wedge, it got located in the clockwise rotating domain of the Bolivian Orocline (Arriagada et al., 2006a,b; Roperch et al., 2006) (Fig. 11C). We speculate that this context may have incremented lateral confinement (Davy and Cobbold, 1988) during pervasive clockwise rotation and continuous southward escape tectonics,

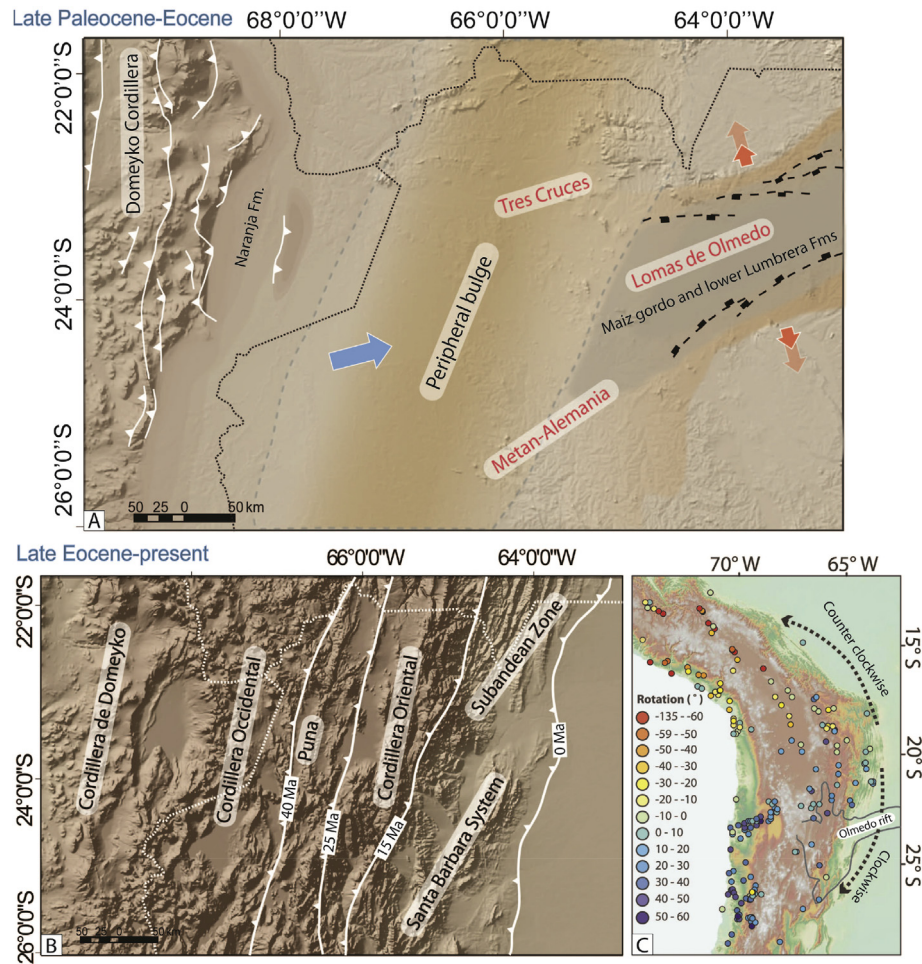


Fig. 11. A) Late Paleocene to Eocene uplift of the Domeyko Cordillera, development of a flexural wave to the east (DeCelles et al., 2011) and mild-late post rift reactivation at the Lomas de Olmedo Sub-Basin. B) Late Eocene to Present incorporation of the Salta Group Basin in the orogenic wedge, and full development of the Andean fold and thrust belt during the Incaic and Quechua phases. Modified after DeCelles et al. (2011). C) Compiled paleomagnetic rotation values during the formation of the Bolivian Orocline (negative and positive values indicate counterclockwise and clockwise rotations respectively) (Modified after Eichelberger et al., 2013). An additional factor associated with the end of the synorogenic foreland rift reactivation in the Lomas de Olmedo Sub-basin could be an increment in the lateral confinement due to the oroclinal bending, with the Salta Group Basin located in the clockwise rotating domain.

progressively contributing to the inhibition of extension and eventually turning to transpressional the western part of the Lomas de Olmedo Sub-basin.

5. Cenozoic extensional basins of southeast Brazil

The southeast margin of Brazil holds an outstanding strip zone of NE-trending sedimentary basins that stand as a testimony of tectonic activity in Cenozoic times (Fig. 1). The Tertiary basins nucleated in crystalline basement of the Brazilian orogeny (700–450 Ma) (de Brito-Neves and Cordani, 1991 among others, Cogné et al., 2013), and comprised the Volta Redonda, Resende and the Taubaté basins (Fig. 12). Several authors noted that these basins in eastern Brazil did not nucleate randomly. The existence of Precambrian fabrics, mostly of mylonitic nature, seemed to be of paramount importance for basin localization, geometry, orientation, as well as internal deformation (e.g. Gontijo-Pascutti et al., 2010; Bezerra et al., 2014; Marques et al., 2014, among others). In the NE Brazilian margin, Kirkpatrick et al. (2013) suggested that mylonitization imparted a grain shape fabric and compositional banding onto the high-strain rocks in the shear zones, which facilitated the localization of subsequent deformation. Particularly,

the Taubaté, Volta Redonda and Resende basins seem to have nucleated in NE-trending ductile shear zones of the Ribeira mobile belt (Cogné et al., 2013). The Taubaté basin is the largest with at least 800 m of sedimentary infill deposited since the Paleogene (Marques et al., 1990; Riccomini et al., 2004) (Fig. 12).

The stratigraphy of this basin is characterized by neighboring Late Cretaceous to Paleocene alkaline intrusions, a Paleocene to early Eocene infill corresponding to clastic deposits identified in subsurface (Units A and B), Eocene to Oligocene clastic deposits of the Taubaté Group mainly recognized at outcrops and Miocene-Pliocene deposits of the Pindamonhangaba Fm. (Riccomini et al., 2004; Cogné et al., 2012, 2013) (Fig. 13).

The mechanism involved in the opening of these basins remains controversial. While some authors related them to intraplate rifting (Almeida et al., 1976; Riccomini et al., 2004 among others), other favored transtension as the trigger mechanism for basin formation (Padilha et al., 1991; Cobbold et al., 2001; Cogné et al., 2013).

Still, there seems to be a general agreement respect to their beginning in Paleogene times and their subsequent inversion/reactivation during compressional to transpressional stages in the Neogene (Riccomini, 1989; Riccomini et al., 2004; Cobbold et al., 2001; Cogné et al., 2013). Also, the origin of the tectonic forces

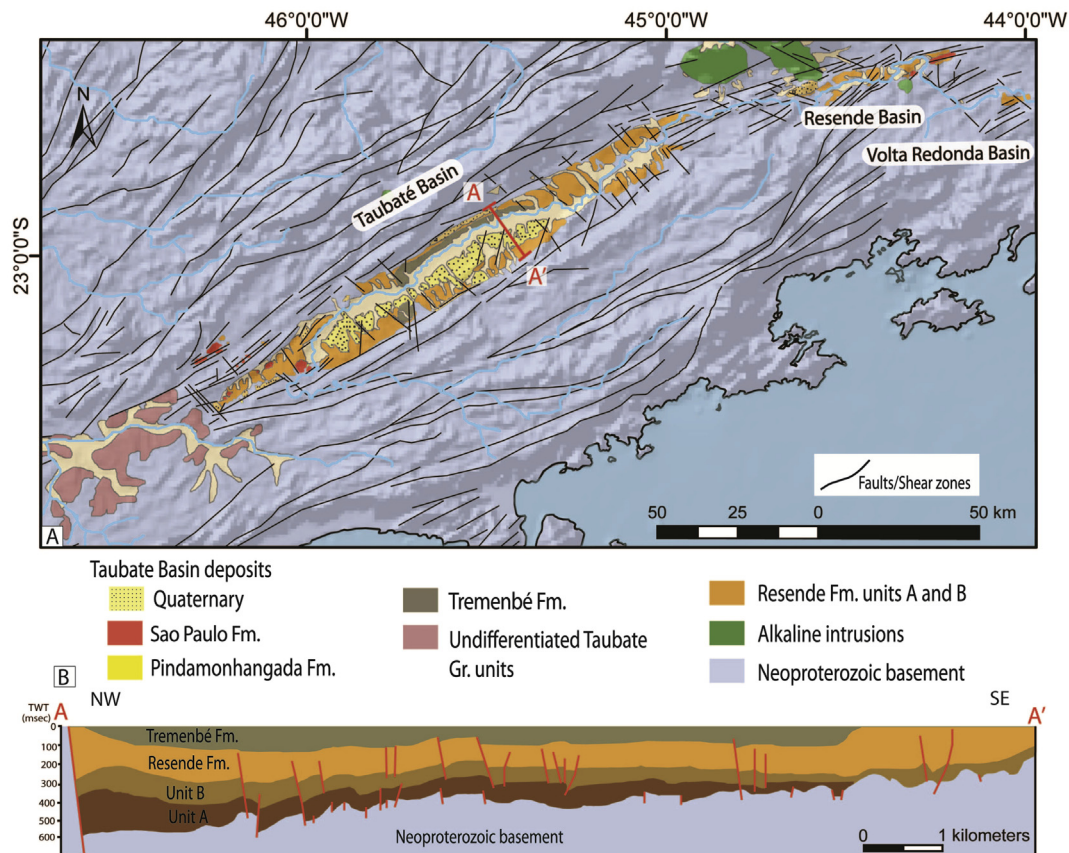


Fig. 12. A) Geological sketch map showing the Tertiary basins of SE Brazil. B) Interpreted seismic line across the Taubaté Basin showing main structures and syn-extensional deposits (modified after Cogné et al., 2013).

that originated these basins is still a matter of ongoing debate. There are basically two contrasting models, those that relate them in one way or another to the dynamics of the Atlantic Ocean (e.g. Almeida, 1976; Padilha et al., 1991; Zalán and Oliveira, 2005) and those that attribute a major role to Andean far-field stress and Atlantic ridge push forces (e.g. Cobbold et al., 2001; Riccomini et al., 2004; Cogné et al., 2011, 2012, 2013). An increasing amount of structural and thermochronological studies supports Andean far-field influence in the evolution of the Brazilian margin. Compressional stresses during the Late Cretaceous appear to have been intense, reaching the Atlantic margin and offshore area of NE and SE Brazil, as evidenced by strong deformation affecting basement rocks and the sedimentary cover (Cobbold et al., 2010; Cogné et al., 2013). More recently, Marques et al. (2014) and Nogueira et al. (2015) showed structural and geophysical data evidencing inversion tectonics in the Mesozoic Araripe and Rio do Peixe basins of NE Brazil respectively, consistent with the stress field imposed by the Andean and Atlantic ridge pushes. Salomon et al. (2014), carried out a paleostress study on correlating margins of S/SE Brazil and NW Namibia and concluded that contrasting stress fields affected both margins. While, the NW margin of Namibia was dominated by extension, the SE/S of Brazil was affected by strike-slip faulting with compression oriented NE–SW in the Paleogene and E–W since the Neogene, presumably related to the Nazca–South America plate convergence at those times. Independently, deformational events recognized in SE Brazil and particularly for the Campanian in the NE of Brazil were associated with widespread cooling events (Viviers and Azevedo, 1988; Cobbold et al., 2001, 2010; Zalán and Oliveira, 2005; Japsen et al., 2012; Cogné et al., 2011, 2012, 2013). In the Taubate Basin, plate-wide compression caused folding of basement

rocks and fast cooling in Late Cretaceous, revealed in the light of seismic and thermochronological data (Cogné et al., 2011, 2012, 2013) (Fig. 14).

More recently, Cogné et al. (2013) based on seismic profiles and structural data, proposed that the Taubaté Basin developed under left-lateral transtension associated with an NE-trending greatest horizontal stress from Paleocene to Eocene (Figs. 13 and 14). According to these authors, during the Oligocene the basin entered in a period of tectonic quiescence that ended in a right-lateral transpressional event related to E–W compression due to a net rotation of the greatest horizontal stress during the Neogene (Figs. 13 and 14).

A final reactivation stage caused basement thrusting onto Tertiary units at outcrops scale (see Salvador and Riccomini, 1995; Riccomini et al., 1989; Cogné et al., 2013). Cobbold et al. (2001) and Cogné et al. (2011, 2012) showed that each basin reactivation corresponded to a fast cooling event revealed through thermochronological data (100–70 Ma, 60–45 Ma and 15 Ma) and that each event was coincident with main Andean orogenic phases registered to the west (ie: Peruvian, Incaic and Quechua phases) (Fig. 13). In this sense, Cogné et al. (2013) suggested that the Taubaté Basin developed in response to NE directed Incaic compression inferred from the oblique angle of plate convergence at that time. During the Miocene convergence accelerated and its direction rotated, from NE to E causing a final transpressional reactivation (Pardo-Casas and Molnar, 1987; Cogné et al., 2013) (Figs. 13 and 14). At this time deformation in the Andes propagated eastwards and produced the N–S trending fold and thrust belts in the Subandes of northern Argentina and southern Bolivia.

Therefore, compression propagating from the Andes during

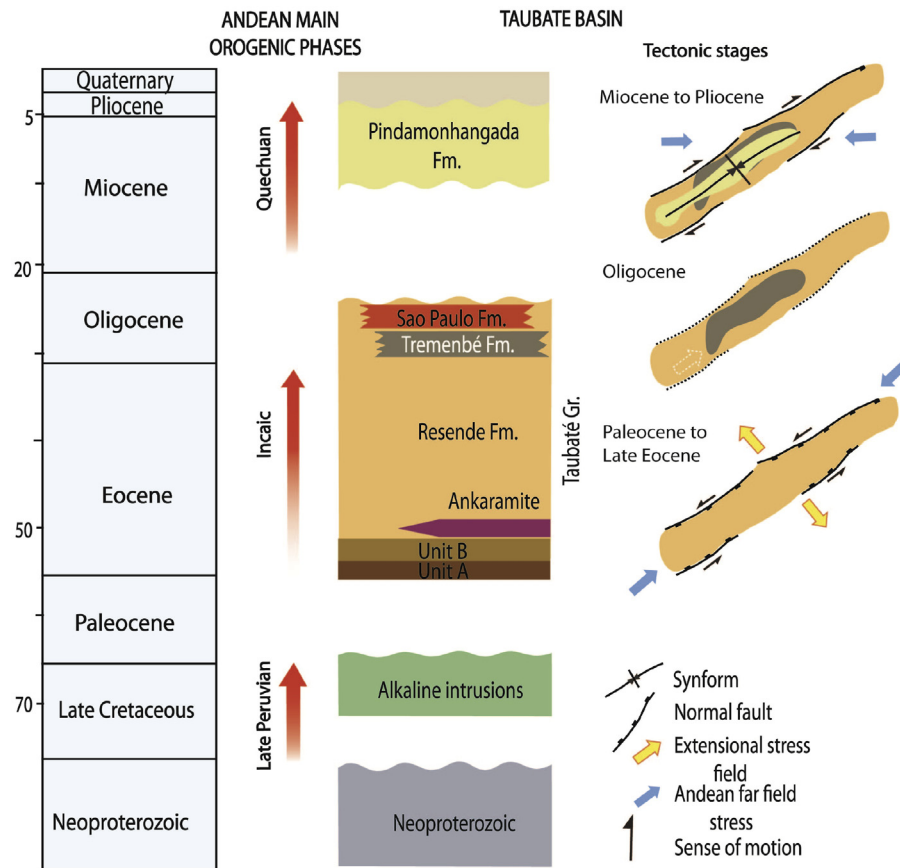


Fig. 13. Stratigraphy and tectonic stages of the Taubaté Basin (modified from Cogné et al., 2013).

Paleogene times seems to have played a major role in the geodynamic context of South America foreland zone at these latitudes. First, inducing a mild and short-lived synorogenic foreland rift reactivation near the Cretaceous to early Paleogene Andean front in the Lomas de Olmedo Sub-basin, and then more distally in SE Brazil, producing the opening of the Taubaté Basin.

6. Discussion and conclusions

Even though, orogenic-triggered foreland rifting has been mainly documented in collisional settings, the evolution of the Golfo de San Jorge, Salta Group (Lomas de Olmedo Sub-basin) and Taubaté Basins seems to be a testimony of the potential held by Andean-type margins to induce similar processes. The examples discussed in previous sections are distinct among them reflecting different intervening factors that favored their formation and subsequent interruption.

As reviewed above, these basins could have been influenced during their tectonic evolution by Andean far-field stresses that propagated throughout the foreland area. In the cases of the San Jorge Gulf Basin and potentially the Lomas de Olmedo Sub-basin, roughly E–W and NE-directed Andean compression would have reutilized pre-existing rift basins. Although in a totally different tectonic setting and scale, the aforementioned cases behaved mechanically similar to the hypothetical collisional rift reactivations of Sengör et al. (1978) and the synorogenic stage in the Baikal rift (Intermediate stage, Mats and Perelepova, 2011). As mentioned in sections 4 and 5, the sub-parallel orientation of both basins respect to the imposed contractional stress-field along with an initial

lateral unconfined state, may have been a key factor to facilitate their extensional reactivation (Figs. 5 and 11). According to Nalpas et al. (1995), an angle of less than 45° with respect to σ_1 is necessary for positively reactivating a pre-existing basin. Thus, we expect that unconfined basins oriented at more than 45°, may ideally experience extension when striking parallel to σ_1 and rifting with different degrees of strike slip component when oriented subparallel to σ_1 .

The Taubaté Basin opened directly as a result of transtensional reactivation of an NE-trending basement fabric under the NE-directed Paleogene Andean compression (Cogné et al., 2013) (Fig. 14). Subsequently, extension or transtension in all basins seem to have come to an end for different reasons. In the San Jorge Gulf Basin and at least secondarily in the Lomas de Olmedo Sub-basin, an increment in lateral confinement during subduction reconfiguration and orocline bending respectively, impeded further contraction-induced rifting (Figs. 5D and 11C).

On the other hand, the Taubaté Basin was inverted due to a rotation of the contractional stress-field from NE–SW to E–W associated with the Cenozoic dynamic of the Nazca plate.

The Andean examples analyzed here are not conceptually impactogenes as defined by Sengör et al. (1978). A notorious difference between impactogenes as defined by Sengör et al. (1978) and the cases here reviewed is that a continental indenter is not necessary to induce transversal rifting or transtension (Fig. 15). In subduction settings, as the analyzed here, changes in plate convergence (velocity and direction) and local modifications to slab geometry (shallowing) seem to be effective triggers to induce discrete amounts of foreland rifting and transtension (Fig. 15).

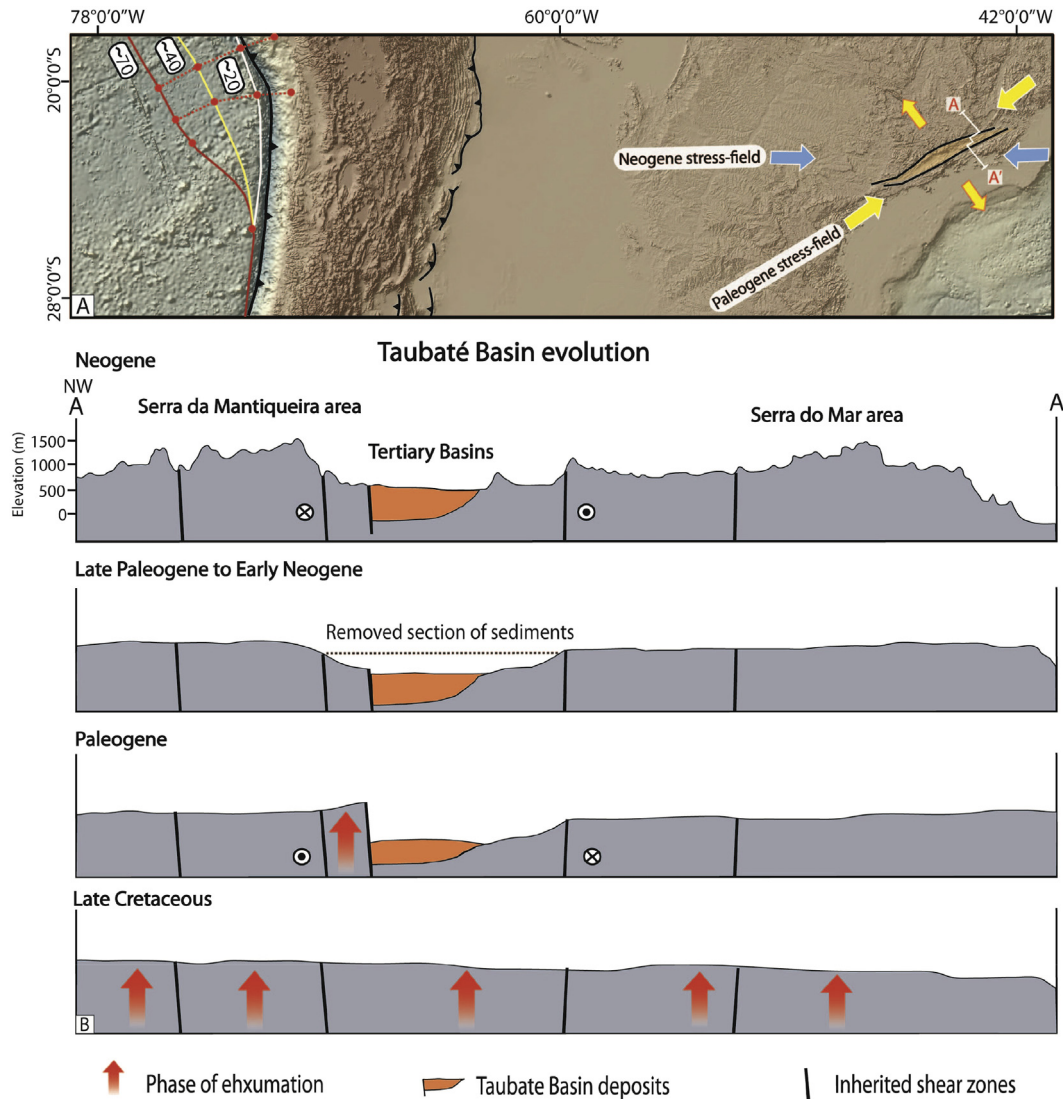


Fig. 14. A) Tectonic evolution of the Taubaté Basin and its relation to the Andean far-field stress. Data taken from Cogné et al. (2013). Reconstructed Pacific margin at different time frames is taken from Barnes and Ehlers (2009). B) Tectonic events in the Taubaté Basin inferred by thermochronological data. Modified from Cogné et al. (2012).

Another important difference between orogenic-induced rifting related to continent–continent collision and ocean–continent collision, is that in the former *impactogenes* are characterized by large and highly subsiding rifts or transtensional basins (e.g. Sengör, 1976; Burke et al., 1985; Gordon and Hempton, 1986; Ziegler and Van Hoorn, 1989; Burke and Lytwyn, 1993; Visser and Praekelt, 1998; Liu et al., 2013). While, at least in the examples here analyzed, extensional depocenters are comparably less subsiding and smaller. Additionally, these differ from *impactogenes* since are either related to small alkaline magmatic activity (Lomas de Olmedo and Taubaté Basins) or are totally amagmatic (Chubutian stage of the San Jorge Gulf Basin), while magmatic activity in *Impactogenes* is highly variable, being associated in some cases to important volumes as documented in the Rhine and Oslo rifts (Sengör, 1995). On the other hand, it is worth noting that the San Jorge Gulf Basin and Lomas de Olmedo Sub-basin were reactivated relatively close to the orogenic front (Figs. 5 and 10). Particularly, the San Jorge Gulf Basin shows interaction and coeval activity between the orogenic front and extensional structures (Fig. 6). Contrastingly, the Taubaté Basin developed farther east from the

Andean front (Fig. 14). All these cases could represent Andean-type equivalents to the two end-members defined for *impactogenes* (Sengör, 1995): *Proximal Impactogenes* as exemplified by the Rhine Basin, developed close to the Alpine collisional front and *distal impactogenes* as the Baikal Basin reactivated far to the north of the Himalayan collisional front.

In spite of general differences, these cases share the common factor that they are genetically related to a contractional stress field (Fig. 15).

Finally, there is not consensus yet about a general term that encompasses synorogenic foreland rift/transtension in both settings so far. Definitions such as mountain-related rifts coined by Merle et al. (2011), appear to fail since these just referred to collisional rifting cases. Hence, in an attempt to develop a broader concept, we propose the use of the term *synorogenic foreland rift/transtensional basins* for intraplate rifts or pull-apart basins, as well as extensional/transtensional reactivations of preexisting basins that form directly in relation to a contractional stress-field. These could take place in continent–continent or ocean–continent collisional settings (Fig. 15). Under this definition *impactogenes* would

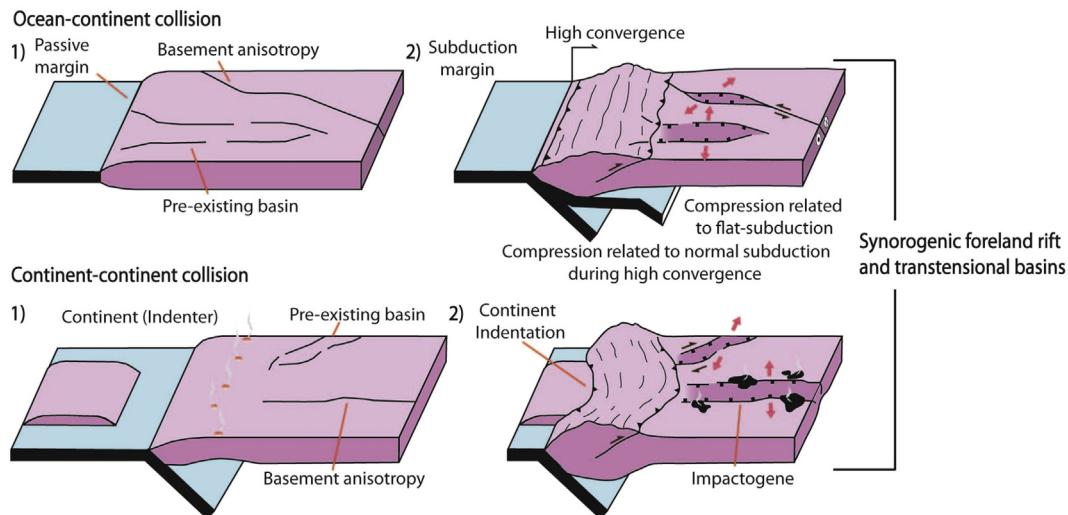


Fig. 15. Tectonic setting of synorogenic foreland rifts and transtensional basins. In both tectonic settings (continent–continent and ocean–continent collision) pre-existing basins may reactivate extensionally or transtensionally depending on their orientation respect to the main horizontal stress. Also, note that new rift or transtensional basins may develop in the foreland area, which in the specific case of continent–continent collisional setting would constitute impactogenes *sensu* Sengör et al. (1978).

constitute a specific case of *Synorogenic foreland rift/transtensional basins*.

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References

- Almeida, F.F.M., 1976. The system of continental rifts bordering the Santos Basin, Brazil. *An. Acad. Bras. Ciências* 48, 15–26.
- Andriessen, P.A.M., Reutter, K.J., 1994. K–Ar and fission track mineral age determination of igneous rocks related to multiple magmatic arc systems along the 23°S latitude of Chile and NW Argentina. In: Reutter, K.J., Scheuber, E., Wigger, P.J. (Eds.), *Tectonics of the Southern Central Andes*. Springer, pp. 141–153.
- Arriagada, C., Cobbold, P.R., Roperch, P., 2006a. Salar de Atacama basin: a record of compressional tectonics in the central Andes since the mid-Cretaceous. *Tectonics* 25, TC1008. <http://dx.doi.org/10.1029/2004TC001770>.
- Arriagada, C., Roperch, P., Mpodozis, C., Fernández, R., 2006b. Paleomagnetism and tectonics of the southern Atacama Desert (25–28°S), northern Chile. *Tectonics* 25, TC4001. <http://dx.doi.org/10.1029/2005TC001923>.
- Assumpção, M., 1998. Seismicity and stresses in the Brazilian passive margin. *Bull. Seismol. Soc. Am.* 88, 160–169.
- Barcat, C., Cortiñaz, J.S., Nevistic, V.A., Zucchi, H.E., 1989. Cuenca Golfo San Jorge. In: Chelbi, G. (Ed.), *Cuencas Sedimentarias Argentinas, Serie Correlación Geológica*, vol. 6, pp. 319–345.
- Barnes, J.B., Ehlers, T.A., 2009. End member models for Andean Plateau uplift. *Earth Sci. Rev.* 97, 105–132.
- Bascuñán, S., Arriagada, C., Le Roux, J., Deckart, K., 2015. Unraveling the Peruvian Phase of the Central Andes: stratigraphy, sedimentology and geochronology of the Salar de Atacama Basin (22°30′–23°S), northern Chile. *Basin Res.* <http://dx.doi.org/10.1111/bre.12114>.
- Bezerra, F.H.R., Rossetti, D.F., Oliveira, R.G., Medeiros, W.E., Neves, B.B., Balsamo, F., Góes, A.M., 2014. Neotectonic reactivation of shear zones and implications for faulting style and geometry in the continental margin of NE Brazil. *Tectonophysics* 614, 78–90.
- Bianucci, H.A., 1999. Estructura y evolución estructural del riftrelación con la estratigrafía. Subcuenca de Lomas de Olmedo (rama oriental). In: González Bonorino, G., Omarini, R., Viramonte, J. (Eds.), *Geología del Noroeste Argentino*, Salta, pp. 292–300.
- Bianucci, H.A., Acevedo, O.M., Cerdan, J.J., 1981. Evolución tectosedimentaria del Grupo Salta en la Subcuenca de Lomas de Olmedo (Provincias de Salta y Formosa). In: 8° Congreso Geológico Argentino, Actas III, San Luis, pp. 159–172.
- Bilmes, A., D’Elia, L., Franzese, J.R., Veiga, G.D., Hernández, M., 2013. Miocene block uplift and basin formation in the Patagonian foreland: the Gastre Basin, Argentina. *Tectonophysics* 601, 98–111.
- Bruni, S., D’Orazio, M., Haller, M.J., Innocenti, F., Manetti, P., Pécskay, Z., Tonarini, S., 2008. Time-evolution of magma sources in a continental back-arc setting: the Cenozoic basalts from Sierra de San Bernardo (Patagonia, Chubut, Argentina). *Geol. Mag.* 145, 714–732.
- Burke, K.C., Lytwyn, J., 1993. Origin of the rift under the Amazon basin as a result of continental collision during Pan-African time. *Int. Geol. Rev.* 35 (10), 881–897.
- Burke, K., Kidd, W.S.F., Kusky, T., 1985. Is the Ventersdorp rift system of Southern Africa related to a continental collision between the Kaapvaal and Zimbabwe cratons at 2.64 Ga ago? *Tectonophysics* 115 (1), 1–24.
- Carrapa, B., DeCelles, P.G., 2015. Regional exhumation and kinematic history of the central Andes in response to cyclical orogenic processes. *Geol. Soc. Am. Mem.* 212, 201–213.
- Carrapa, B., Decelles, P.G., Reiners, P.W., Gehrels, G., Biswas, A., 2008. Exhumation and basin evolution of the Puna plateau of NW Argentina revealed by a multi geo-thermochronological approach. *Geochim. Cosmochim. Acta* 72 (12), A139.
- Chelotti, L., 1997. Evolución tectónica de la Cuenca del Golfo San Jorge en el Cretácico y Terciario; algunas observaciones desde la interpretación sísmica. *Bol. Inf. Pet.* 49, 62–82.
- Chiarenza, D.G., Ponzoni, E., 1989. Contribución al conocimiento geológico de la Cuenca Cretácica en el ámbito oriental de la Subcuenca de Olmedo, provincia de Salta. In: Republica Argentina: 1° Congreso Nacional de Exploración de Hidrocarburos, Actas I, pp. 209–228.
- Clavijo, R., 1986. Estratigrafía del Cretácico Inferior en el sector occidental de la Cuenca del Golfo San Jorge. *Bol. Inf. Pet.* 9, 15–32.
- Cobbold, P.R., Rossello, E.A., 2003. Aptian to recent compressional deformation, foothills of the Neuquén Basin, Argentina. *Mar. Petrol. Geol.* 20, 429–443.
- Cobbold, P.R., Meisling, K.E., Mount, V.S., 2001. Reactivation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil. *AAPG Bull.* 85 (11), 1925–1944.
- Cobbold, P.R., Rossello, E.A., Roperch, P., Arriagada, C., Gómez, L.A., Lima, C., 2007. Distribution, Timing, and Causes of Andean Deformation across South America. In: Geological Society of London, Special Publication, vol. 272, pp. 321–343.
- Cobbold, P.R., Chiossi, D., Green, P.F., Japsen, P., Bonow, J., 2010. Compressional reactivation of the Atlantic Margin of Brazil: structural styles and consequences for hydrocarbon exploration. *Search Discov.* 2010, 30114.
- Cogné, N., Gallagher, K., Cobbold, P.R., 2011. Post-rift reactivation of the onshore margin of southeast Brazil: evidence from apatite (U–Th)/He and fission-track data. *Earth Planet. Sci. Lett.* 309, 118–130. <http://dx.doi.org/10.1016/j.epsl.2011.06.025>.
- Cogné, N., Gallagher, K., Cobbold, P.R., Riccomini, C., Gautheron, C., 2012. Post-breakup tectonics in southeast Brazil from thermochronological data and combined inverse-forward thermal history modeling. *J. Geophys. Res. Solid Earth* (1978–2012) 117 (B11).
- Cogné, N., Cobbold, P.R., Riccomini, C., Gallagher, K., 2013. Tectonic setting of the Taubaté Basin (Southeastern Brazil): insights from regional seismic profiles and outcrop data. *J. S. Am. Earth Sci.* 42, 194–204.
- Comínguez, A.H., Ramos, V.A., 1995. Geometry and seismic expression of the Cretaceous Salta Rift of Northwestern Argentina. In: Tankard, A.J., Suarez, R., Welsink, H.J. (Eds.), *Petroleum Basins of South America*, AAPG, Spec. Publ., Mem., vol. 62, pp. 325–340.

- Cornejo, P., Matthews, S.J., 2001. Evolution of magmatism from the uppermost Cretaceous to Oligocene and its relationship to changing tectonic regime. In: *Proc. III South Am. Symp. Isotop. Geol.*, Santiago, pp. 558–561.
- Cornejo, P., Mpodozis, C., Matthews, S., 1999. Geología y Evolución Magmática del Distrito Indio Muerto y Yacimiento El Salvador. *Serv. Nac. Geol. Min.* 1–99. Informe Registrado, IR-98-14.
- Coughlin, T.J., O'Sullivan, P.B., Kohn, B.P., Holcombe, R.J., 1998. Apatite fission-track thermochronology of the Sierras Pampeanas, central western Argentina: Implications for the mechanism of plateau uplift in the Andes. *Geology* 26, 999–1002 doi:10.1130/0091-7613(1998)026<0999:AFTTOT>2.3.CO;2.
- Coutand, I., Gautier, P., Cobbold, P.R., de Urreiztieta, M., Chauvin, A., Gapais, D., Rossello, E.A., Lopez-Gammundi, O., 2001. Style and history of Andean deformation, Puna plateau, northwestern Argentina. *Tectonics* 20 (2), 210–234. <http://dx.doi.org/10.1029/2000TC900031>.
- Coutand, I., Carrapa, B., Deeken, A., Schmitt, A.K., Sobel, E.R., Strecker, M.R., 2006. Propagation of orographic barriers along an active range front: insights from sandstone petrography and detrital apatite fission-track thermochronology in the intramontane Angastaco Basin, NW Argentina. *Basin Res.* 18 (1), 1–26. <http://dx.doi.org/10.1111/j.1365-2117.2006.00283.x>.
- Davy, P., Cobbold, P.R., 1988. Indentation tectonics in nature and experiment. 1. Experiments scaled for gravity. *Bull. Geol. Inst. Upps.* 14, 129–141.
- de Brito Neves, B.B., Cordani, U.G., 1991. Tectonic evolution of South America during the Late Proterozoic. *Precambrian Res.* 53, 23–40. [http://dx.doi.org/10.1016/0301-9268\(91\)90004-T](http://dx.doi.org/10.1016/0301-9268(91)90004-T).
- DeCelles, P.G., Giles, K.A., 1996. Foreland basin systems. *Basin Res.* 8, 105–123.
- DeCelles, P.G., Carrapa, B., Horton, B.K., Gehrels, G.E., 2011. Cenozoic foreland basin system in the central Andes of northwestern Argentina: Implications for Andean geodynamics and modes of deformation. *Tectonics* 30 (6).
- Dèzes, P., Schmid, S.M., Ziegler, P.A., 2004. Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. *Tectonophysics* 389, 1–33.
- Di Persia, D.E., Carle, R.J., Belotti, H., 1991. Geología petrolera en la subcuenca de Lomas de Olmedo. *Bol. Inf. Pet. Terc. Epoca* 25, 14–29.
- Eichelberger, N., McQuarrie, N., Ehlers, T.A., Enkelmann, E., Barnes, J.B., Lease, R.O., 2013. New constraints on the chronology, magnitude, and distribution of deformation within the central Andean orocline. *Tectonics* 32, 1432–1453.
- Figari, E., 2014. Cuenas cretácicas de la Patagonia Central: génesis, evolución tectosedimentaria e interconexiones. In: 14^ª Reunión Argentina de Sedimentología Puerto Madryn, Argentina, Actas electrónicas.
- Figari, E.G., Strelkov, E., Laffitte, G., Cid De La Paz, M.S., Courtade, S.F., Celaya, J., Vottero, A., Lafourcade, P., Martinez, R., Villar, H., 1999. Los Sistemas Petroleros de la Cuenca del Golfo San Jorge: Síntesis Estructural, Estratigrafía y Geoquímica. In: *Actas 4^º Congreso de Exploración y Desarrollo de Hidrocarburos*, Mar del Plata, pp. 197–237.
- Fink, R.J., 2002. Sedimentology and Stratigraphy of the Upper Cretaceous–paleocene El Molino Formation, Eastern Cordillera and Altiplano, Central Andes, Bolivia: Implications for the Tectonic Development of the Central Andes (Phd Thesis). Montana State University, p. 125.
- Fitzgerald, M.G., Mitchum, R.M., Uliana Jr., M.A., Biddle, K.T., 1990. Evolution of the San Jorge Basin, Argentina. *AAPG. Bull.* 74, 879–920.
- Foix, N., Paredes, J.M., Giacosa, R.E., 2013. Fluvial architecture variations linked to changes in accommodation space: Río Chico Formation (Late Paleocene), Golfo San Jorge basin, Argentina. *Sediment. Geol.* 294, 342–355.
- Folguera, A., Iannizzotto, N.F., 2004. The lagos La Plata and Fontana fold-and-thrust belt: long-lived orogenesis at the edge of western Patagonia. *J. S. Am. Earth Sci.* 16, 541–566.
- Galliski, M.A., Viramonte, J.G., 1988. The Cretaceous paleorift in northwestern Argentina: a petrologic approach. *J. S. Am. Earth Sci.* 4, 329–342.
- Giamboni, M., Ustaszewski, K., Schmid, S.M., Schumacher, M.E., Wetzel, A., 2004. Plio-Pleistocene transpressional reactivation of Paleozoic and Paleogene structures in the Rhine-Bresse transform zone (northern Switzerland and eastern France). *Int. J. Earth Sci.* 93, 207–223.
- Gianni, G., Navarrete, C., Orts, D., Tobal, J., Folguera, A., Giménez, M., 2014. Cuenca de Chubut: su relación con el antepaís fragmentado y el impactogeno andino. In: 19^º Congreso Geológico Argentino, Córdoba, Argentina, Actas Electrónicas.
- Gianni, G., Navarrete, C., Orts, D., Tobal, J., Folguera, A., Giménez, M., 2015. Patagonian broken foreland and related synorogenic rifting: The origin of the Chubut Group Basin. *Tectonophysics* 649, 81–99.
- Gómez Omil, R., Boll, A., 2005. Cuenca Cretácica del Noroeste Argentino. In: *Frontera Exploratoria de la Argentina*, pp. 63–76.
- Gómez Omil, R.J., Boll, A., Hernández, R.M., 1989. Cuenca cretácica-terciaria del Noroeste Argentino (Grupo Salta). In: Chebli, G., Spalletti, L. (Eds.), *Cuenas Sedimentarias de la Argentina: Universidad Nacional de Tucumán, Serie Correlación Geológica*, vol. 6, pp. 43–64.
- Gontijo-Pascutti, A., Bezerra, F.H., La Terra, E., Almeida, J.C., 2010. Brittle reactivation of mylonitic fabric and the origin of the Cenozoic Rio Santana Graben, south-eastern Brazil. *J. S. Am. Earth Sci.* 29, 522–536.
- Gordon, M.B., Hempton, M.R., 1986. Collision-induced rifting: the Grenville Orogeny and the Keweenaw rift of North America. *Tectonophysics* 127, 1–25.
- Haschke, M., Günther, A., Melnick, D., Echlter, H., Reutter, K.J., Scheuber, E., Oncken, O., 2006. Central and southern Andean tectonic evolution inferred from arc magmatism. In: Oncken, O., Chong, G., Franz, G., Giese, P., Gotze, H.-J., Ramos, V.A., Strecker, M.R., Wigger, P. (Eds.), *The Andes: Active Subduction Orogeny*. Springer-Verlag, Berlin, pp. 337–353.
- Hechem, J., Strelkov, E., 2002. Secuencia sedimentaria mesozoica del Golfo San Jorge. In: Haller, M.J. (Ed.), *Relatorio del 15^º Congreso Geológico Argentino, Geología y Recursos Naturales de Santa Cruz*, pp. 1–9.
- Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., Müller, B., 2008. The World Stress Map Database Release 2008. <http://dx.doi.org/10.1594/GFZ.WSM.Rel2008>.
- Homocv, J., Conforto, G., Lafourcade, P., Chelotti, L., 1995. Fold Belt in the San Jorge Basin, Argentina: an Example of Tectonic Inversion. In: Buchanan, J., Buchanan, P. (Eds.), *Basin Inversion, Geological Society Special Publication*, pp. 235–248.
- Homocv, J., Navarrete, C., Marshall, P., Masquere, S., Cerdan, J., 2011. Inversión tectónica intra-cretácica de la Subcuenca de Río Mayo, Chubut, Argentina. In: 18^º Congreso Geológico Argentino, Neuquén, Actas, pp. 1418–1419.
- Insel, N., Grove, M., Haschke, M., Barnes, J.B., Schmitt, A.K., Strecker, M.R., 2012. Paleozoic to early Cenozoic cooling and exhumation of the basement underlying the eastern Puna plateau margin prior to plateau growth. *Tectonics* 31, TC6006. <http://dx.doi.org/10.1029/2012TC003168>.
- Jalfin, G., Manceda, R., Palacio, L., Belloso, E., Chebli, P., Coria, C., Miguel, K., Sanz, A., 2005. Caracterización de trampas y sellos de la cuenca del Golfo San Jorge: Esquema de compartimentación. In: Kozłowski, E., Vergani, G., Boll, A. (Eds.), *Simposio: Las trampas de Hidrocarburos en las cuencas productivas de Argentina*, 6^º Congreso de Exploración y Desarrollo de Hidrocarburos, pp. 415–450.
- Japsen, P., Bonow, J., Green, P.F., Cobbold, P.R., Chiossi, D., Lilletveit, R., Magnavita, L.P., Pedreira, A., 2012. Episodic burial and exhumation in NE Brazil after opening of the South Atlantic. *Geol. Soc. Am. Bull.* 124, 800–816. <http://dx.doi.org/10.1130/B30515.1>.
- Jolivet, M., Arzhannikov, S., Chauvet, A., Arzhannikova, A., Vassallo, R., Kulagina, N., Akulova, V., 2013. Accommodating large-scale intracontinental extension and compression in a single stress-field: a key example from the Baikal Rift System. *Gondwana Res.* 24, 918–935.
- Jordan, T.E., Muñoz, N., Mpodozis, C., Blanco, N., Pananont, P., Gardeweg, M., 2007. Cenozoic subsurface stratigraphy and structure of the Salar de Atacama basin, northern Chile. *J. S. Am. Earth Sci.* 23, 122–146.
- Juez-Larré, J., Kukowski, N., Dunai, T.J., Hartley, A.J., Andriessen, P.A.M., 2010. Thermal and exhumation history of the Coastal Cordillera arc of northern Chile revealed by thermochronological dating. *Tectonophysics* 495, 48–66.
- Kirkpatrick, J.D., Bezerra, F.H.R., Shipton, Z.K., Do Nascimento, A.F., Pytharoulis, S.I., Lunn, R.J., Soden, A.M., 2013. Scale-dependent influence of pre-existing basement shear zones on rift faulting: a case study from NE Brazil. *J. Geol. Soc.* 170, 237–247.
- Liu, S., Su, S., Zhang, G., 2013. Early Mesozoic basin development in North China: indications of cratonic deformation. *J. Asian Earth Sci.* 62, 221–236.
- Maffione, M., Speranza, F., Faccenna, C., Rossello, E., 2010. Paleomagnetic evidence for a pre-early Eocene (50Ma) bending of the Patagonian orocline (Tierra del Fuego, Argentina): paleogeographic and tectonic implications. *Earth Planet. Sci. Lett.* 289, 273–286.
- Maksaev, V., Zentilli, M., 2000. Fission track thermochronology of the Domeyko Cordillera, northern Chile: implications for Andean tectonics and porphyry copper metallogenesis. *Explor. Min. Geol.* 8 (1–2), 65–89.
- Marques, A., 1990. Evolução tectono-sedimentar e perspectivas exploratórias da Bacia de Taubaté, São Paulo, Brasil. *Bol. Geosci. Petrobrás* 4, 253–262.
- Marques, F.O., Nogueira, F.C.C., Bezerra, F.H.R., de Castro, D.L., 2014. The Araripe Basin in NE Brazil: An intracontinental graben inverted to a high-standing horst. *Tectonophysics* 630, 251–264.
- Marquillas, R., del Papa, C., Sabino, I., Heredia, J., 2003. Prospección del límite K/T en la cuenca del Noroeste, Argentina. *Rev. la Asoc. Geol. Argent.* 58, 271–274.
- Marquillas, R.A., Salfity, J.A., Matthews, S.J., Matteini, M., Dantas, E., 2011. U–Pb zircon age of the Yacoraite Formation and its significance to the Cretaceous–Tertiary boundary in the Salta Basin, Argentina. In: Salfity, J.A., Marquillas, R.A. (Eds.), *Cenozoic Geology of the Central Andes of Argentina*. SCS Publisher, pp. 227–246.
- Mats, V.D., 2013. Late cretaceous and cenozoic stratigraphy of the Baikal Rift sediments. *Stratigr. Geol. Correl.* 21, 637–651.
- Mats, V.D., Perepelova, T.I., 2011. A new perspective on evolution of the Baikal Rift. *Geosci. Front.* 2, 349–365.
- Merle, O., 2011. A simple continental rift classification. *Tectonophysics* 513 (1), 88–95.
- Mitrovica, J.X., Beaumont, C., Jarvis, G.T., 1989. Tilting of continental interiors by the dynamical effects of subduction. *Tectonics* 8 (5), 1079–1094.
- Molnar, P., Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. *Science* 189 (4201), 419–426.
- Monaldi, C.R., Salfity, J.A., Kley, J., 2008. Preserved extensional structures in an inverted Cretaceous rift basin, northwestern Argentina: Outcrop examples and implications for fault reactivation. *Tectonics* 27, TC1011. <http://dx.doi.org/10.1029/2006TC001993>.
- Moreno, J., 1970. Estratigrafía y paleogeografía del Cretácico superior de la cuenca del Noroeste Argentino, con especial mención a los Subgrupos Balbuena y Santa Bárbara. *Asoc. Geol. Argent. Rev.* 15, 9–44.
- Mortimer, E., Carrapa, B., Coutand, I., Schoenbohm, L., Sobel, E.R., Gomez, J.S., 2007. Fragmentation of a foreland basin in response to out-of-sequence basement uplifts and structural reactivation: El Cajon- Campo del Arenal basin, NW Argentina. *Geol. Soc. Am. Bull.* 119 (5–6), 637–653. <http://dx.doi.org/10.1130/B25884.1>.
- Mpodozis, C., Arriagada, C., Basso, M., Roperch, P., Cobbold, P., Reich, M., 2005. Late Mesozoic to Paleogene stratigraphy of the Salar de Atacama Basin, Antofagasta,

- Northern Chile: implications for the tectonic evolution of the Central Andes. *Tectonophysics* 399 (1), 125–154.
- Muñoz, N., Jordan, T.E., Charrier, R., 2002. Interactions between basement and cover during the evolution of the Salar de Atacama basin, northern Chile. *Rev. Geol. Chile* 29, 3–29.
- Nalpas, T., Le Douaran, S., Brun, J.P., Unternehr, P., Richert, J.P., 1995. Inversion of the Broad Fourteens Basin (offshore Netherlands), a small-scale model investigation. *Sediment. Geol.* 95, 237–250.
- Navarrete, C., Gianni, G., Folguera, A., 2015. Pre-Neogene inversion in the western San Jorge Gulf Basin. *J. S. Am. Earth Sci.* (in this issue).
- Nogueira, F.C., Marques, F.O., Bezerra, F.H., de Castro, D.L., Fuck, R.A., 2015. Cretaceous intracontinental rifting and post-rift inversion in NE Brazil: insights from the Rio do Peixe Basin. *Tectonophysics* 644, 92–107.
- Padilha, A.L., Trivedi, N.B., Vitorello, I., Costa, J.M. da, 1991. Geophysical constraints on tectonic models of the Taubaté Basin, southeastern Brazil. *Tectonophysics* 196, 157–172.
- Pardo-Casas, F., Molnar, P., 1987. Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time. *Tectonics* 6 (3), 233–248.
- Paredes, J.M., Plazibat, S., Crovetto, C., Stein, J., Cayo, E., Schiuma, A., 2013. Fault kinematics and depocenter evolution of oil-bearing, continental successions of the Mina del Carmen Formation (Albian) in the Golfo San Jorge basin, Argentina. *J. S. Am. Earth Sci.* 46, 63–79.
- Pedoja, K., Husson, L., Regard, V., Cobbald, P.R., Oustanciaux, E., Johnson, M.E., Delcaillau, B., 2011. Relative sea-level fall since the last interglacial stage: are coasts uplifting worldwide? *Earth Sci. Rev.* 108 (1), 1–15.
- Pérez, D., García, V., Likerman, J., Winocur, D., Morabito, E., Dopico, C., Yagupsky, D., Guzmán, C., Cristallini, E., Díaz, T., Czeplowodzki, R., Crovetto, C., Yllañez, E., Aymar, E., Liberman, A., 2011. Análisis estructural y tectónico yacimiento Cerro Dragón, Provincia de Chubut (Argentina). Pan american energy, Informe Inédito.
- Peroni, G.O., Hegedus, A.G., Cerdan, J., Legarreta, L., Uliana, M.A., 1995. Hydrocarbon Accumulation in an Inverted Segment of the Andean Foreland: San Bernardo Belt, Central Patagonia. In: Tankard, A.J., Suárez, R., Welsink, H.J. (Eds.), *Petroleum Basins of South America*, pp. 403–419.
- Ramos, V.A., 1981. Descripción geológica de la hoja 47 ab Lago Fontana, Provincia de Chubut. *Serv. Geol. Nac. Bol.* 183, 1–130.
- Ramos, V.A., 2014. Evolución de la Cuenca Golfo San Jorge: Su estructuración y régimen tectónico. *Rev. la Asoc. Geol. Argent.* 72 (1), 16–24.
- Reyes, F.C., Salfity, J., 1973. Consideraciones sobre la estratigrafía del Cretácico (Subgrupo Pirgua) en el Noroeste Argentino. In: 5° Congreso Geológico Argentino, Actas III, pp. 355–385.
- Reyes, F.C., Salfity, J.A., Viramonte, J.G., Gutiérrez, W., 1976. Consideraciones sobre el vulcanismo del Subgrupo Pirgua (Cretácico) en el Norte Argentino. In: 6° Congreso Geológico Argentino, Actas I, pp. 205–223.
- Riccomini, C., 1989. O Rift Continental do Sudeste do Brasil (PhD thesis). Instituto de Geociências, Universidade de São Paulo, p. 256.
- Riccomini, C., Peggia, A.U.G., Saloni, J.C.L., Kohnke, M.W., Figueira, R.M., 1989. Neotectonic activity in the Serra do Mar rift system (southeastern Brazil). *J. S. Am. Earth Sci.* 2, 191–197.
- Riccomini, C., Sant'Anna, L.G., Ferrari, A.L., 2004. Evolução geológica do Rift Continental do Sudeste do Brasil. In: Mantesso Neto, V., Bartorelli, A., Carneiro, C.D.R., Brito-Neves, B.B. (Eds.), *Geologia do Continente Sul-Americano: Evolução da Obra de Fernando Flávio Marques de Almeida*. Ed. Beca, São Paulo, pp. 383–405.
- Roperch, P., Sempere, T., Macedo, O., Arriagada, C., Fornari, M., Tapia, C., Gracia, M., Laj, C., 2006. Counterclockwise rotation of late Eocene-Oligocene fore-arc deposits in southern Peru and its significance for oroclinal bending in the central Andes. *Tectonics* 25, tc3010. <http://dx.doi.org/10.1029/2005tc001882>.
- Salfity, J.A., Marquillas, R.A., 1994. Tectonic and sedimentary evolution of the Cretaceous-Eocene Salta Group basin, Argentina. In: Salfity, J.A. (Ed.), *Cretaceous Tectonics of the Andes*, pp. 266–315.
- Salomon, E., Koehn, D., Passchier, C., Hackspacher, P.C., Glasmacher, U.A., 2014. Contrasting stress fields on correlating margins of the South Atlantic. *Gondwana Res.* <http://dx.doi.org/10.1016/j.gr.2014.09.006>.
- Salvador, E.D., Riccomini, C., 1995. Neotectônica da região do alto estrutural de Queluz (SP-RJ, Brasil). *Rev. Bras. Geosci.* 25, 151–164.
- Schumacher, M.E., 2002. Upper Rhine Graben: role of preexisting structures during rift evolution. *Tectonics* 21, 1–6.
- Sengör, A.M.C., 1976. Collision of irregular continental margins: implications for foreland deformation of Alpine-type orogens. *Geology* 4, 779–782.
- Sengör, A.M.C., 1995. Sedimentation and tectonics of fossil rifts. In: Busby, C.J., Ingersoll, R.V. (Eds.), *Tectonics of Sedimentary Basins*. Blackwell, Oxford, pp. 53–117.
- Sengör, A.M.C., Burke, K., Dewey, J.F., 1978. Rifts at high angles to orogenic belts: tests for their origin and the Upper Rhine Graben as an example. *Am. J. Sci.* 278 (1), 24–40.
- Somoza, R., Ghidella, M.E., 2005. Convergencia en el margen occidental de América del Sur durante el Cenozoico: subducción de las placas de Nazca, Farallón y Aluk. *Rev. la Asoc. Geol. Argent.* 60 (4), 797–809.
- Somoza, R., Tomlinson, A.J., Caffé, P.J., Vilas, J.F., 2012. Paleomagnetic evidence of earliest Paleocene deformation in Calama (22° S), northern Chile: Andean-type or ridge-collision tectonics? *J. S. Am. Earth Sci.* 37, 208–213.
- Starck, D., 2011. Cuenca Cretácica-Paleógena del Noroeste Argentino. 8° Congreso de Exploración y Desarrollo de Hidrocarburos. Simposio Cuenas Argentinas: Visión Actual, Instituto Argentino del Petróleo y el Gas 407–453.
- Strecker, M.R., Hilley, G.E., Bookhagen, B., Sobel, E.R., 2011. Structural, geomorphic, and depositional characteristics of contiguous and broken foreland basins: examples from the eastern flanks of the central Andes in Bolivia and NW Argentina. In: Busby, C., Azor Pérez, A. (Eds.), *Tectonics of Sedimentary Basins Recent Advances*. Wiley-Blackwell, pp. 508–521.
- Suárez, M., De La Cruz, R., 2001. Jurassic to Miocene K–Ar dates from eastern Central Patagonian Cordillera plutons, Chile (45°–48°S). *Geol. Mag.* 138, 53–66.
- Suárez, M., De La Cruz, R., Bell, M., Demant, A., 2010. Cretaceous slab segmentation in southwestern Gondwana. *Geol. Mag.* 147 (02), 193–205.
- Suárez, M., Márquez, M., De La Cruz, R., Navarrete, C., Fanning, M., 2014. Cenomanian–? early Turonian minimum age of the Chubut Group, Argentina: SHRIMP U–Pb geochronology. *J. S. Am. Earth Sci.* 50, 67–74.
- Sylvan, C.A., 2001. Geology of the Golfo San Jorge Basin, Argentina. *J. Iber. Geol.* 27, 123–157.
- Uliana, M.A., Biddle, K.T., Cerdan, J., 1989. Mesozoic extension and the formation of Argentine sedimentary basins. In: Tankard, A.J., Balkwill, H.R. (Eds.), *Extensional Tectonics and Stratigraphy of the North Atlantic Margin*, pp. 599–613.
- Viramonte, J.G., Kay, S.M., Becchio, R., Escayola, M., Novitski, I., 1999. Cretaceous rift related magmatism in central-western South America. *J. S. Am. Earth Sci.* 12, 109–121.
- Visser, J.N.J., Praekelt, H.E., 1998. Late Palaeozoic crustal block rotation within the Gondwana sector of Pangea. *Tectonophysics* 287, 201–212.
- Viviers, M.C., Azevedo, R.L.M. de, 1988. The southeastern area of the Brazilian continental margin: its evolution during the Middle and Late Cretaceous as indicated by paleoecological data. *Rev. Bras. Geociências* 18, 291–298.
- Zalán, P.V., Oliveira de, J.A.B., 2005. Oríem e evolução estrutural do sistema de riftes Cenozóicos do Sudeste do Brasil. *Bol. Gesoci. Petrobras* 13, 269–300.
- Ziegler, P.A., Dèzes, P., 2006. Crustal evolution of Western and Central Europe. In: Gee, D.G., Stephenson, R.A. (Eds.), *European Lithosphere Dynamics*, Geological Society of London, pp. 43–56.
- Ziegler, P.A., van Hoorn, B., 1989. Evolution of the North Sea Rift. In: Tankard, A.J., Balkwill, H.R. (Eds.), *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, pp. 471–500.