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Tectonic inversion events in the western San Jorge Gulf Basin from seismic, borehole and field data

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ABSTRACT

The San Jorge Gulf Basin, located in Central Patagonia, has been interpreted as a Jurassic-Cretaceous rift basin that was later inverted mainly in its western sector. Consequently, the Bernardides System formed as a set of foreland contractional structures that constitute the core of the Patagonian broken foreland, exhuming continental deposits of the Cretaceous Chubut Group, 500 km away from the Pacific trench. In spite of the intense research done in the San Jorge Gulf Basin many aspects remain under discussion, particularly those regarding the age of uplift of the Bernárdides System. In order to unravel the tectonic evolution of the western San Jorge Gulf Basin (Río Mayo Sub-Basin), we analyzed subsurface information (2D and 3D seismic lines and oil wells) located in the western area of the basin and compared this with surface data of the southern Bernárdides System. Based on our interpretation, the western part of the basin could have been uplifted in a series of deformational events that began as early as late Early Cretaceous, related to the initial uplift of the Patagonian broken foreland, during the early stages of South Atlantic opening. Subsequent stages of tectonic reactivation identified in this system have selectively inverted previous extensional structures according to the variable direction of the greatest horizontal stress (σ1) acting at each time.

1. Introduction

The San Jorge Gulf Basin (SJGB), located in Central Patagonia of Argentina, is a major hydrocarbon producer basin known worldwide due to its paleontological content, especially for its dinosaurs and Cenozoic land mammals. The origin of this basin is closely related to the breakup of Western Gondwana and consequently involves several episodes of crustal stretching. Its western sector known as Río Mayo Embayment/Sub-Basin or Aysén Basin constitutes the oldest part of the basin. This sector is characterized by shelf deposits related to a marine to mixed back-arc setting (Fig. 1) (Aguirre Urreta and Ramos, 1981; Clavijo, 1986; Suárez et al., 2009a). The Río Mayo Sub-Basin was associated with several intra-arc and retroarc depocenters, that developed contemporaneously to a westward jump of the arc front between 150 and 140 Ma (Late Jurassic to Early Cretaceous) (Rolando et al., 2002, 2003).

Tectonic inversion of the western sector of the SJGB has been classically considered as a direct aftermath of the Andean deformation (Peroni et al., 1995; Homovc et al., 1995). Hence, numerous depocenters were inverted at varying degrees depending on their orientation respect to the main Andean stress field (Homovc et al., 1995). As a result of these deformational events, an intraplate orogenic system known as the Bernárdides System developed about 300 km east of the Andes in the west central part of the SJGB, east of the study area (Fig. 1). The most prominent topographic feature of this system is the Sierra de San Bernardo, where extensive deposits of the late Early to Late Cretaceous Chubut Group crop out (Lesta, 1968). The Bernárdides System is currently considered as part of the broad Patagonian broken foreland that extends from the western flank of the North Patagonian Massif to the core of the Deseado Massif (Folguera and Ramos, 2011; Bilmes et al., 2013; Gianni et al., 2015a, b). Despite intense research in the SJGB, the age of the initial uplift of the Bernárdides System remains somehow controversial: Even though the most accepted contractional event had been considered as late Miocene for decades (Peroni et al., 1995; Homovc et al., 1995), a few works pointed out to earlier uplift events: In this line, Paredes et al. (2006) described locally,

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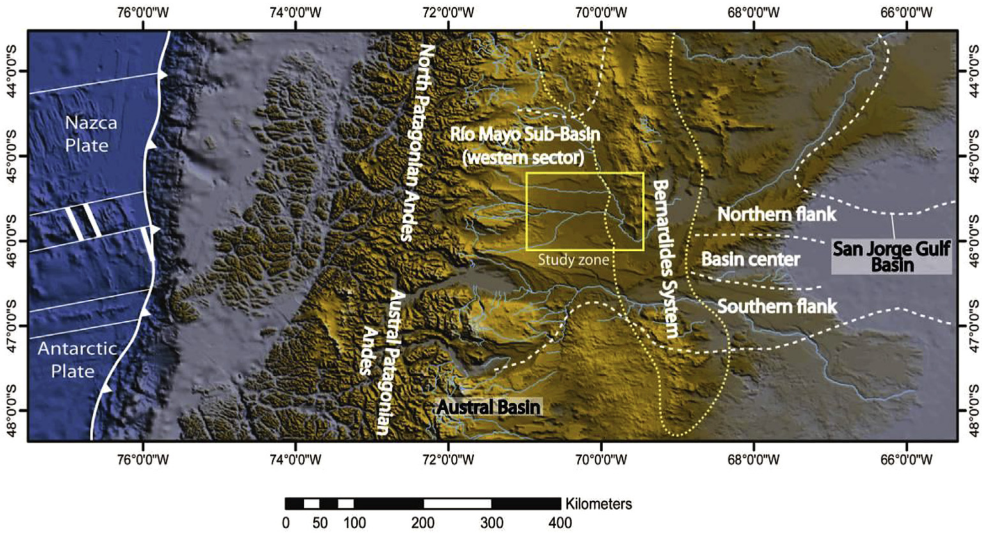

Fig. 1. Location of the study area in the Central Patagonian foreland region in the western sector of the San Jorge Gulf Basin. Regions analyzed in this work, based on the dominant structural style and orientation, are indicated. The location of the study zone shown in Fig. 2 is also indicated.

thickness variations in the late Paleocene Río Chico Group in the subsurface area of the Bernárdides System near the orogenic front of the broken foreland system. Interestingly, early works of Feruglio (1949) and Lesta et al. (1980) had suggested an even earlier uplift event in Late Cretaceous times to explain the lack of transgressive marine deposits of the Salamanca Formation (Danian) over the Chubut Group in the Sierra de San Bernardo area. In this line, Barcat et al. (1989) posed stages of tectonic inversion contemporaneous to the deposition of the Chubut Group (late Early to Late Cretaceous), after which Homovc et al. (2011), through the analysis of subsurface seismic data in the Rio Mayo Sub-Basin, showed direct evidence of late Early Cretaceous contractional deformation (Fig. 1). More recently, synorogenic deposition in all units belonging to the Chubut Group has been described from surface and subsurface data over the Sierra de San Bernardo (Gianni et al., 2015a). In the northern sector of the Bernardides System, Marquez and Navarrete (2011) proposed an even older contractional event affecting the foreland zone based on the description of an angular unconformity between the Chubut Group and the Early to Middle Jurassic Lonco Trapial Group. A similar tectonic event has been described in the Deseado Massif, south of the San Jorge Gulf Basin (Fig. 1), where Neocomian deposits were folded and unconformably covered by sedimentary sections equivalent to the lower section of the Chubut Group (Giacosa et al., 2010).

To the west, in the North Patagonian Andes where the Río Mayo Sub –Basin filling is partially exposed, an angular unconformity between the Neocomian deposits and the volcanic rocks of the Divisadero Group (120–100 Ma) has been interpreted as a consequence of the early uplift of this belt in the late Early Cretaceous (Suarez and De la Cruz, 2000; Folguera and Iannizzotto, 2004; Suárez et al., 2009a, b). In this sense, Iannizzotto et al. (2004) concluded that most of the contractional structure exposed in this region developed prior to 90 Ma.

Cretaceous contraction affecting Central Patagonia has been either explained by high convergence rates during fast westward motion of South America after the initial stages of formation of the South Atlantic ocean (Somoza and Zaffarana, 2008) as well as the shallowing of the subducted slab (Barcat et al., 1989), evidenced by an eastward arc migration at that time (Gianni et al., 2015a). The latter authors proposed that such slab shallowing may have occurred by a combination of high convergence rate and fast overriding of young lithosphere attached to two consecutive mid-ocean ridges that subducted beneath Central Patagonia in late Early Cretaceous times.

This work focuses in a broad subsurface sector of the retroarc area of the Río Mayo Sub-Basin, where Neocomian depocenters have been identified and in the adjacent southern Bernárdides System (Clavijo, 1986; Strelkov et al., 1994; Figari et al., 1996; Homovc et al., 2011) (Fig. 1). The main objective of this study is to characterize and determine the age of the contractional deformation of the western sector of the SJGB (Río Mayo Sub-Basin) from seismic and field information, through identification of growth strata associated with tectonic inversion. Then, Danian paleogeography characterized by a widespread Atlantic marine transgression through Central Patagonian is discussed. Finally, variable orientation of the contractional stress field through time is evaluated through the degree of inversion of the recognized structures, determined from seismic information, considering their different strike.

2. Location of the study area, material and methods

The study area is located at the central sector of Patagonia in Argentina, as part of the San Jorge Gulf Basin (Fig. 1). This basin has been usually divided by the oil industry into five regions depending on the dominant structural style: on the Atlantic passive margin the North and South flanks and Basin Center, and to the west next to the Andean front the Bernárdides System and the Western Sector (Fig. 1). This work focuses on the last two areas analyzing subsurface and field information.

In order to study the subsurface area of the Río Mayo Sub-Basin, 2200 km of 2D and 200 km^2 of 3D seismic data, mainly recorded in the past decades by the YPF oil company, have been analyzed. Currently, this area is operated by the Energial SA Company, which has generated valuable information through the acquisition of additional 3D seismic images that are also inspected in this work. Moreover, we used information obtained from 46 drilling wells, drilled since the 1960's to the present (Fig. 2). The seismic information was analyzed using the software Kingdom Suite version 8.6, for all the interpretations and grilled.

3. Geological framework

The SJGB is the result of extensional stresses that affected the

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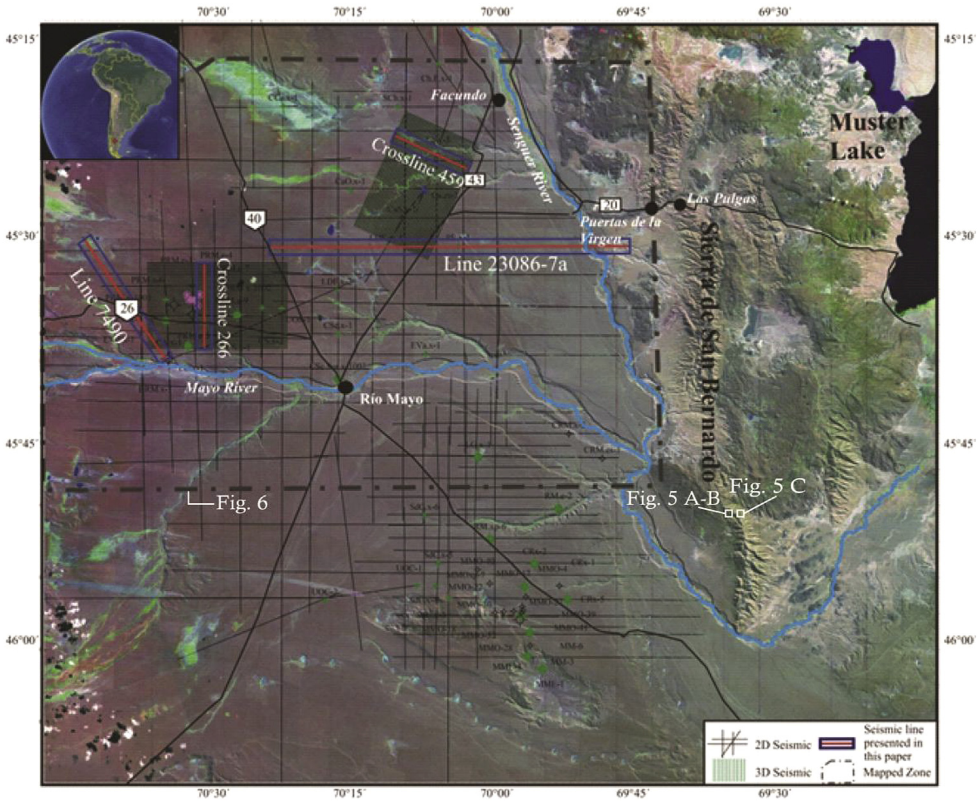

Fig. 2. 2D and 3D seismic information and drilling wells used in this study, draped on top of a TM image and indication of field data. The dashed square indicates the outline of the 3D seismic data used in this work.

southern portion of western Gondwana during Middle Jurassic to Cretaceous times (Fig. 3). Prior to the formation of this basin, an extensional event in the region had taken place during the Early Jurassic producing a set of NW-SE-trending half-grabens (Ferello and Lesta, 1973) essentially filled with marine sediments of Pacific provenance. These Liassic successions are exposed in the Andean front at these latitudes and have been found in wells drilled by the oil industry. Their age has been assigned to the Toarcian based on the finding of Rhynchonellids, which allowed a direct correlation with the Mulanguineu Formation of Pliensbachian-Toarcian age (Fernández Garrasino, 1977).

In the foreland zone, similarly NW–SE oriented Liassic extensional structures have been described associated with a continental infill corresponding to the Roca Blanca Formation (Giacosa et al., 2010).

During the Middle Jurassic a widespread rifting stage was related to a large volume of lavas, ignimbrites and pyroclastic fall deposits, forming one of the largest siliceous igneous provinces on the Earth (Chon-Aike Province and equivalent units; Fig. 3) (Pankhurst et al., 1998).

In the Late Jurassic and Early Cretaceous, renewed extension led to the initial opening of the SJGB (Figari et al., 1999; Sylwan, 2001). This event nucleated a series of deep depocenters in specific sectors of the basin, informally gathered as Neocomian depocenters (Cortiñas, 1984). These were filled by lacustrine and deltaic sediments in the eastern sector of the SJGB, while marine and mixed lacustrine environments prevailed in the western sector of the SJGB (Río Mayo Sub-Basin) indicating a general westward basin polarity (Aguirre Urreta and Ramos, 1981). These deposits were grouped in the informal well unit Paso Río Mayo Formation (PRMF), also known as "Pelitic Section", which correlates with the Aguada Bandera and Cerro Guadal formations described in the eastern sector (Fig. 1). The distribution of depocenters implies partial disconnection between them, so that these contain slightly different sedimentation histories (Strelkov et al., 1994). However, basal sections of the Paso Río Mayo Formation are constituted by thick packages of lacustrine mudstones and blackshales with rare marine intercalations at the top determined by palinomorphs found in a well core of the YPF.Ch.PRM.es-1 well at 1420–1430 m of depth (Cesari, 1977). The upper portion of the Paso Río Mayo Formation, also called "Sandy Section," is composed of marine and continental facies, formed by mudstones, sandstones and tuffs and in some cases glauconite. Micropaleontological studies of dinoflagellates, microforaminifera and palinomorphs in well cores (UOS-1; YPF.CH.PRM.es-1), yielded Valanginian-Barremian ages (Archangelsky et al., 1983). The marine origin of these levels and the similarity in age allowed a correlation with the Katterfeld Formation exposed in the North Patagonian Andes (Ramos, 1976). This marine transgression coming from Austral Basin to the south is present only in the western portion of the SJGB, in the Río Mayo Sub-Basin, (Aguirre Urreta and Ramos, 1981) (Fig. 1).

In the eastern sector, the Neocomian sections were deposited in purely continental, lacustrine and deltaic environments in starved half-grabens, represented by the Anticlinal Aguada Bandera (Lesta et al., 1980) and Pozo Cerro Guadal formations (Ferello and Lesta, 1973), which were gathered in the Las Heras Group (Lesta et al., 1980) (Fig. 3). Thus, a marine transgression flooded the western area concomitant to lacustrine environments to the east. Both sectors were isolated from each other by a topographic high in the Rio Mayo area, known as the Alto Carril-El Vasco High (Clavijo, 1986). By the end of the Early Cretaceous, both sectors connected marking the beginning of a common depositional history.

During the late Early to Late Cretaceous (Aptian-Cenomanian), the most voluminous stratigraphic unit of Central Patagonia,

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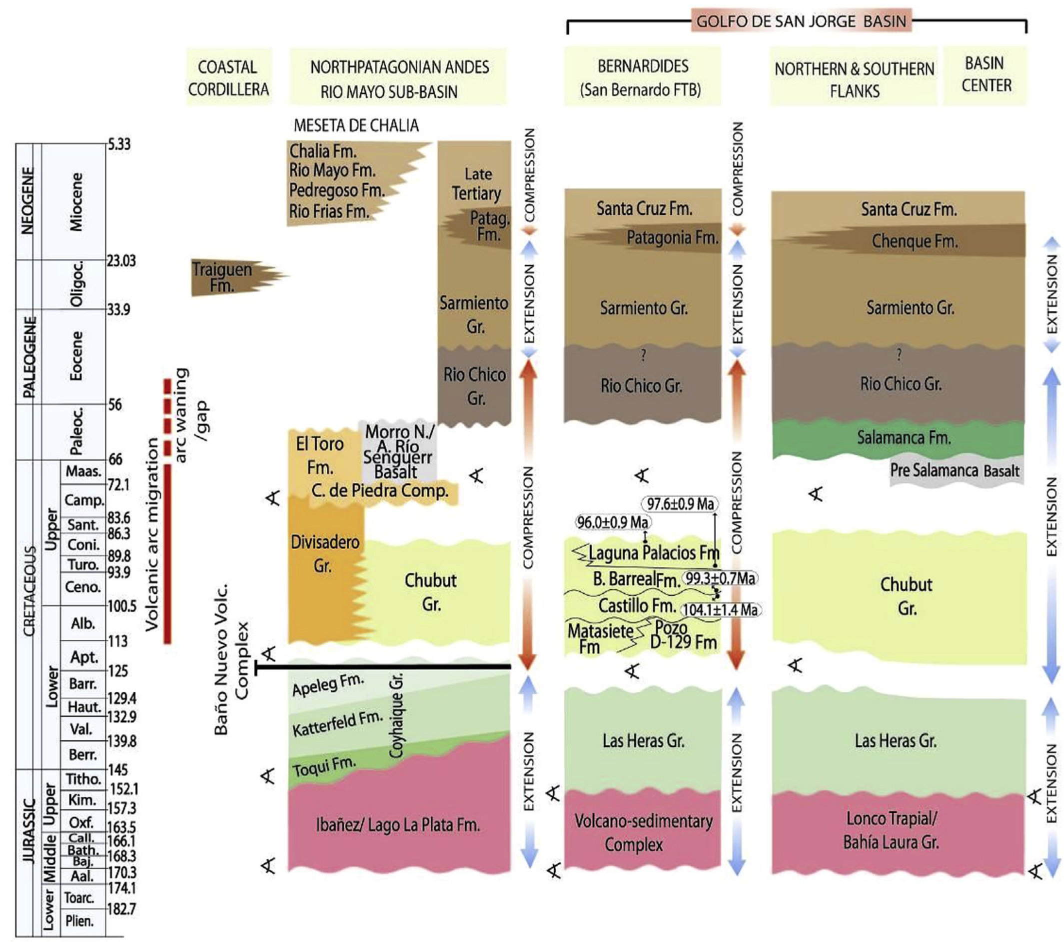

Fig. 3. Stratigraphic chart at 45°–46°S comparing the Coastal Cordillera and North Patagonian known geology in the arc and forearc zones with the retroarc domains (Río Mayo Sub-Basin and San Jorge Gulf Basin in the broken foreland system) (taken from Gianni et al., 2015b and references therein).

referred to as the Chubut Group deposited in the SJGB (Lesta, 1968). This unit is composed of thick beds of pyroclastic material reworked in fluvial and lacustrine environments that exceed 6000 m in the deepest part of the basin. Its economic importance, as a hydrocarbon producer, and its paleontological content have caught the attention of geoscientists for decades (see Casal et al., 2007; Navarrete et al., 2011, 2008; Martinez et al., 2004; and references therein). The basal unit of the Chubut Group is represented by the PozoD-129 Formation (Sciutto, 1981) deposited in an alkaline lacustrine environment, representing the hydrocarbon source rock of the basin. This unit deposited between 121.5 and 112 Ma during Aptian times (Fitzgerald et al., 1990; Paredes et al., 2007) is laterally related to the fluvial Matasiete Formation, which is covered by volcaniclastic rocks of the Castillo Formation deposited in low-sinuosity fluvial systems (Mina del Carmen Formation). The age of the latter unit has been initially assigned on the basis of pollen, charophytes and ostracodes to the Aptian-Albian (Mussacchio and Chebli, 1975; Fitzgerald et al., 1990). However, recently, a U/Pb zircon age of ~104 Ma provided an Albian age for this unit (Suárez et al., 2009b). The overlying Bajo Barreal Formation consists of sediments deposited in meandering fluvial environments with extensive flood plains with a large input of pyroclastic material. Finally, the Laguna Palacios Formation is capping the Chubut Group, consisting in falling tuffs, stacked paleosols and in specific sectors minor fluvial systems. Recently, Suárez et al. (2014) provided a new set of U/Pb zircon ages of ~99 Ma for the Bajo Barreal Formation and a 96–98 Ma age for the Laguna Palacios Formation, determining a Cenomanian to late Cenomanian-early Turonian (?) age.

Even though Fitzgerald et al. (1990) and Bridge et al. (2000) had indicated a depositional lapse for the Chubut Group from approximately 120 to 67 Ma, the work of Suárez et al. (2014) indicates that the youngest age would be approximately 96 Ma, based on U/Pb zircon ages obtained from the upper levels of the Laguna Palacios Formation and from the equivalent Puesto Manuel Arce Member, of the Cerro Barcino Formation. Thus, the new ages reduce in several millions of years the lapse of this sedimentary episode, implying a hiatus of approximately 30 million years from latest Cretaceous to Paleocene times (Fig. 4). These U/Pb SHRIMP ages are coherent with the age of the Divisadero Group, corresponding to the contemporaneous arc volcanism emplaced in the North Patagonian Andes between 120 and 100 Ma (Fig. 3) (Suárez et al., 2009b). Therefore, the Chubut Group most likely represents distal facies for the large volumes of pyroclastic materials that fed the Chubut Group Basin (Tunik et al., 2004; Paredes et al., 2007; among others).

During the early Paleogene, a first Atlantic marine transgression is registered on the southern edge of South America, represented in the SJGB by the Salamanca Formation (Figs. 3 and 4) (Lesta et al., 1980). This shallow marine unit recently dated in ca. 65.7–63.5 Ma (Danian) (Clyde et al., 2014), overlies the Cenomanian Laguna Palacios Formation in the SJGB. Above, the Rio Chico Group (Fig. 3) was partially fed from a late Paleocene western fluvial system (Feruglio, 1949), which replaced laterally and overlaid progressively the Salamanca Formation. From Eocene to early Miocene times,

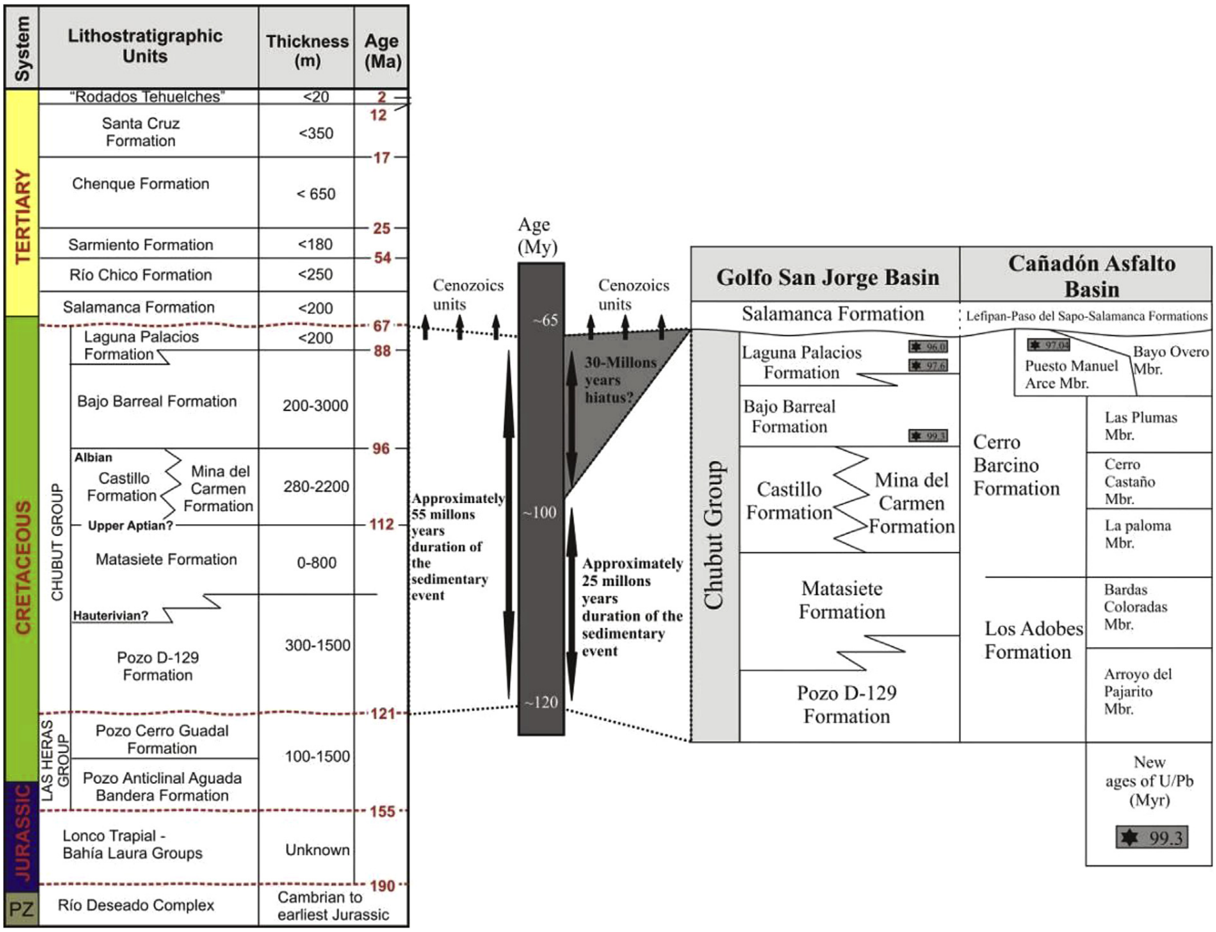

Fig. 4. Comparison between the stratigraphical scheme of the Chubut Group taken from Paredes et al. (2013) and the new ages obtained by Suárez et al. (2014) (right).

deposition of the Sarmiento Group (Fig. 3) took place in Central Patagonia (Simpson, 1941), consisting essentially of reworked falling tuffs in fluvial, aeolian and lacustrine systems (Mazzoni, 1985). From the Oligocene to the early Miocene, the marine sediments of the Patagonia or Chenque Formation flooded the SJGB representing a second Atlantic derived transgression (Fig. 3) (Barreda, 1992). This unit consists of tuffaceous sandstones, cinerític levels, mudstones and shales with varying fossil content. During the middle Miocene, the Santa Cruz Formation (Fig. 3) (Fleagle et al., 1995) deposited in fluvial and aeolian environments in response to the final uplift of the Patagonian Andes (Ramos, 1999; Blisniuk et al., 2005).

4. Surface and subsurface structural data

Synorogenic deposition of the Chubut Group has been mostly documented to the east of the study area in relation to the uplift of the northern and central sectors of the Sierra de San Bernardo (Gianni et al., 2015a). In the southernmost sector of this range growth strata are found in the Codo del Senguer Anticline. Here, the Castillo Formation (Albian) shows systematic dip changes and strata thickening away from the anticline hinge (Fig. 5). Description of growth strata in the forelimb as well as in the backlimb of this structure is indicative of syntectonic deposition during compressional folding in late Early Cretaceous times.

To the west of the study area, seismic data from the Río Mayo Sub-Basin is provided to determine the tectonic evolution of the westernmost SJGB. Here, based on the interpretation of our data, four tectonostratigraphic sequences can be differentiated in relation to the different stages of basin formation: Thus, Early Jurassic marine sediments are part of the Pre-rift units, followed by the Lonco Trapial Group (Middle Jurassic) that is interpreted as part of the early Syn-rift stage, the "Pelitic Section" (lower member) of the Paso de Río Mayo Formation (Early Neocomian) that corresponds to the main Syn-rift stage and the "Sandy Section" (upper member) identified as a late syn-rift stage. The Chubut Group (late Early to Late Cretaceous) is considered as part of an early Post-rift stage, while the Cenozoic units as part of a late Post-rift stage.

This sector of the study area holds four depocenters characterized by half-graben geometries with a general E-W-trend in the western sector that passes to a NE–SW trend in the central sector and finally N–S at the easternmost sector (Fig. 6). Homovc et al. (2011) had detected and denominated these as Campo Schulze for the southernmost depocenter, Cañadon Cantado Depocenter for the northernmost, Paso Rio Mayo Depocenter for the largest located in the central sector, and finally Senguer Depocenter for the one located in the easternmost sector close to the Sierra de San Bernardo (Fig 6).

The NE–SW Paso Rio Mayo Depocenter is limited by a normal fault (fault A) roughly 50 km long characterized by a variable trend. While its western segment trends NE–SW and dips to the NW, its eastern segment trends to the NNE-SSW dipping to the NNW (Fig. 6). An antithetic shorter E-W-trending and S-dipping fault (fault B) is recognized in association to it. This fault B is about 20 km long and is limiting the western deepest sector of the depocenter (Fig. 6). Extensional activity of these structures began during the Middle Jurassic generating the space that accommodated thick

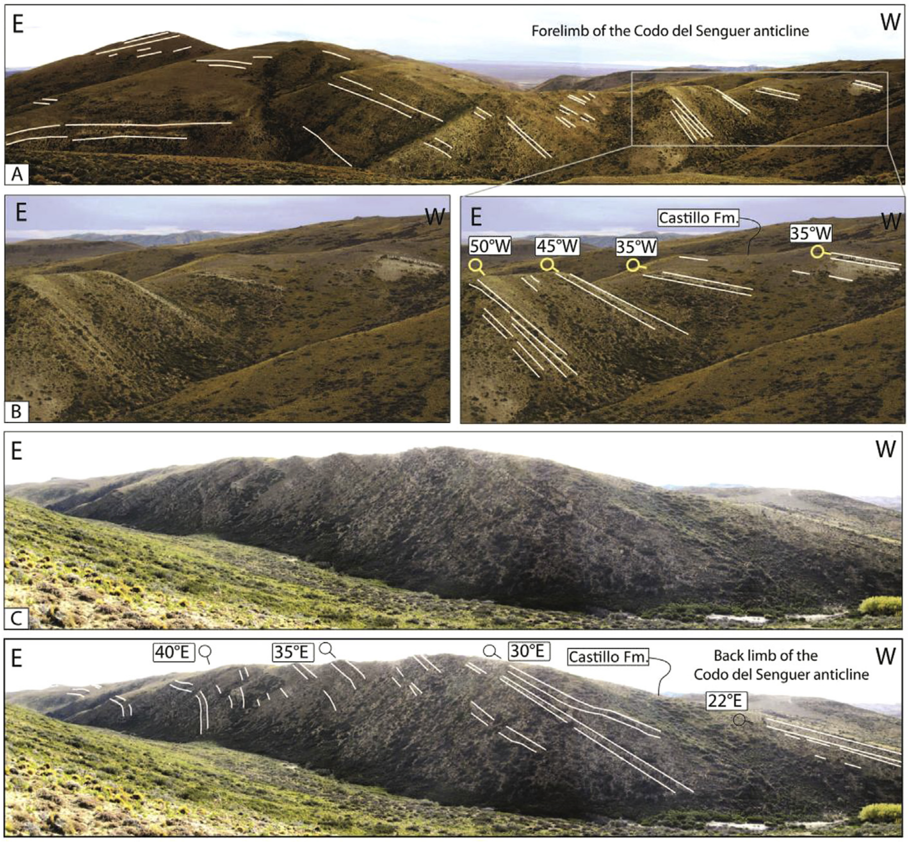

Fig. 5. Late Cretaceous growth strata in the Castillo Formation in the El Codo del Senguer anticline located in the southernmost Bernárdides System next to the Río Mayo depocenters (see location in Fig. 2). A) Growth strata over the anticline forelimb. B) Close up to growth strata. C) Growth strata over the anticline backlimb. Preservation of growth geometries with strata fanning away from the anticline hinge in the forelimb and the backlimb, suggest a syn-compressional deposition of the Castillo Formation in relation to the fold growth.

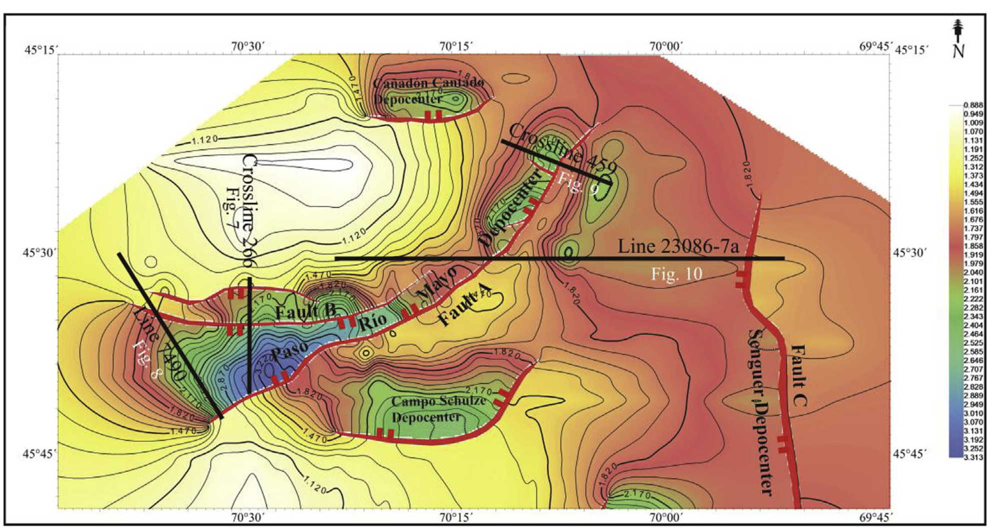

Fig. 6. Isochron map of the top Pre-rift (Liassic) and location of seismic lines (colors indicate depth in meters, see vertical scale in the right) (see location in Fig. 2). Color scale is TWT in mseg. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sections of the Lonco Trapial Group that represents the early Syn-rift stage, with its maximum thickness in the vicinity of the fault trace and decreasing towards the NW (Figs. 7 and 8).

The maximum subsidence of this depocenter limited by faults A and B occurred during the deposition of the Paso de Río Mayo Formation (Neocomian), reaching up to 3100 m (Figs. 7 and 8).

In the westernmost sector of the study area seismic line 7490 depicts tectonic inversion of E-W- Fault B (Fig. 8). On the other hand, reactivation of NE-segment of fault A involved an important degree of strike-slip component as denoted by the development of a positive flower structure (Fig. 8). Initial tectonic reactivation produced a local angular unconformity observed between folded

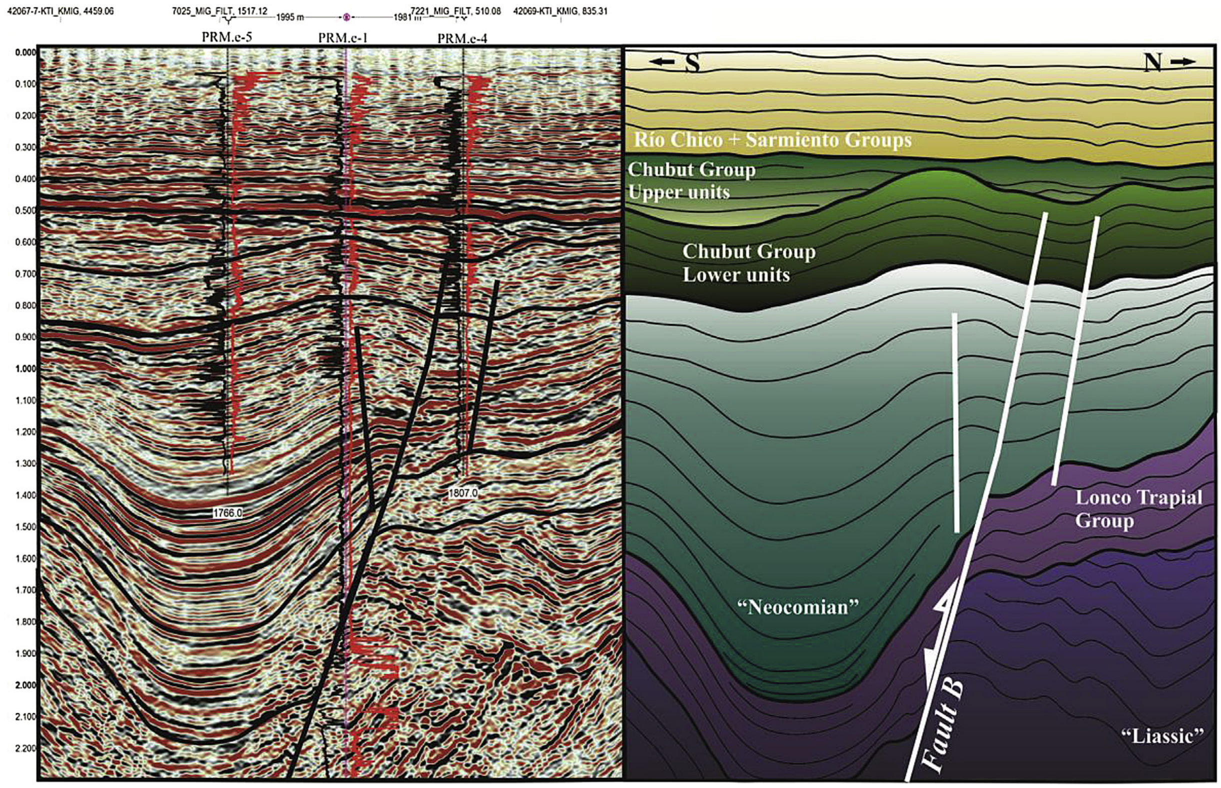

Fig. 7. 3D seismic line crossline 266 in Paso Río Mayo Depocenter showing the Cretaceous tectonic inversion of fault B and the unconformity between the upper and lower terms of the Chubut Group. Vertical scale is TWT in mseg.

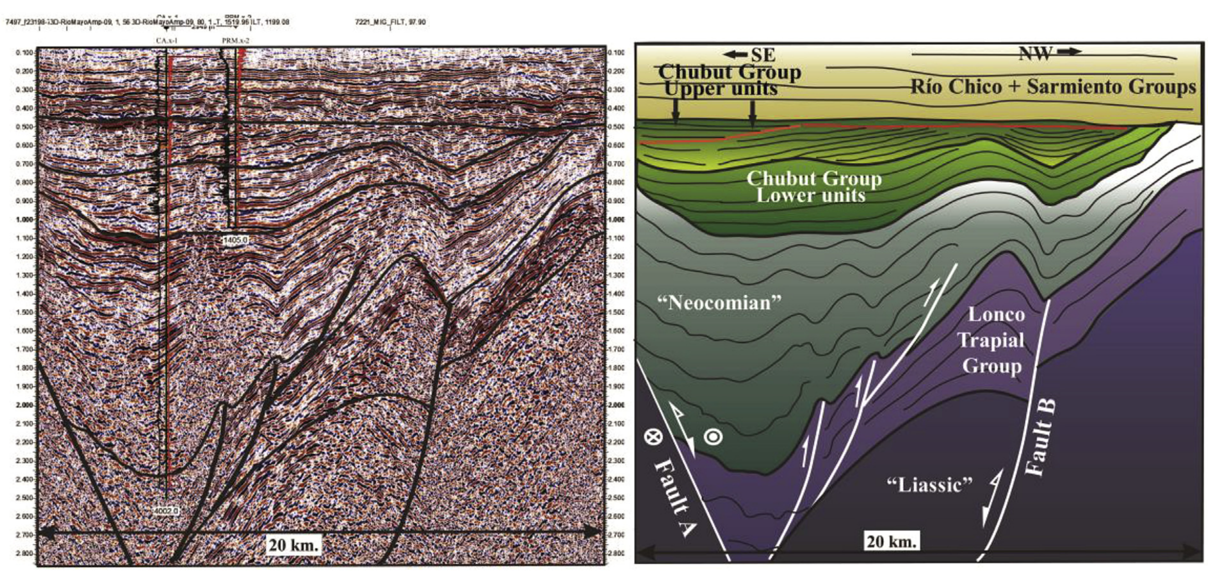

Fig. 8. 2D seismic line 7490 in Paso Río Mayo Depocenter showing the Cretaceous tectonic inversion of E-W-trending fault B and the positive flower structure related to reactivation of NE-trending fault A. Note the unconformity between the folded Neocomian deposits and the lower Chubut Group, as well as, the syntectonic character of the latter units in the SE sector of the Seismic line 7490. Also, a synorogenic character of the upper units of the Chubut Group is inferred based on a strong internal angular unconformity and onlapping reflectors over the folded lower units. Note that reactivation of faults A and B ended before Cenozoic times as denote by flat lying Paleogene to early Neogene deposits. Vertical scale is TWT in mseg.

Neocomian sections and Lower Chubut Group units (Fig. 8). Positive inversion of faults A and B produced a local depocenter which the lower Chubut Group units filled syntectonically. It is revealed by strata thickening in these units towards the depocenter deepest sector and onlapping reflectors over the Neocomian paleo-relief (Fig. 8). This is consistent with previous observations in other sectors of the Río Mayo Sub-Basin as well as regional data in The North Patagonian Andes and Central Patagonian foreland (Clavijo, 1986; Folguera and Iannizzotto, 2004; Iannizzotto et al., 2004; Suárez et al., 2009a, b; Giacosa et al., 2010).

Then, before and during the deposition of the upper units of the Chubut Group, fault B underwent a new tectonic reactivation

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folding the lower Chubut Group units as shown in 3D seismic line (crossline-266) and 2D seismic line 7490 (Figs. 7 and 8). A synorogenic character of the upper units of the Chubut Group is recognized through a strong internal angular unconformity and onlapping reflectors over the folded lower units (Figs. 7 and 8). On the other hand, the overlying Cenozoic units are preserved resting upon previous Mesozoic deposits without any evident deformation (Figs. 7 and 8).

Where fault A undergoes a flexion from NE to NNE, the depocenter becomes shallower (Fig. 6). In crossline 459 (crossing the NNE segment of fault A), folding of the lower Chubut Group is observed, as well as, internal wedging of the upper Chubut Group that onlaps the flanks of an anticline (Fig. 9). This denotes a synorogenic character of the upper Chubut Group and inversion of fault A, starting in the Late Cretaceous and continuing after the deposition of the Cenozoic units (Río Chico and Sarmiento Groups), as evidenced by subsequent folding of these units (Fig. 9).

As a summary, the entire E-W- trending fault B and the NE to NNE fault A experienced noticeable tectonic inversion in Cretaceous times (Figs. 7–9). Nevertheless, reactivation in NE-segment of fault A involved an strike-slip component (Fig. 8), while in the NNE-segment of this fault as well as in fault B, such inversion mechanisms are not seen (Fig. 9). Also, fault A experienced subsequent tectonic reactivation localized in its eastern NNE-segment, folding Paleocene to early Miocene deposits (Río Chico and Sarmiento Groups) (Fig. 9). Contrastingly, fault B (E-W- oriented) and the western sector of fault A (NE- oriented) did not experience evident reactivation at this time, keeping the deformational features of the previous Cretaceous inversion events.

To the east, an N–S-trending structure, denominated fault C, recognized in the 2D seismic line 23086-7a (Fig. 10), shows a similar kinematic history to the faults that delimit the Paso Río Mayo Depocenter. Here, the Lonco Trapial Group is characterized by a syn-rift geometry wedging westwards, with a maximum thickness next to fault C (Fig. 10). The Neocomian Paso Río Mayo Formation also shows maximum thicknesses associated with fault C, although considerably narrower than those found at the Paso Río Mayo Depocenter. Above, the lower units of the Chubut Group present a uniform thickness with a tabular shaped geometry. Contrastingly, the upper units of the Chubut Group show a strong control during its deposition in association with reverse reactivation of fault C (Fig. 10). This reactivation seems to be synsedimentary respect to the upper sections of the Chubut Group, based on an internal unconformity described between these and previous units (Fig. 10). The internal unconformity of the Chubut Group becomes more evident close to Fault C, where the upper units onlap the more tilted lower reflectors corresponding to the base of this Group (Fig. 10).

The basal levels of Río Chico Group wedge from west to east as these are close to the inverted sector of the Río Senguer Depocenter (fault C) (Fig. 10). Therefore maximum thicknesses of the Río Chico Group occur to the east of the deepest depocenter of the Upper Chubut Group. This could be interpreted in terms of depocenter migration by tectonic reactivation of fault C and synorogenic deposition of the Rio Chico Group. Thus, the Cretaceous orogenic event is interpreted as continuing in Paleogene times. A final stage of tectonic inversion during the Neogene (Peroni et al., 1995; Homovc et al., 1995) becomes evident from deformation of the uppermost sedimentary levels. However, its distribution is not uniform; since the upper Cenozoic units have been deformed only by reactivation of fault C characterized by a N–S orientation along its length. On the other hand, along the NE–SW segment of fault A no post-Cretaceous reactivation is observed.

5. Discussion: distribution of the recognized deformational stages

As described in previous sections, contractional deformation

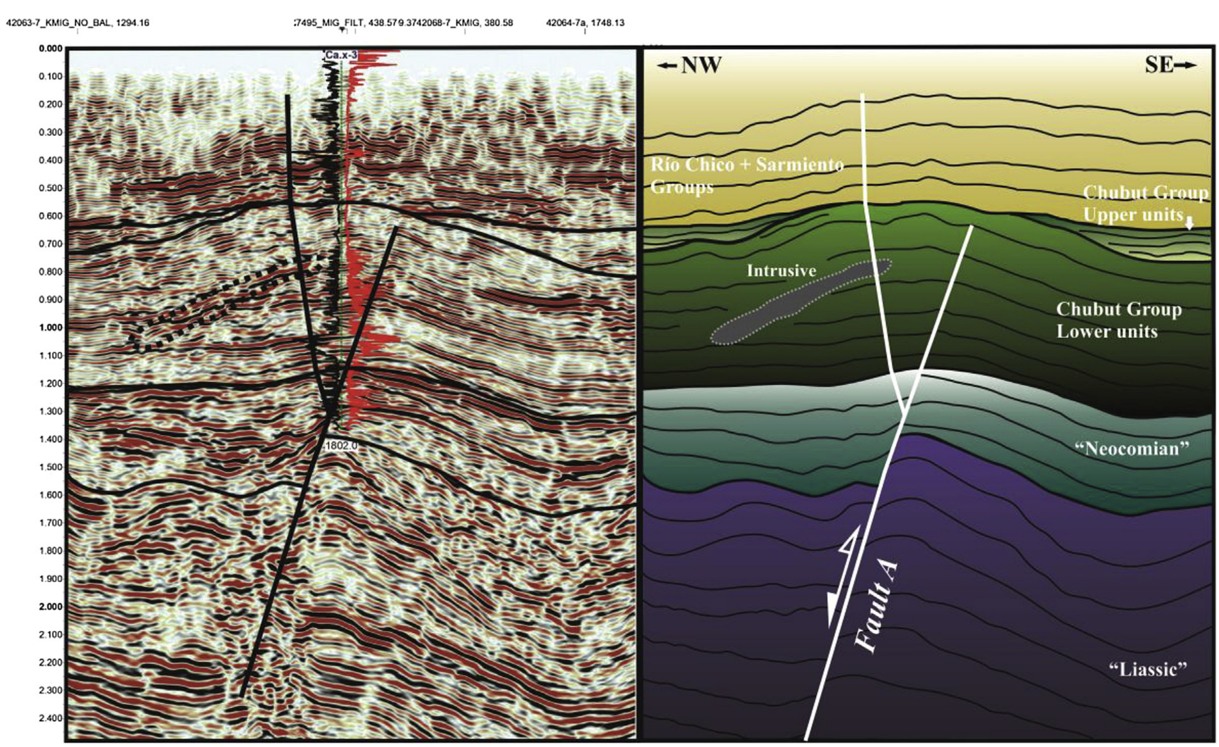

Fig. 9. 3D seismic line crossline 459 showing the Cretaceous tectonic inversion of the NNE-SSW segment of fault A and the unconformity between the upper and lower terms of the Chubut Group. This line also shows a local Neogene fault reactivation. Vertical scale is TWT in mseg.

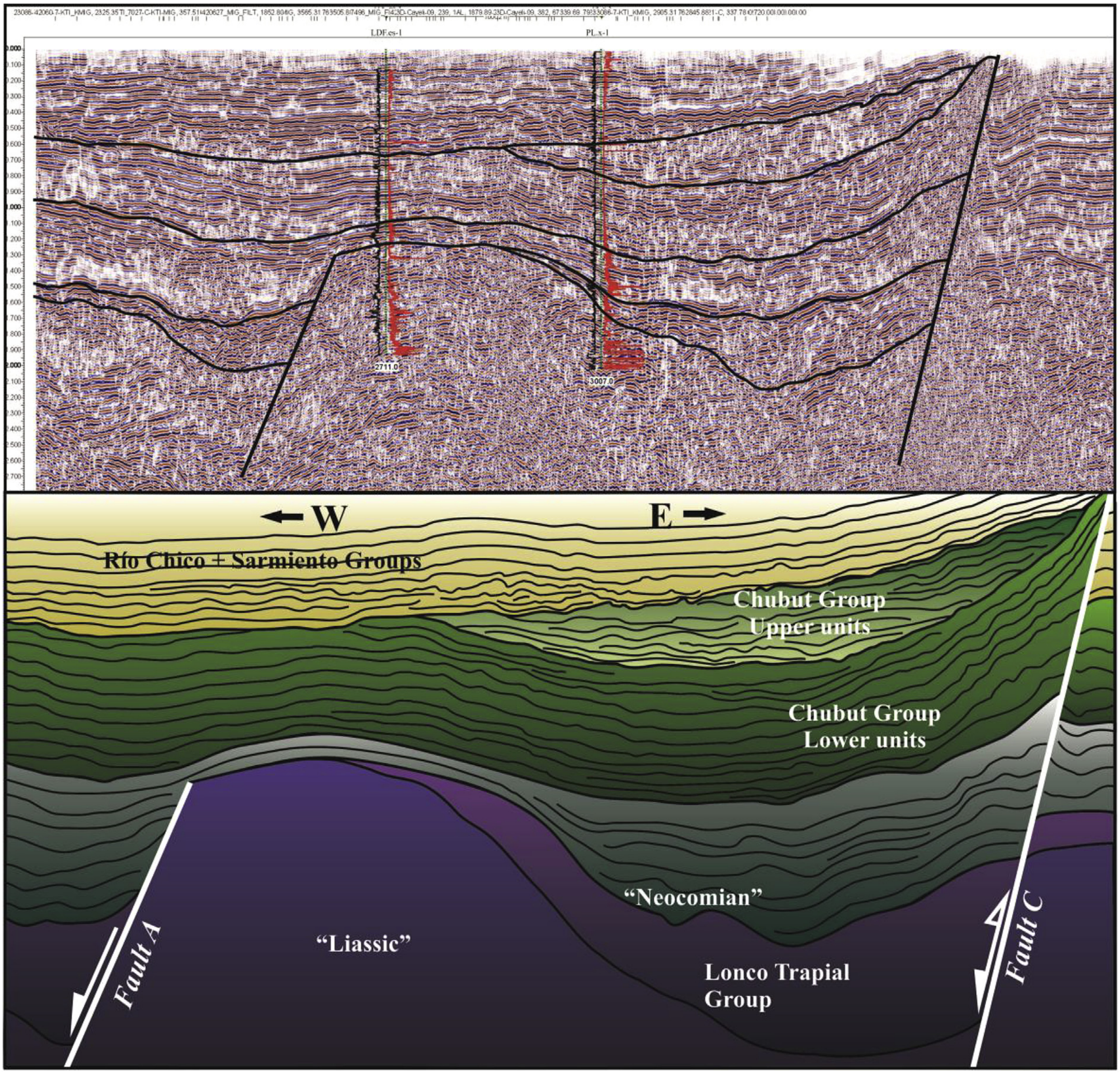

Fig. 10. 2D seismic line 23086-7a crossing fault A associated with the Río Mayo Depocenter and fault C with the Río Senguer Depocenter. This interpretation indicates an unconformity between the upper and lower terms of the Chubut Group associated with tectonic inversion of fault C. Two subsequent interpreted stages of tectonic inversion would have produced the wedging of reflectors from west to east in the Rio Chico Formation and the deformation of the upper Cenozoic units. See that fault A is not reactivated in this sector (modified from Gianni et al., 2015a, b). Vertical scale is TWT in mseg.

beginning in late Early Cretaceous and generalizing in Late Cretaceous times selectively inverted previous-extensional structures trending E–W, N–S and those close to N–S (faults B, C and eastern segment of fault A respectively, Figs. 7–10). Whereas, the western NE-segment of Fault A was transpressively reactivated (Fig. 8). These progressive deformational episodes were responsible for the development of local angular unconformity at the base of the lower Chubut Group units and their syn-contractional deposition, as well as more regional internal unconformity and syntectonic deposition of Chubut Group upper units (Figs. 5 and 7–10). Taking into account the strike-slip reactivation of the NE-segment of fault A and the strong compressive reactivation of the E–W, N–S and NNE-SSW striking faults at this stage, the corresponding largest horizontal stress ($\sigma1$) should have been oriented approximately in the SW direction (Fig. 11A).

During the late Paleocene, compression acted in concert with the deposition of the Rio Chico Group affecting only the N–S trending structures (fault C) (Fig. 10). This deformation is associated with large thickness variations of the basal section of the Río Chico Group in the Río Senguer Depocenter (Fig. 10) In this case, the largest horizontal stress ($\sigma1$) is interpreted as been aligned to a SW direction, although with a lower obliquity respect to the north, which would make N–S structures favorable to reactivation but precluding significant reactivation of the NNE-SSW segment of fault A. Therefore, the most likely direction of $\sigma1$ would be around N65°E to N70°E in Paleocene times (Fig. 11B).

Finally, the Miocene contractional stage affected structures with N–S and NNE-SSW strikes (fault C and north-eastern section of fault A) (Figs. 9 and 10). A few kilometers to the east of the analyzed area, Cretaceous to Cenozoic rocks are exposed in the western flank of the Sierra de San Bernardo through reactivation of N–S- structures parallel to fault C (Homovc et al., 1995 among others). At this time, the principal contractional stress ($\sigma1$) would have been nearly orthogonal to the western border of South America and main

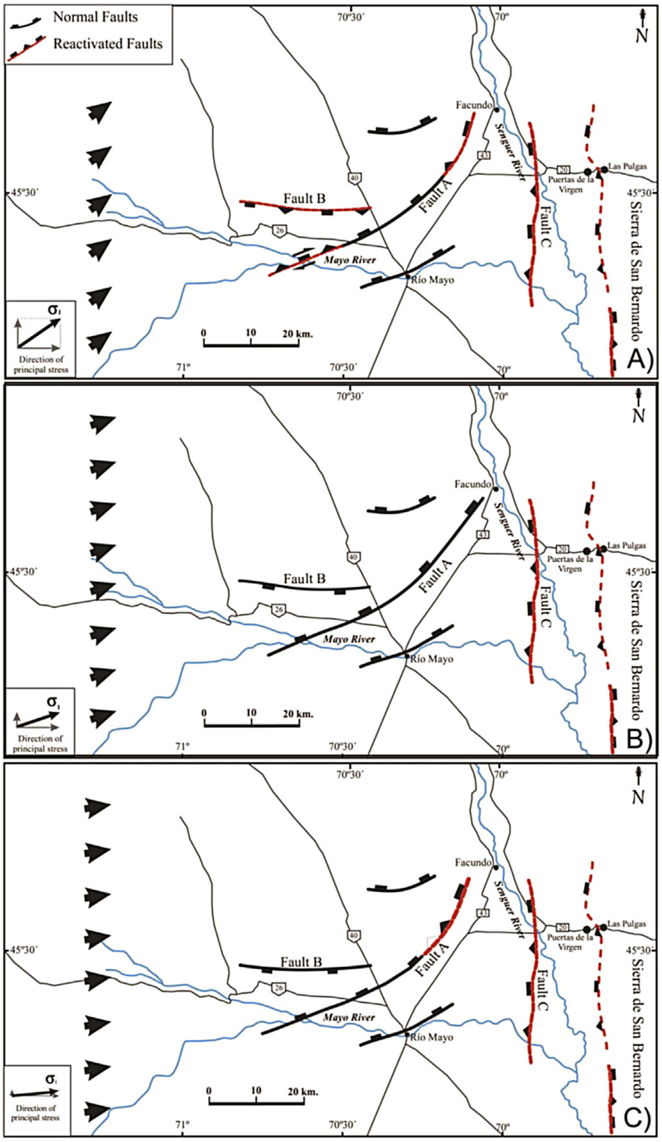

Fig. 11. A) Map showing the structures that were reactivated (red) during the late Early to Late Cretaceous and the inferred direction of the largest horizontal stress (σ1) at that time. B) Map showing the structures that were reactivated (red) during the Paleogene and the inferred direction of the largest horizontal stress (σ1). C) Map showing the structures that were reactivated (red) during the Neogene and the inferred direction of the largest horizontal stress (σ1). Note that faults trending N–S and close to that strike have absorbed contraction in all tectonic inversion episodes, explaining the higher topography over the eastern sector of the study area (Sierra de San Bernardo). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Andean trend, as previously indicated by Pardo Casas and Molnar (1987), reactivating preferentially N–S and NNE-SSW striking faults (Fig. 11C). Finally, even though substantial Neogene deformation has been absorbed in the subsurface zone of the Río Mayo Sub-Basin, no topography has emerged such as in the Sierra de San Bernardo immediately to the east. This can be discussed based on the our proposed kinematic evolution: While the N–S-trending fault C was affected by the three major stages of tectonic inversion described in the Río Mayo Sub-Basin (Late Cretaceous, Early Paleogene and Neogene) (Fig. 11) and fault A was reactivated by two events in Cretaceous and Neogene times in its NNE-SSW segment, the E–W striking fault B and NE-segment of fault A only experienced Cretaceous tectonic inversion (Fig. 11). Therefore, N–S structures and closely striking fault segments of the Rio Mayo Sub-Basin depocenters and the Sierra de San Bernardo have accumulated successive stages of contractional deformation, due to a more favorable orientation respect to the imposed contractional stress-field in comparison to W-E– and NE-trending structures. Thus, faults striking N–S and close to that strike have built a higher topography over the eastern sector of the study area (Sierra de San Bernardo) through absorption of contraction in all tectonic inversion stages.

In a more regional perspective, as early noticed by Feruglio (1949) and Lesta et al. (1980), the Maastrichtian Atlantic marine transgression did not overcome the central sector of the Patagonian region in coincidence with the Sierra de San Bernardo (Fig. 12), implying the existence of a latest Cretaceous topographic barrier. Subsurface data presented in this work show the existence of previous tectonic inversion stages in late Early to Late Cretaceous times in the Rio Mayo Sub-Basin. These deformational episodes were syntectonic respect to the deposition of the Chubut Group as previously proposed for the Sierra de San Bernardo. This is in agreement with the initial uplift of the Patagonian Andes and the raise of the Early Patagonian Broken foreland (Barcat et al., 1989; Folguera and Iannizzotto, 2004; Suárez et al., 2009a; Gianni et al., 2015a). This orogenic event would have reached the foreland sector in Central Patagonia building a topographic barrier for the marine transgressions of the Salamanca Formation (Feruglio, 1949; Lesta et al., 1980). However, local coeval marine synorogenic deposition of the Lefipan Formation took place in the northernmost sector of the Bernárdides System (Ruiz et al., 2005). This contractional stage continued during the deposition of the late Paleocene Rio Chico Group, as previously proposed by Paredes et al. (2006). Late Early Cretaceous to Paleocene uplift of the Patagonian Andes and foreland fragmentation acted in concert with transversal rifting in the eastern sector of the SJGB (Figari et al., 1999). These apparently opposite stress-fields have been causally related and interpreted as a synorogenic foreland rifting stage (Gianni et al., this issue).

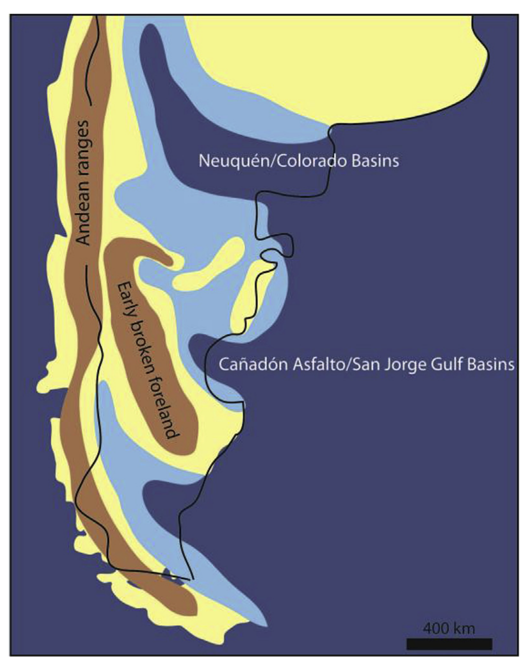

Fig. 12. Map showing the location of the proposed Early Patagonian Broken Foreland that could have acted as a topographical barrier for the Maastrichtian marine transgression (modified from Scasso et al., 2012).

The final deformational event is related to the reactivation of the Río Senguer Depocenter and the uplift of the Sierra de San Bernardo where Oligocene to early Miocene volcanic plateau sequences were folded (See Barcat et al., 1984).

6. Conclusions

Incorporation of the Río Mayo Sub-Basin into the Early Patagonian broken foreland took place during the late Early Cretaceous to Paleocene times, involving the reactivation of E-W- and N—S-striking faults. This stage was associated with synorogenic deposition of the Chubut and Río Chico Groups. In the Late Cenozoic, N—S-striking faults were preferentially reactivated in association with the final uplift of the Bernardides System. This behavior is explained by a progressively changing orientation of the maximum horizontal stresses through time.

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