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Patagonian broken foreland and related synorogenic rifting: The origin of the Chubut Group Basin

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ABSTRACT

The Central Patagonia is characterized by prominent continental deposits that belong to the Cretaceous Chubut Group Basin, whose tectonic setting remains controversial. It has been interpreted as a foreland basin, an extensional basin and even as a sag stage of a rift event. Related deposits outcrop as part of the Patagonian broken foreland, east of the Patagonian Andes. Particulary, the San Bernardo fold and thrust belt, between 42° and 48°S, as the main sector of the broken foreland, constitutes a NNW-trending intraplate belt located 450 km away from the trench. Coincidentally, at these latitudes, 1200 km east of the trench, intraplate deformation has caused tectonic inversion of Mesozoic basins presently located at the Atlantic offshore area. Additionally, at the San Jorge Gulf area this orogenic system interferes with a conspicuous E–W extensional system, transversally disposed to the Andean strike, mainly active between the late Early Cretaceous and late Paleocene. We carried out an integrated analysis from structural, 2-D and 3-D seismic data at the San Bernardo FTB and the adjacent Río Mayo Basin, studying sections of the Chubut Group Basin to unravel the different evolutionary stages. Thus, surface and subsurface evidence of syn-compressional deposition indicate the development of a broken foreland basin related to the formation of the San Bernardo FTB, suggesting an initial growth during the late Early Cretaceous and probably up to the late Paleocene. Our results imply that the Cretaceous compression acted in concert with transversal foreland extension. Hence, we propose a syncontractional rift reactivation of a potential lithospheric anisotropy, triggered by regional contraction. Finally, the origin of compression during this time is discussed in relation to multiple processes that go from high convergence between plates and trenchward motion of South America, collision of mid-ocean ridges, to potential dip changes in the subducted slab, as suggested by arc expansion.

1. Introduction

The Andean Cordillera is a post Pangea break-up orogen related to the subduction of different Panthalassic and Pacific plates, where the Patagonian Andes represent a key record of the earliest evolutionary stages of this system. This sector of the Andes has been studied for decades (Aguirre Urreta and Ramos, 1981; Folguera and Iannizzotto, 2004; Suárez et al., 2009a), although, some aspects of the Andean deformation have been somehow overlooked, specifically the broad orogenic development acquired at its northern part (42–46.5°S) (Fig. 1). This abnormal amplitude is determined by the presence of a conspicuous mountain system known as the San Bernardo fold and thrust belt (FTB) located in the extra-Andean region, ~450 km away from the trench, as part of the Patagonian broken foreland (Bilmes et al., 2013) (Fig. 1). Moreover, intraplate compressional deformation extended even farther to the east at these latitudes reaching the present Atlantic offshore area (~1200 km from the trench) (Ross et al., 1996; Thomson and Underhill, 1999; Homovc and Constantini, 2001; Continanzia et al., 2011; Micucci et al., 2011) (Fig. 1). Understanding the processes that acted in the foreland area would constitute a link to explain the tectonic development of Central Patagonia from the Andes to the Atlantic offshore region.

An important feature of the Central Patagonian foreland, is the broad Chubut Group Basin (Folguera and Ramos, 2011). This basin is placed above older Mesozoic depocenters and its genesis is marked by a distinguishable evolutionary stage that coincides with a change in the strain field during Cretaceous times (Clavijo, 1986; Figari et al., 1999; Paredes et al., 2013) (Fig. 1). The Chubut Basin contains a fossil-rich continental succession known as the Chubut Group, that constitutes one of the most prominent oil-bearing sedimentary sequences in Patagonia (Lesta, 1968). Its tectonic origin has been contrastingly interpreted as

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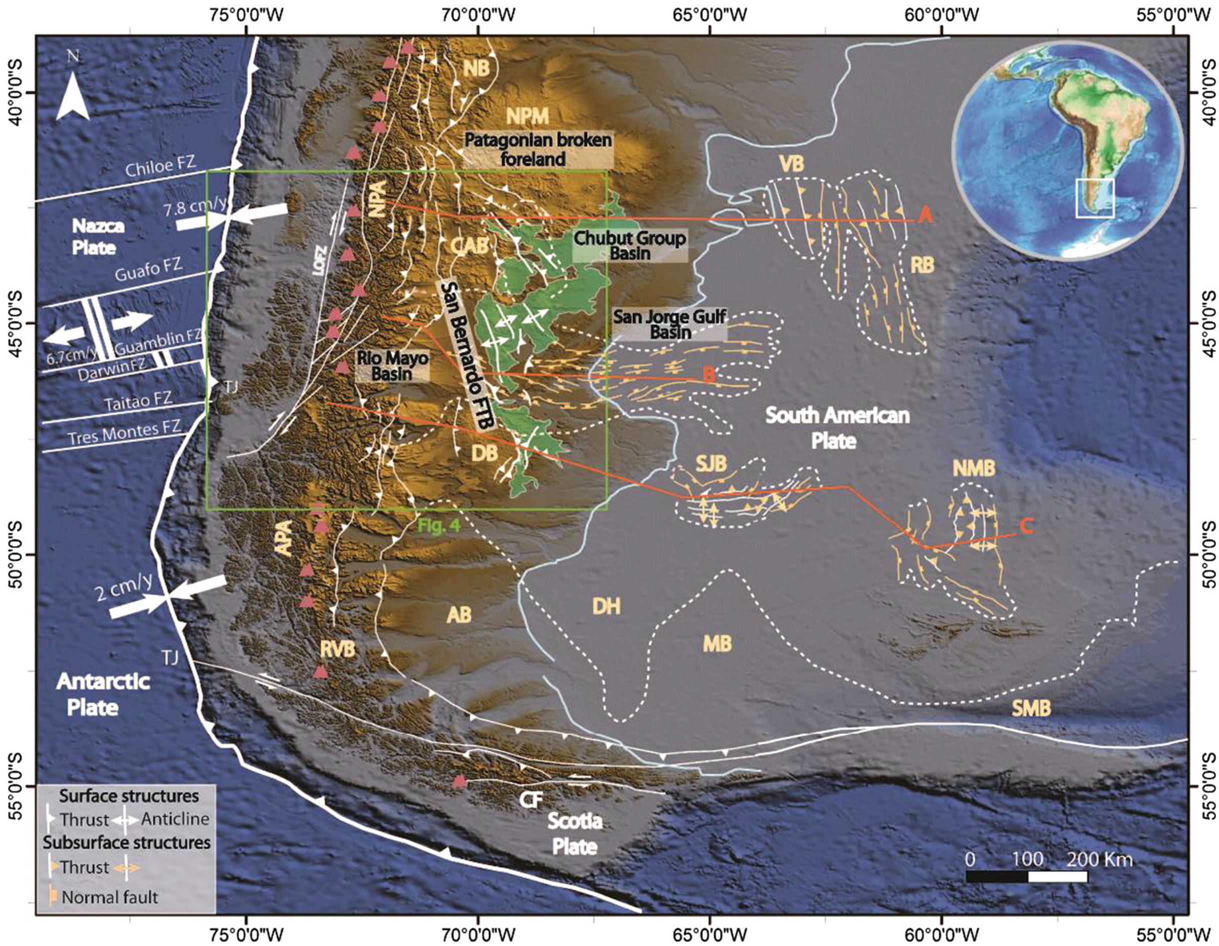

Fig. 1. Structural sketch map showing the different morphostructural units of Central Patagonia. Note inverted structures in the offshore area that were positively reactivated mostly in Cretaceous times as a distal broken foreland sector 1200 km from the trench. Dashed white lines indicate basin inferred limit; blue line represents the coast line; and red lines indicate the location of the crustal scale cross sections of Fig. 2; green area represents the outcrops of the Chubut Group and equivalent units. NB: Neuquén Basin, NPM: North Patagonian Massif, DB: Deseado Massif Basin, NPA: North Patagonian Andes, APA: Austral Patagonian Andes, CF: Fueguinian cordillera, CAB: Cañadón Asfalto Basin, VB: Valdés Basin, CR: Rawson Basin, SJB: San Julian Basin, NMB: North Malvinas Basin, RVB: Rocas Verdes Basin; AB: Austral Basin, DH: Dungeness High, MB: Malvinas Basin, SMB: South Malvinas Basin, LOFZ: Liquiñe-Ofqui Fault Zone, FZ: Pacific Fracture Zones. Arrows indicate the present-day plate convergence and mid-ocean spreading rates from Cande and Leslie (1986) and Somoza (1998). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

related to a foreland basin associated with the Andean growth (Barcat et al., 1989), as a sag stage of the Jurassic to Early Cretaceous rifting in the region (Fitzgerald et al., 1990), and even as related to a late extensional reactivation of a previous rift (Figari et al., 1999). This last hypothesis has been supported by subsurface data at the San Jorge Gulf Basin, where deposition of different units belonging to the Chubut Group shows to be controlled by extensional structures (Hechem, 1998; Rodriguez and Littke, 2001; Georgieff et al., 2009; Paredes et al., 2013) (Fig. 1). This basin is characterized by a complex structural pattern that involves mainly NW-trending Neocomian extensional structures, that turned into a deep E–W elongated depocenter in the late Early Cretaceous during deposition of the Chubut Group (Clavijo, 1986; Barcat et al., 1989; Hechem et al., 1990) (Fig. 1). West of the San Jorge Gulf Basin, the extensional structures interact with NNW-trending contractional structures of the San Bernardo FTB (Fig. 1). The most accepted age of uplift of these structures is as young as Miocene (Homovc et al., 1995; Peroni et al., 1995; Sylwan, 2001; Bilmes et al., 2013), although other studies point out to an older contractional activity in the late Oligocene–early Miocene (Folguera and Iannizzotto, 2004), Paleocene (Paredes et al., 2006) and even in the Late Cretaceous (Feruglio, 1949; Lesta et al., 1980).

This work is aimed to determine the mechanisms associated with the formation of the Chubut Basin, its spatio-temporal relationship with the San Bernardo FTB and its potential relation to the eastern E–W extensional San Jorge Gulf Basin (Fig. 1). Thus, an integrated evolution of the Central Patagonia during Cretaceous to Cenozoic times will be put forward, linking orogenesis from the Patagonian Andes to the inverted Mesozoic basins presently located at the present offshore area.

2. Methodology

We have analized sedimentary successions at main structures of the San Bernardo FTB and adjacent Río Mayo Basin in order to unravel the earliest evolutionary stages of the Chubut Basin (Fig. 1). Additionally, we have established a structural frame constructed from previous and new field data consisting on field mapping of structures and related syntectonic deposits, and seismic data. In order to make a detailed description of depocenters developed at depth, we analyzed one 2D and two 3D seismic lines across the San Bernardo FTB and Río Mayo Basin (provided by Y.P.F. and Energial S.A.), using as constraints surface and borehole data. Additionally, seismic lines were used to analyze the different constructional episodes, restituting the structure to the different recognized deformational stages. In order to do this, we restored seismic profiles at different horizons by applying the flexural slip unfolding algorithm (Griffiths et al, 2002) with the Move® software (Midland Valley Ltd.). Also, we studied the magmatic arc behavior as an indicative of potential past subduction configurations. In order to do this, a radiometric dataset was compiled from several previous works (detailed references are provided in caption of Fig. 4). We also used Seton et al. (2012) plate tectonic model and average changes in trench-normal convergence velocity and trench-normal component of the absolute velocity of South America (constructed with data taken from Maloney et al., 2013) to understand the deformational history of the different morphostructural systems known in Central Patagonia.

3. Geodynamic setting

The present configuration of the Patagonian Andes is related to the subduction of the Nazca and Antarctic plates beneath the South American plate. The three plates presently interact along the South American margin at 46° 30′ S, in the Chilean triple junction (Fig. 1). The triple junction point separates two morphostructural domains along the Andes: The Austral and Northern Patagonian Andes (Fig. 1).

The pre-Mesozoic evolution of the Patagonian basement is related to a complex evolution, still a matter of important debate (Ramos, 2008; Dalla Salda et al., 1990; Pankhurst et al., 2006; see Rapalini et al., 2010 for a discussion). During Triassic times continental rift basins developed in the Patagonian region heralding further extension and magmatism during Jurassic to Early Cretaceous (Ramos, 2009). At this time, several extensional depocenters, informally referred to as Neocomian Basins, filled by marine and non-marine associations developed in the Patagonian and offshore regions. These are known as the Río Mayo, San Jorge Gulf, Deseado, San Julian, North Malvinas, Rawson and Valdes Basins (Figs. 1 and 2) (Aguirre Urreta and Ramos, 1981; Fitzgerald et al., 1990; Richards and Hilliers, 2000; Homovc and Constantini, 2001; Suárez et al., 2009a, 2009b; Continanzia et al., 2011; Micucci et al., 2011). In late Early Cretaceous times, a new continental sedimentary cycle, referred to as the Chubut Group (Lesta, 1968) (Fig. 2), started covering vast portions of the Patagonia and offshore areas. These rocks contain a high proportion of distal, ash-fall deposits reworked in lacustrine and fluvial settings (Sciutto, 1981; Tunik et al., 2004; Paredes et al., 2007; Umazano et al., 2009, 2012). Even though, an important amount of fossils has been found and new geochronological studies have been carried out, the age of the Chubut group is under review, particularly at its upper section (See Casal et al., 2014; Suárez et al., 2014). Several works have described an angular unconformity between the Chubut Group and the underlying Neocomian deposits, generally interpreted as related to a major compressional/transpressional event that would have affected the foreland region (Clavijo, 1986; Barcat et al., 1989; Homovc and Constantini, 2001; Giacosa et al., 2010; Ranalli et al., 2011; Marquez and Navarrette, 2011, among others) (Fig. 2). This discontinuity has been correlated with the earliest episode of Andean uplift at these latitudes (Ramos, 1981; Folguera and Iannizzotto, 2004; Iannizzotto et al., 2004; Suárez et al., 2009a; Ghiglione et al., 2013). Particularly, in the Northern Patagonian Andes, Suárez et al. (2009a, 2009b) have constrained this tectonic event with U/Pb ages to the 121–118 Ma interval. More recently, in the northern part of the Austral Patagonian Andes, Ghiglione et al. (2013) have dated detrital zircons by U/Pb method, in synorogenic strata obtaining a maximum age of ~122 Ma. The authors pointed out that these data indicate a late Early Cretaceous (post ~122 Ma) uplift of the Deseado Massif and the western rim of the North Patagonian Massif. The Chubut Group across the foreland and offshore areas is capped by a regional angular unconformity. This has been interpreted as a major compressional event occurring in Late Cretaceous times (Feruglio, 1949; Proserpio, 1978; Lesta et al., 1980; Ramos, 1981; Barcat et al., 1989; Ross et al., 1996; Thomson and Underhill, 1999; Anselmi et al., 2000; Panza et al., 2001; Thomson et al., 2001; Ramos, 2002; Silva Nieto, 2005; Continanzia et al., 2011; Micucci et al., 2011) (Fig. 2). Such orogenic event has been associated with the tectonic emplacement of the Patagonian Batholith in the Andes and the final closure of the Rocas Verdes Basin to the south (Dalziel et al., 1974; Fosdick et al., 2011; Bernhardt et al., 2012). These two contractional pulses represent different stages of the Patagonidic cycle that define basal and top relationships of the Chubut Group (Keidel, 1925) (Fig. 2). In spite of these relationships, synorogenic deposits associated with widespread compression in the foreland area at this time have not been described yet.

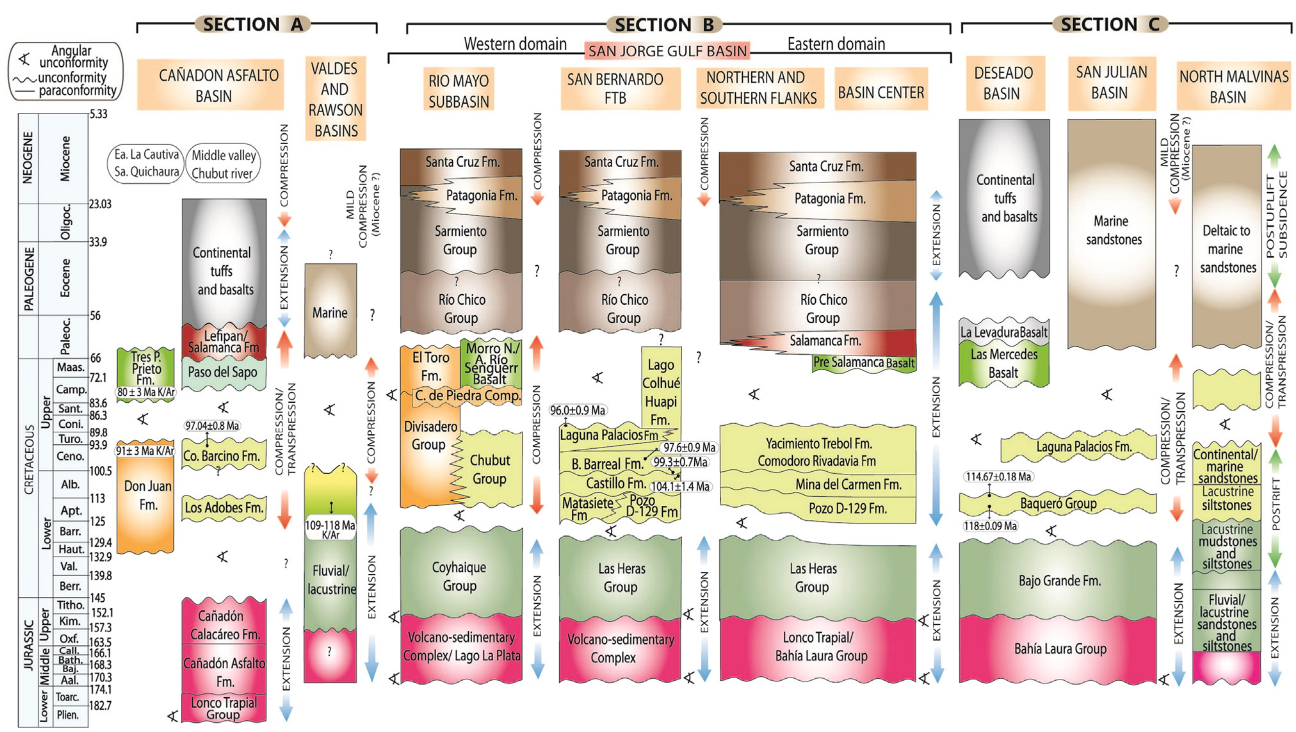

Fig. 2. Stratigraphic correlations and tectonic events of the onshore and offshore basins of the Central and Northern Patagonia. Colors indicate the proposed lateral correlations among the different units. Data taken from Franchi and Page (1980), Sciutto (1981), Barcat et al. (1989), Fitzgerald et al. (1990), Richards and Hilliers (2000), Homovc and Constantini (2001), Panza et al. (2001), Parada et al. (2001), Demant et al. (2007), Suárez et al. (2009a, 2014), Sylwan (2001), Figari (2005), Ruiz et al. (2005), Césari et al. (2011), Continanzia et al. (2011), Homovc et al. (2011), Foix et al. (2013), Perez Loinaze et al. (2013). Note that no formal units have been described in the Rawson, Valdes and North Malvinas Basins. See text for further details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In fact, studies at the San Jorge Gulf Basin have revealed a synextensional control for the sedimentation of the late Early Cretaceous Chubut Group and for the Early Cenozoic deposits (Salamanca Fm. and Río Chico Group) (Figari et al., 1999; Paredes et al., 2013) (Fig. 2).

Finally, middle Miocene times are represented by continental deposits of Andean provenance, related to a renewed episode of orogenic growth (Blisniuk et al., 2005; Ramos, 2005; Giacosa et al., 2010; Orts et al., 2012; Bilmes et al., 2013). As a result of these deformational stages that affected the Patagonian Andes, foreland and offshore areas, a series of morphostructural units were formed (Fig. 3), associated with mild to strong tectonic inversion of Pangea break-up-related Mesozoic extensional basins.

4. The Patagonian broken foreland area

The Patagonian broken foreland constitutes a 600 km long belt that extends from the southwestern margin of the North Patagonian Massif to the Deseado Massif (Bilmes et al., 2013) (Figs. 1, 3 and 4). The northern segment, in the Gastre area (Figs. 3A and 4), is characterized by reverse faults that exhumed depocenters of the Middle Jurassic to Early Cretaceous Cañadon Asfalto Basin (Figari, 2005; Bilmes et al., 2013). These thick-skinned structures have a predominant W–NW strike and produce local folding in the late Oligocene to early Miocene volcanic sequences, indicating a Neogene stage of deformation (Figari, 2005) (Fig. 4). More recently, Bilmes et al. (2013) described syn-orogenic sequences associated with contractional structures developed between 16–14 Ma, evidencing a last episode of uplift in the area. In the Río Chubut area, where contractional deformation advanced differentially as far as 67° W (~650 km from the trench), a gradual change in the mean strike of the fault-bounded blocks from W–NW to N–NW is visualized (Fig. 4) (Anselmi et al., 2000) (Fig. 4). The central segment of this broken foreland zone is characterized by the San Bernardo FTB (Figs. 3B and 4). Here, a continuous cover of the Cretaceous Chubut Group crops out and is locally capped by Eocene to Pliocene volcanic rocks (Fig. 4). These volcanic sections are composed of two minor pulses of late Eocene and Pliocene lava flows and a major volcanic component of late Oligocene to early Miocene age (Bruni et al., 2008). Barcat et al. (1984) described the folding of these volcanic rocks with a predominant N–NW trend. This evidences an important Neogene contractional event, as pointed out in subsurface studies at the San Bernardo FTB (Homovc et al., 1995) (Fig. 4).

To the south, the structure gradually looses topographic expression as it interferes with an E–W extensional domain (Figs. 3B and 4). Finally, the southernmost segment corresponds to the southern extent of the San Bernardo FTB in the Deseado Massif (Figs. 3C and 4) (Peroni et al., 1995; Giacosa et al., 2010).

5. The Chubut Group at the San Bernardo FTB

The San Bernardo FTB and its subsurface expression to the south represent the western domain of the San Jorge Gulf Basin (Fig. 4). The oldest exposed rocks at this belt are continental successions of the Chubut Group (Fig. 2). This succession is stratigraphically arranged as follows: The Pozo D-129/Matasiete, Castillo, Bajo Barreal and Laguna Palacios Fms. The Matasiete Fm., and locally the equivalent Pozo D-129 Fm., are exposed dominantly in the western part over the San Bernardo FTB. There, it is composed of different fluvial and pyroclastic facies that laterally interfinger with the Pozo D-129 Fm. to the east, in the San Jorge Gulf Basin (Fig. 2). The latter constitutes an organic-rich lacustrine unit whose most accepted age of deposition is 121.5–112 Ma (Fitzgerald et al., 1990; Paredes et al., 2007). This is consistent with U/Pb zircon ages of Césari et al. (2011) and Perez Loinaze et al. (2013) who communicated an Aptian age (~118–114 Ma) for the continental Baqueró Group, an equivalent unit to the Pozo D-129 Fm. in the Deseado Massif (Fig. 2) (Hechem and Homovc, 1987). Overlying these, the Castillo Fm. is a volcaniclastic fluvial to shallow lacustrine unit (Sciutto, 1981; Bridge et al., 2000; Umazano et al., 2012) with an Aptian–Albian age assigned on the basis of pollen and charophytes/ostracods (Musacchio and Chebli, 1975; Fitzgerald et al., 1990). More recently, an U/Pb zircon age of ~104 My in magmatic zircons provided a general Albian age for this unit (Suárez et al., 2009b). To the top, the Bajo Barreal Fm., deposited in a fluvial to lacustrine environment, constitutes the main hydrocarbon reservoir of the San Jorge Gulf Basin (Fig. 2) (Umazano et al., 2009). Its upper section is a lateral equivalent of the Laguna Palacios Fm., a tuffaceous-loess-paleosol succession (Sciutto, 1981) (Fig. 2). The age of these units has been variably assigned to the Senonian (Bonaparte and Gasparini, 1978), Campanian–Maastrichtian (Lesta and Ferello, 1972) and Santonian–Maastrichtian (Bellosi et al., 2002). Suárez et al. (2014) provided a new set of U/Pb zircon ages of ~99 My for the Bajo Barreal Fm. and a 96–98 My age for the Laguna Palacios Fm., determining a Cenomanian to late Cenomanian–early Turonian (?) age (Fig. 2). Recently, Casal et al. (2014) individualized the Lago Colhué Huapi Fm. a new

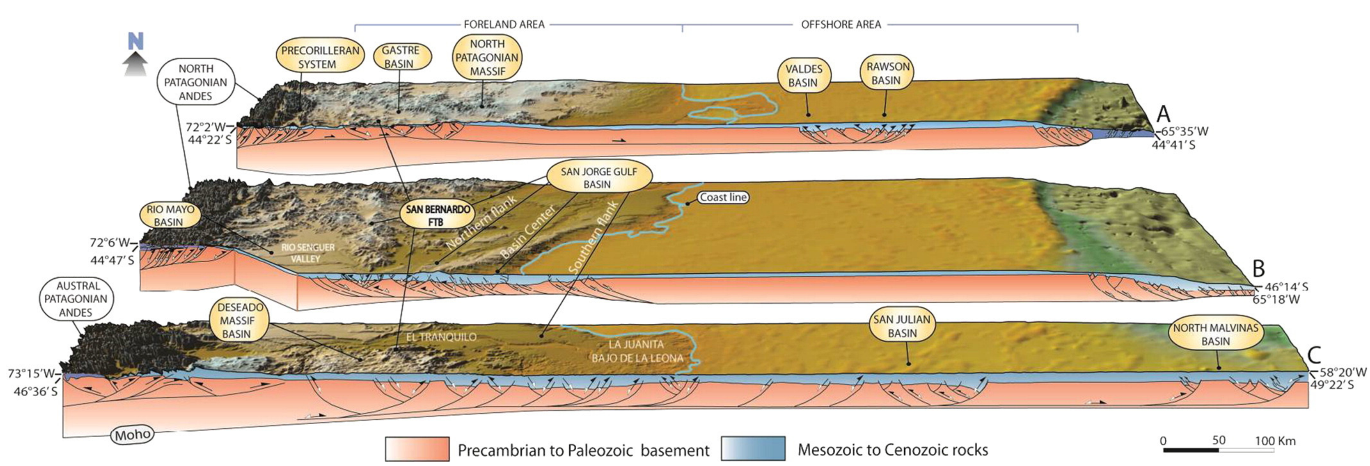

Fig. 3. Schematic structural profiles of the onshore and offshore basins across the central and northern Patagonia. See Fig. 1 for location of sections A, B and C. Structural data taken from Ross et al. (1996), Figari et al. (1999), Homovc and Constantini (2001), Sylwan (2001), Lagabrielle et al., 2004; Folguera and Iannizzotto (2004), Anselmi et al. (2000), Silva Nieto (2005), Continanzia et al. (2011), Micucci et al. (2011), Orts et al. (2012), Bilmes et al. (2013). Moho geometry at section B has been taken from Cornaglia et al. (2009). Note how compressional deformation in sections A and C is localized in previous extensional basins determining relatively non-deformed zones among them.

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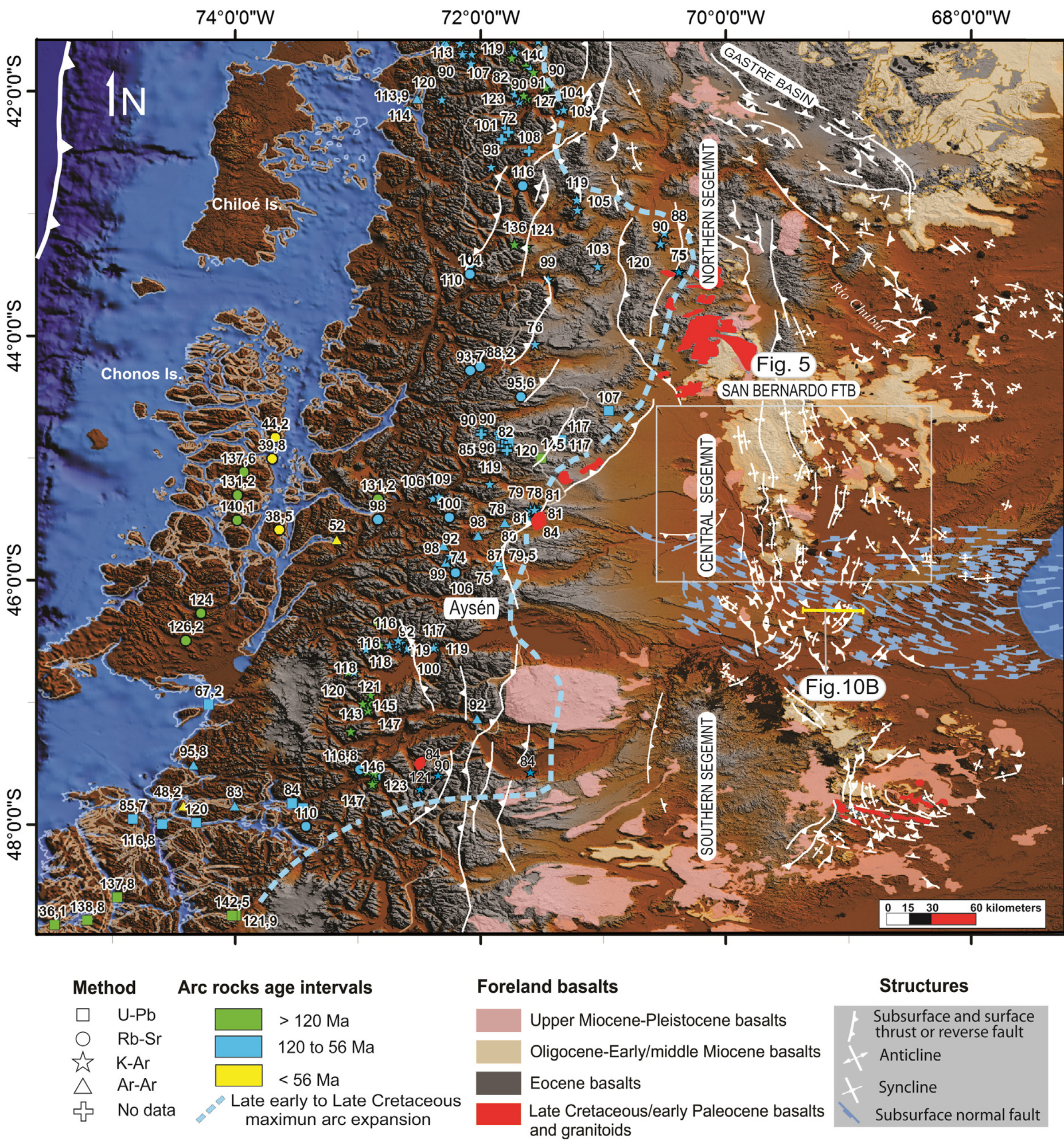

Fig. 4. Patagonian broken foreland, subsurface structures of the San Jorge Gulf Basin and geochronological dataset of arc-related rocks emplaced during Cretaceous times on the North Patagonian Andes. Note the spatial relation between the anomalous development of contractional structures in the foreland area and the latitudinal extent of eastward expansion of Cretaceous arc rocks (42°30′S–48°S), during the ~120 to 75 Ma interval. Age interval from ~74 to 50 Ma is not well represented, provably related to a gap in the volcanic arc or a magmatic waning at that time. Structural data taken from Orts et al., 2012; Bilmes et al. (2013); Lagabrielle et al., 2004; Folguera and Iannizzotto (2004), Anselmi et al. (2000), Silva Nieto (2005), Figari et al. (1999); Giacosa et al., 2010 and this work. Radiometric dataset compiled from Turner (1978), Haller and Lapido (1980), Lizuaín (1980, 1981), Ramos (1981), González Díaz (1982), Rapela et al. (1987), Munizaga et al. (1988), Weaver et al. (1990), Carrasco (1995), Sernageomin-BRGM (1995), Pankhurst et al. (1999), Martin et al. (2001), Suárez and De La Cruz (2001), Parada et al. (2001), Welkner et al. (2010), Rolando et al. (2002, 2004), Demant et al. (2007) and Hervé et al. (2007).

stratigraphic unit represented by fluvial deposits of Coniacian to Maastrichtian age based on dinosaur findings (Fig. 2).

6. Structure and syntectonic deposits of the San Bernardo FTB and Río Mayo Basin

The general structure of the San Bernardo FTB is characterized by east- and west-verging asymmetrical folds related to the inversion of Neocomian depocenters (Homovc et al., 1995). These folds are associated with high-angle reverse faults (Peroni et al., 1995) that have a general NNW-trend and are dissected by E–SE to E–NE transfer zones that accommodated minor strike-slip displacements (Barcat et al., 1984) (Fig. 5). The eastern and southern parts of the San Bernardo FTB have been the locus of most structural studies due to the exposure of deeper structural levels, where anticlines deforming the Cretaceous cover are well preserved (Barcat et al., 1984; Homovc et al., 1995). To the north, exposures of the Mesozoic sections are scarce due to the development of a Cenozoic continuous volcanic cover (Fig. 5). This volcanic plateau is folded as described by Barcat et al. (1984) (Figs. 5 and 6). A cross section through the northern San Bernardo FTB is

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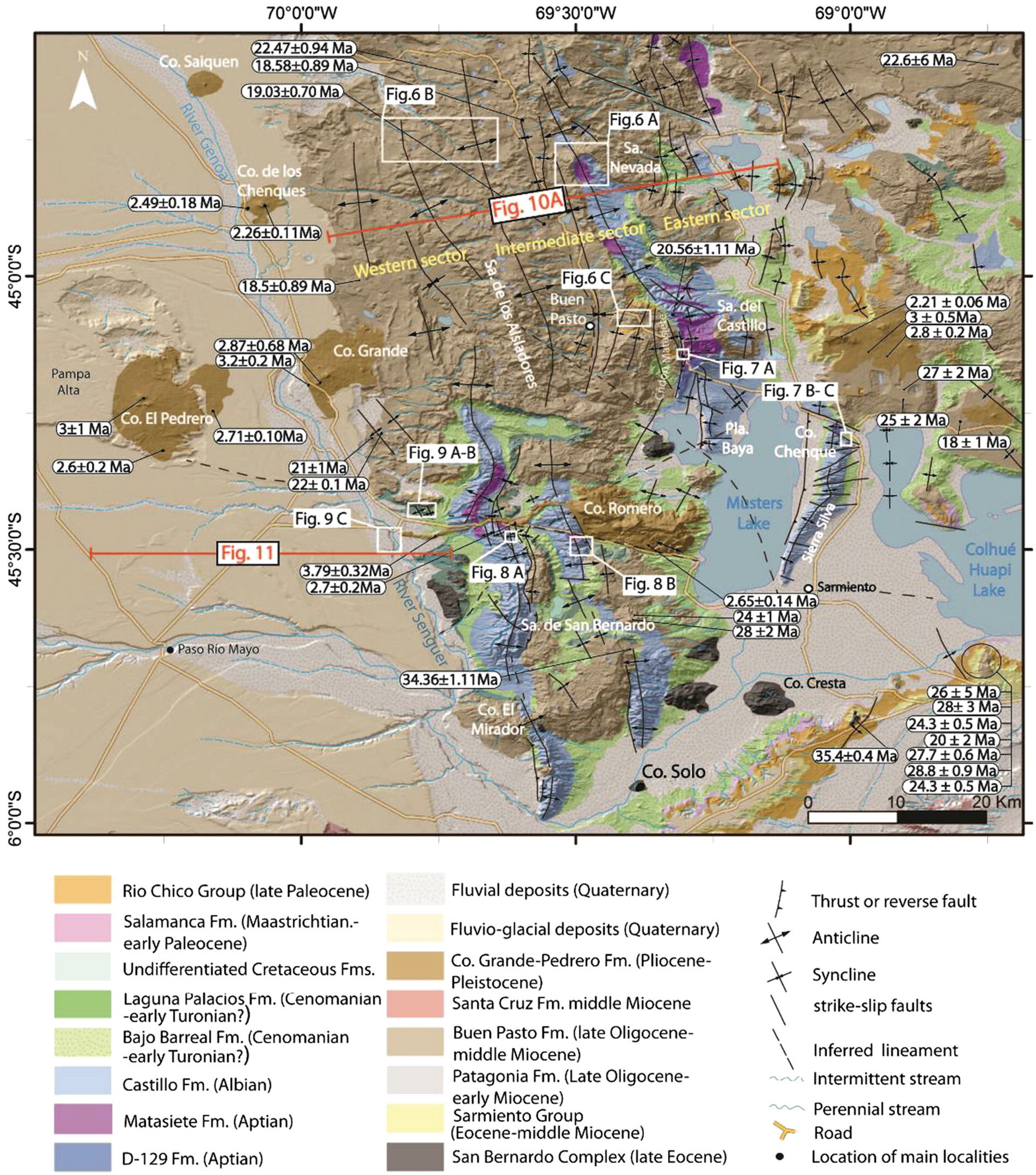

Fig. 5. Geological map of the San Bernardo FTB. Data taken from Sciutto (1981, 2008), Barcat et al. (1984), Anselmi et al. (2000), Paredes et al. (2007), Umazano et al. (2012) and this work. K/Ar ages from Marshall et al. (1977), Baker et al. (1981), Panza (1981), Linares (2001), Sinito (1980) and Bruni et al. (2008). Labels Figs. 11 and 10A are locations of seismic lines analyzed in Section 7.

analyzed in this work, across a seismic line (Fig. 11B, see location in Fig. 5), where, from east to west, three general sectors can be identified. The easternmost sector is characterized by symmetrical short wave-length folds (~1–1.5 km) that affect partly the Cenozoic basaltic cover (Fig. 5). To the west, the intermediate sector is characterized by two opposite verging structures, the Sierra de los Aisladores and Sierra Nevada anticlines (Fig. 5). Both folds are characterized by a long wave-length (~8–10 km) and a west- and east- vergence respectively. The Sierra Nevada anticline exposes a lower structural level with Matasiete and Castillo Fms. outcrops (Fig. 5 and 6A); and immediately to the west, a series of short wave-length folds are affecting the Cenozoic volcanic cover (Fig. 5). Finally, the westernmost sector is characterized by two long-wave length (~7–9 km) NNW-trending anticlines that folded the Cenozoic cover (Fig. 5).

In order to study the earliest evolution of the San Bernardo FTB, we inspected older sedimentary sequences of the Chubut Group that would allow constraining potential earlier growth episodes.

To the south, at the frontal-western limb of Sierra Nevada anticline (Fig. 5), a strong angular unconformity separates the Castillo Fm. from Bajo Barreal and Laguna Palacios Fms. (Fig. 7A). Additionally, these

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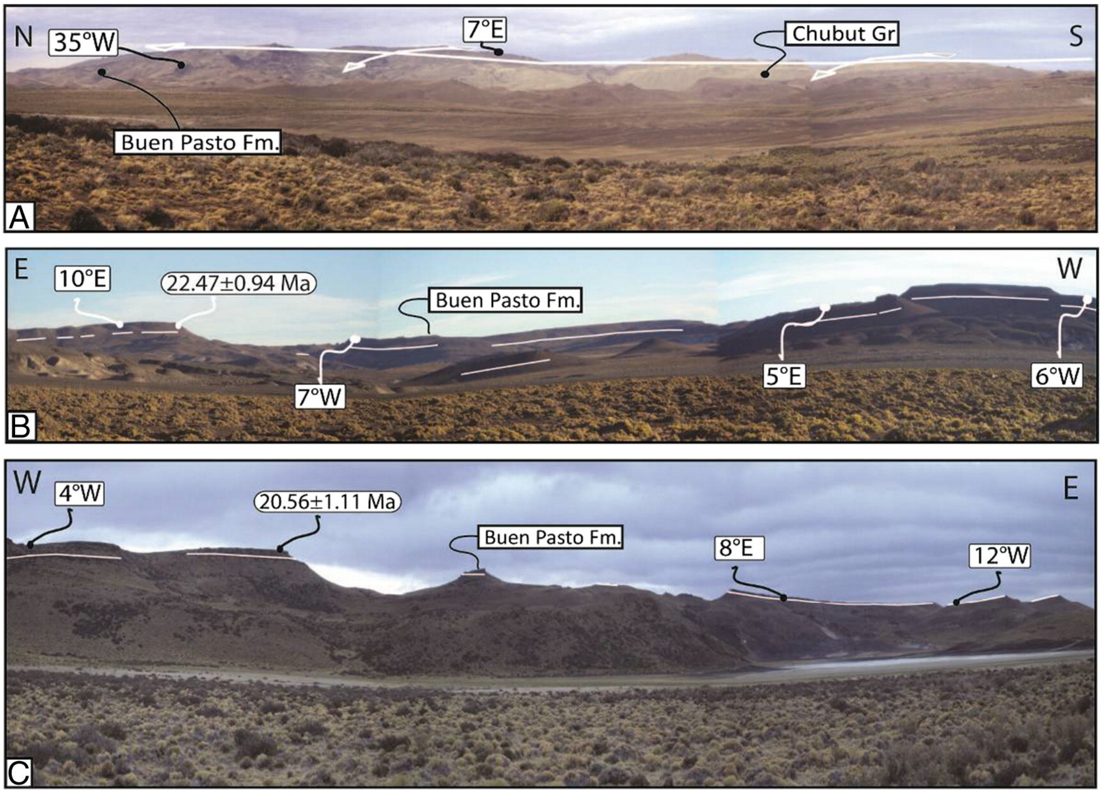

Fig. 6. Folded Miocene strata at different locations of the study area (radiometric ages are taken from Bruni et al., 2008). A Neogene contractional event was associated with the San Bernardo FTB based on the age of younger deformed strata (see Fig. 5 for location).

last units show progressive unconformities and dip variations in strata. At the easternmost sector, in the general west-verging Sierra de Silva anticline (Figs .5 and 7B–C), a series of backthrusts are related to two eastward verging anticlines (Fig. 7B and C). One of these, a short wave-length and highly asymmetric anticline, has a back limb characterized by growth strata in the Matasiete Fm. These thicken westward and show a systematic dip change, where it is conformably overlain by the Castillo Fm. (Fig. 7B). At the frontal limb, growth strata of the Matasiete Fm. are folded into a tight syncline that is unconformably overlain by slightly folded growth strata of the Castillo Fm. (Fig. 7B). The latter shows strata dip changes that thicken eastwards and onlap against the frontal limb of an anticline (Fig. 7B). To the east, the second anticline shows a complete fan of growth strata and progressive unconformities in the Castillo Fm. (Fig. 7C). To the southwest in the axial sector of the San Bernardo FTB, an asymmetric east-verging anticline shows a complete fan of growth strata in the Castillo Fm. that thickens eastwards (Fig. 8A). To the east, an east-verging anticline shows progressive unconformities and growth strata that thicken eastwards, where beds of the Bajo Barreal Fm. onlap against its frontal limb (Fig. 8B).

At the westernmost sector of the San Bernardo FTB (see Fig. 5 for location), a NW-trending structure is affecting beds of the Laguna Palacios Fm. (see inset map in Fig. 9A). In the south, the frontal part of this structure is associated with a west-vergent thrust that repeats the Laguna Palacios Fm. This thrust is associated with growth strata in its hanging wall as depicted by slight dip changes (Fig. 9A). To the north, this thrust does not reach the surface, propagating an asymmetric fold (see inset map in Fig. 9A), where the frontal limb shows well preserved growth strata, as evidenced by a sedimentary fan thickening to the southwest (Fig. 9B). To the west of the San Bernardo FTB, a deep incision at the Río Senguer Valley allowed studying subsurface structures of the Río Mayo Basin. At this place, a short wave length (300–250 m) symmetric anticline is found affecting beds of the Laguna Palacios Fm. Here, syntectonic deposits of the Laguna Palacios are evidenced by a dip change and strata thickening away from the anticline flank (Fig. 9C).

7. Description of subsurface structure

With the aim of analyzing the structures at depth, we interpreted one 2D and two 3D seismic lines across the San Bernardo FTB and Río Senguer areas (Figs. 10 and 11). With the only exception of Fig. 10B that shows a seismic line previously published by Homovc et al. (1995), the rest of the seismic information will be interpreted and discussed for the first time. The northernmost seismic line (Fig. 10A) crosses the northern analyzed sector of the San Bernardo FTB. Main contacts at depth were determined and extrapolated from surface data. The Bajo Barreal–Castillo Fms. and Castillo–Matasiete Fms. belonging to the Chubut Group were tied to surficial data and extrapolated recognizing their seismic character. Deeper contacts were identified only from their seismic character following the previous works of Homovc et al. (1995) and Figari et al. (1999). Finally, interpretation of this seismic line (Fig. 10A) shows a central structural high bounded by opposite dipping inverted extensional sets of faults. To the east, one set is associated with long wave-length anticlines that can be directly tied to folds described from surface data (see Fig. 5). The development of this belt is therefore related to tectonic inversion of previous normal faults that controlled the accumulation of the Neocomian units (Fig. 10A). A noticeable feature in this interpretation is that the different units belonging to the Chubut Group (Matasiete, Castillo, Bajo Barreal and Laguna Palacios Fms.) are characterized by tabular geometries with a lateral continuity, that show no obvious extensional control on its deposition, as previously described in the subsurface of the San Jorge Gulf Basin to the east (Figari et al., 1999; Paredes et al., 2013) (Fig. 10A). Indeed,

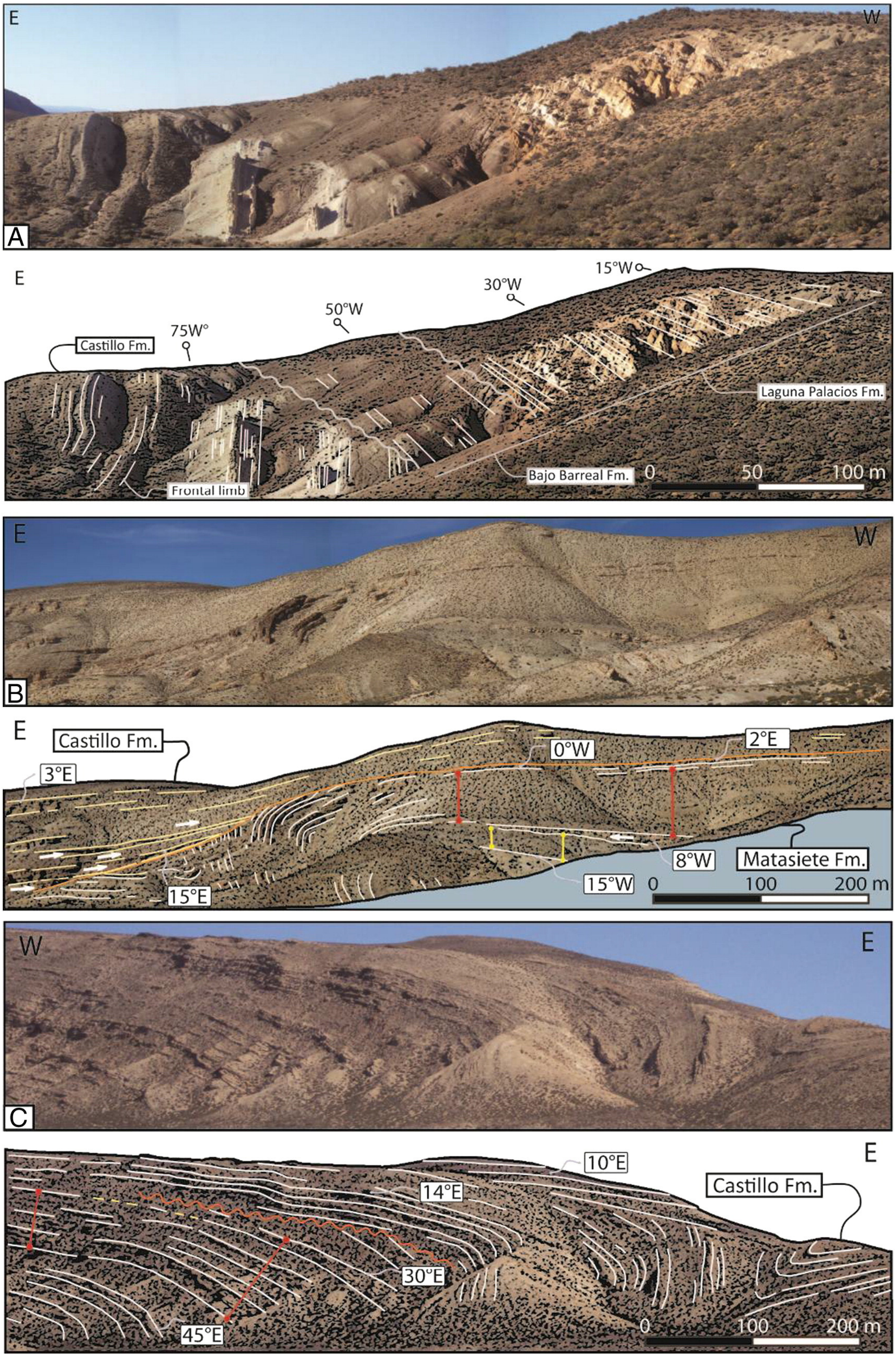

Fig. 7. Progressive unconformities and growth strata in the Matasiete, Castillo, Bajo Barreal, and Laguna Palacios Fms. associated with contractional structures (see Fig. 5 for location). A) Western flank of the anticline at the Matasiete Canyon. B) and C) Eastern flank of the Sierra de Silva.

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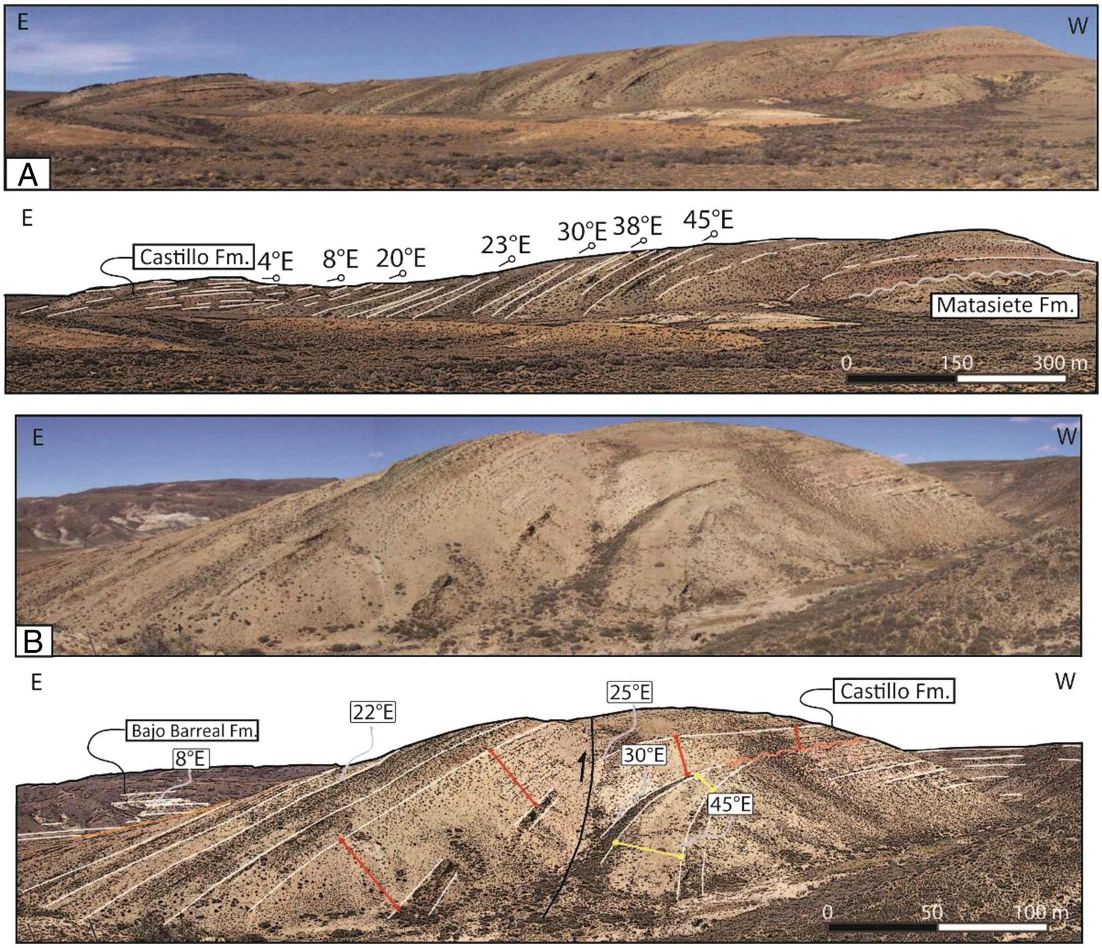

Fig. 8. Progressive unconformities and growth strata in the Castillo Fm. associated with contractional structures in the San Bernardo FTB (see Fig. 5 for location). Note the onlapping relation of the Bajo Barreal Fm. against the frontal flank of a contractional structure affecting the Castillo Fm. in B).

Neocomian extensional faults seem to have stopped activity before the deposition of Chubut Group in this region (Fig. 10A).

A vertical slice of a 3D seismic line is analyzed at the southern end of the San Bernardo FTB, where this belt looses topographic expression as it interferes with an E–W extensional domain (Figs. 4 and 10B). This line crosses the Perales anticline and shows an inverted halfgraben of Neocomian age previously described by Homovc et al. (1995). This halfgraben is highlighted where synextensional deposits of Neocomian age thicken towards the fault plane (Fig. 10B). Overlying the Neocomian deposits, a completely different sedimentary pattern in the Chubut Group deposits suggests a change in tectonic behavior (Fig. 10B). The Perales anticline folds different units of the Chubut Group where the D-129, Castillo and lower member of Bajo Barreal Fms. show thickness increase at both flanks away from the hinge (Fig. 10B). This is interpreted here as synorogenic strata associated with the early uplift of this structure.

In order to analyze the structure beyond the San Bernardo FTB, we inspected a 3D seismic line across its westernmost part and adjacent Río Mayo Basin (Fig. 11, see Fig. 5 for location). This seismic line is tied to two boreholes. Here, two half-grabens control wedge-like depocenters of Jurassic to Early Cretaceous age. These sedimentary wedges thicken towards fault planes evidencing a clear extensional control on its deposition.

Overlying both halfgrabens, the complete section of the Chubut Group (Matasiete, Castillo, Bajo Barreal and Laguna Palacios Fms.) shows a different sedimentary pattern respect to Neocomian deposits. (Fig. 11). At the western half-graben, The Chubut Group covers the previous extensional depocenter and no extensional control is evidenced (Fig. 11). Also, the Laguna Palacios Fm. is absent, being beds of the Rio Chico Group and the underlying Bajo Barreal Fm. onlapping against the forelimb of an east-verging anticline folding the Castillo and Matasiete Fms. (Fig. 11). The latter unit shows at its base onlapping reflectors against folded Neocomian deposits (Fig. 11). At the eastern half-graben, a complete section of the Chubut Group is present. Near the fault plane, deposits belonging to the Matasiete Fm. are folded apparently in relation to the inversion of the previous normal fault, similarly to the western half-graben (Fig. 12A, see inset in Fig. 11 for location). Seismic line depicted in Fig. 11 was then flattened to the top of the Matasiete Fm. This shows that the upper Chubut Group, represented by Castillo, Bajo Barreal and Laguna Palacios Fms., are onlapping against the backlimb of the anticline produced by the inversion of the western normal fault, defining a series of sedimentary wedges separated by local angular unconformities (Fig. 12A).

Fig. 12B shows seismic line displayed in Fig. 11 flattened to the top of the Río Chico Group in order to isolate the Cretaceous–Paleocene contractional structure and the geometry and relations of syn-tectonic sedimentation. This image shows a Paleocene depocenter located between two anticlines produced by inversion of previous normal faults. Onlapping relations are described against the backlimb of the eastern structure and forelimb of the western anticline (Fig. 12B). This reconstruction shows an angular unconformity between the late Early Cretaceous Chubut Group and late Paleocene (early Eocene?) strata.

8. Interpretation of surface and subsurface data

The youngest deformed rocks across the San Bernardo FTB have been dated in ~18 Ma (Bruni et al., 2008), above which, not deformed

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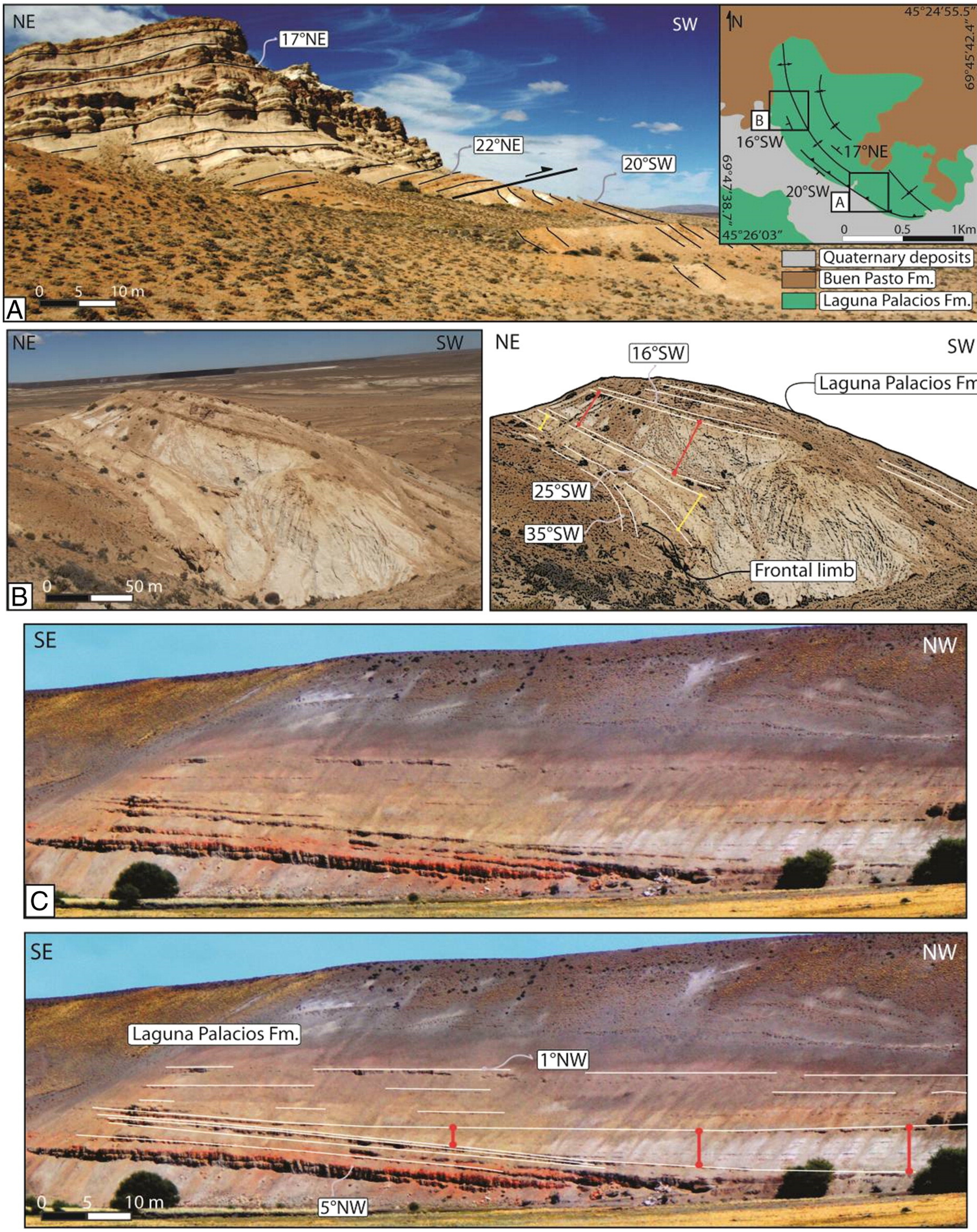

Fig. 9. Progressive unconformities and growth strata in the Laguna Palacios Fm. associated with contractional structures of the San Bernardo FTB (A and B) and Rio Mayo Basin (C) (see Fig. 5 for location). Inset map shows locations of A and B.

volcanic rocks of ~3.5 to 2.5 Ma rest unconformably. Hence, this indicates a middle to late Miocene contractional episode sometime between 18 and 3 Ma, in agreement with other studies (Peroni et al., 1995; Homovc et al., 1995; among others) (Figs. 5 and 6).

Surface data described in Section 6 have shown growth strata and progressive unconformities related to contractional structures in all units belonging to the Chubut Group (Figs. 7, 8 and 9). Similar evidence has been described from subsurface data exposed in Section 7, where Neocomian and post-Neocomian successions were clearly deposited in different tectonic scenarios. In the latter, unconformities and onlapping reflectors related to growth of contractional structures were described in the Chubut Group and possibly in the late Paleocene–early Eocene (?) Río Chico Group (Figs. 10B, 11 and 12). The relatively tabular geometry of the Chubut Group, the lack of a clear extensional

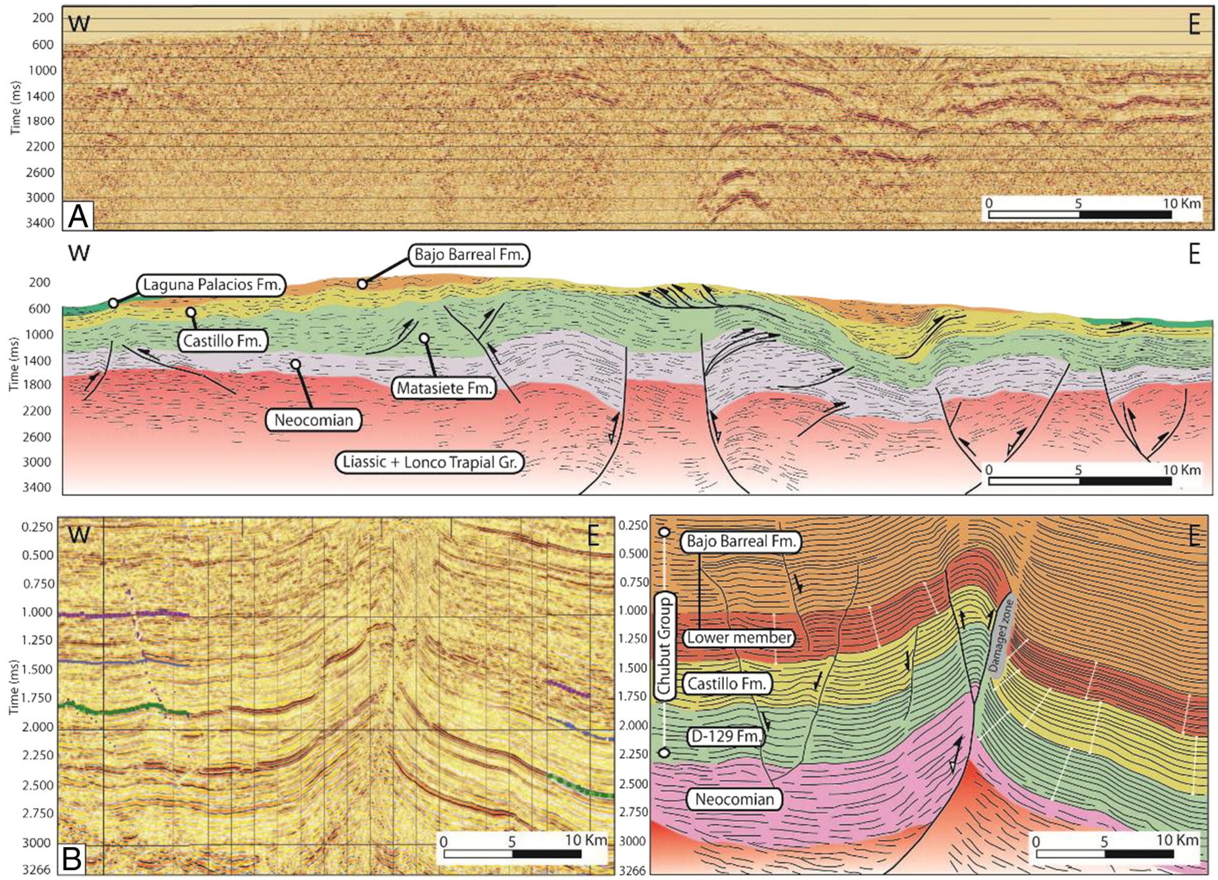

Fig. 10. A) 2D seismic line across the northern San Bernardo FTB (see location in Fig. 5) (vertical scale is TWT in msec). Note that the Chubut Group covers Neocomian depocenters and does not show an extensional control on its deposition in this region. B) Vertical slice of a 3D seismic line across the southern part of the San Bernardo FTB at the Perales Anticline (see Fig. 4 for location) (vertical scale is TWT in mseg). Note that thickness variations in synorogenic strata at both flanks, are probably related to different growth stages of this structure during the late Early Cretaceous.

control on its deposition and the presence of growth strata related to contractional structures, suggest a synorogenic deposition related to the inversion of Neocomian depocenters in the San Bernardo FTB and Río Mayo Basin. This is consistent with regional events depicted in Fig. 2 and more locally the deformational events identified at the western part of the Río Mayo Basin by Folguera and Iannizzotto (2004), Iannizzotto et al. (2004) and Suárez et al. (2009a). Moreover, in the eastern Río Mayo Basin, Clavijo (1986) concluded that deposition of the Matasiete and Pozo D-129 Fms. were products of erosion of the upper Neocomian units (Las Heras Group) exhumed by a transpressional event. Furthermore, syntectonic growth in the Paleocene Río Chico Group has been interpreted by Paredes et al. (2006) at the subsurface sector of the San Bernardo FTB (Figs. 2 and 3). Thus, Initial growth and structuring of the Patagonian foreland area could be as early as late Early Cretaceous and would have continued during Late Cretaceous and possibly into the Early Cenozoic. Finally, reactivation of these structures occurred during Miocene times, as surface data indicate.

In order to show this evolution across the San Bernardo FTB and Río Mayo Basin, we restored the interpreted seismic profiles (Figs. 10 and 11) at different selected horizons (Fig. 13). The stage D of Fig. 13 represents a schematic cross section of the general structure from the Rio Mayo Basin to the San Bernardo FTB. This reconstruction shows that a complete set of compressional structures is active from the Río Mayo Basin to the San Bernardo FTB in late Early Cretaceous times. However, during the Neogene these are selectively reactivated into the eastern domain.

9. Tectonic evolution: discussion

9.1. Patagonian broken foreland and synorogenic foreland rifting

The development of the San Bernardo FTB since the late Early Cretaceous has important implications for the tectonic evolution of the Central Patagonian region and particularly for the Chubut Group Basin. Based on the description of synorogenic deposits belonging to the Chubut Group, we suggest that the Chubut Group Basin is related to the early development of the Patagonian broken foreland (Fig. 14A). Contrastingly, 2-D and 3-D seismic data recorded to the east at the San Jorge Gulf Basin, suggest that rifting occurred during the deposition of the Chubut Group, and even during following stages related to the deposition of Salamanca Fm. and Rio Chico Group (Hechem, 1998; Figari et al., 1999; Georgieff et al., 2009; Foix et al., 2012, 2013; Paredes et al., 2013) (Figs. 2 and 14A). During this basin stage an important change in the stress field, with respect to the previous Neocomian depocenters of NW, NNW and minor E–W trending, reactivated and nucleated WNW and E–W extensional structures that defined a general E–W rift (Uliana et al., 1989; Chelotti, 1997; Figari et al., 1999) (Fig. 14A). Figari et al. (1999) hypothesized that reactivation was related to a transtensional event caused by differential rotation between the neighboring North Patagonian and Deseado Massifs during westward drift of South America. However, paleomagnetic data implied vertical axis rotations north and south the San Jorge Gulf Basin since Jurassic to Early Cretaceous times, previously to deposition of the Chubut Group and equivalents (Geuna et al., 2000; Somoza et al., 2008). This

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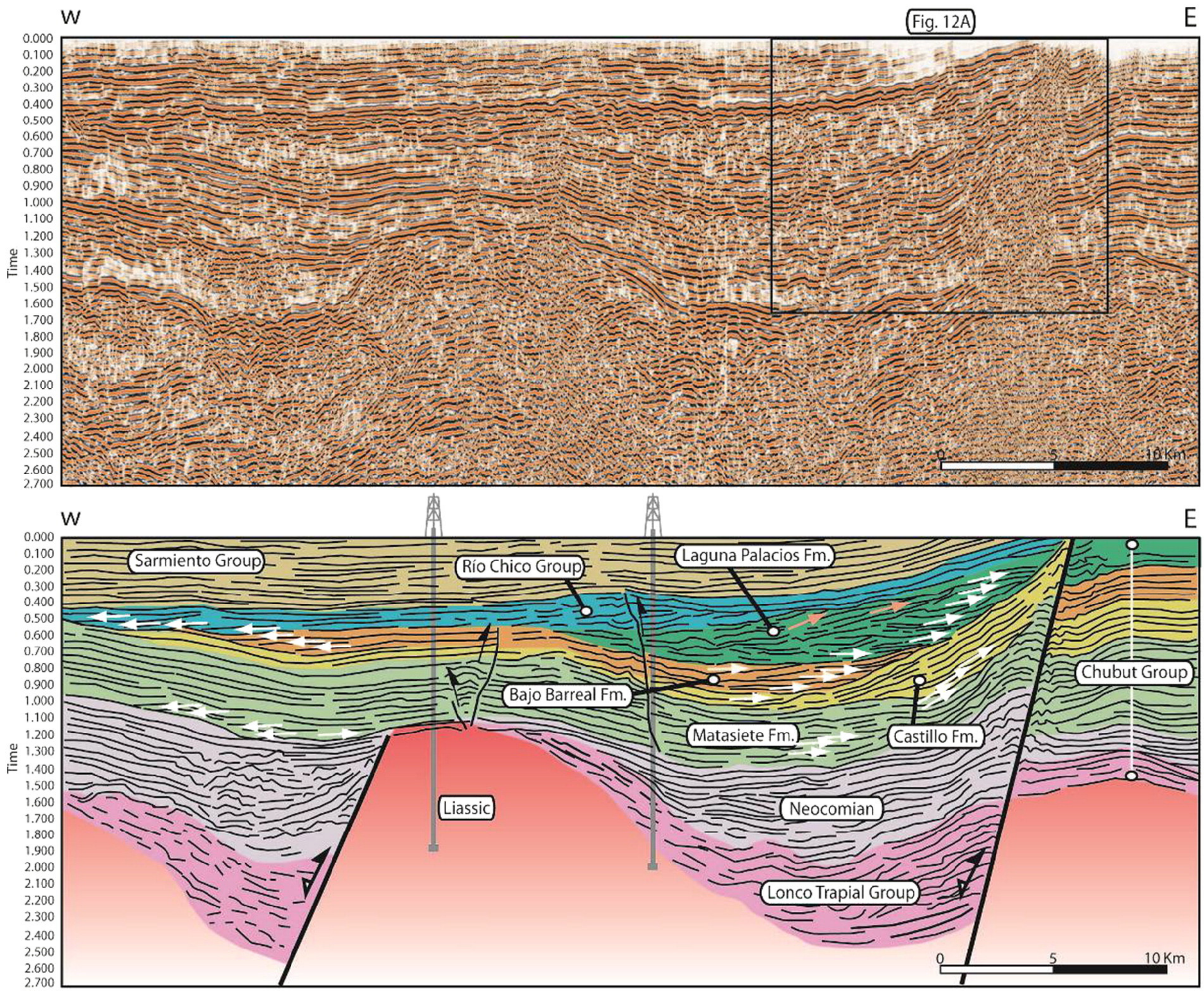

Fig. 11. 3D seismic line across the Río Mayo Basin and western flank of the San Bernardo FTB (see Fig. 5 for location) (vertical scale is TWT in mseg). This sector of the Río Mayo Basin is formed by a series of NE half-grabens that controlled the sedimentation of Middle to Upper Jurassic and Neocomian sections. These depocenters were inverted initially in late Early Cretaceous times, and lately reactivated in Paleogene and Miocene times. Evidence of syn-sedimentary contractional activity comes from onlapping reflectors in the Early Cretaceous Matasiete, Castillo, Bajo Barreal, Laguna Palacios Fms. White and red arrows indicate onlapping relations and erosional truncation of reflectors respectively.

precludes the possibility of substantial block rotations during synextensional deposition of the Chubut Group at the San Jorge Gulf Basin. An alternative mechanism for normal fault reactivation has been proposed by Cristallini et al. (2009) at the Neuquen Basin. These authors explained the nucleation of normal faults above the edges of halfgrabens, as related to tension produced by stretching layers, caused by differential subsidence of the halfgraben infill. However, this model hardly applies to the Chubutian stage in the San Jorge Gulf Basin. Here, several rifting episodes have been recognized in relation to the different units of the Chubut Group, where transtensional and even transpressional features have been described (Figari et al., 1999; Paredes et al., 2013). These, point out to a tectonic origin of the basin reactivation. Indeed, the less subsiding sector during the Neocomian stage was the most subsiding area in the following Chubutian stage, where up to 7000 m of continental deposits filled the basin center (Figari et al., 1999, Fig. 6B).

On the other hand, reactivation at the San Jorge Gulf Basin seems to be marked by several episodes of basin subsidence that show almost synchronic activity with respect to the contractional events in the Patagonian Andes and broken foreland region, as evidenced by synorogenic deposits described in Sections 6 and 7 (Fig. 14A and B). This constitutes an important point regarding the evolutionary context of the Central Patagonia, where contractional tectonics coexisted with a rift reactivation transversal to the main orogenic trend in late Early Cretaceous and also possibly in late Paleocene (Fig. 14A and B). This spatio-temporal relation between orogenic events and development or reactivation of rifts transversally disposed to the main orogenic trend, has been interpreted in collisional settings of Europe and Asia as impactogene basins (e.g. Rhine and Baikal rift) (Sengor, 1995; Mats and Perepelova, 2011). During continent–continent collision, compression may reactivate perpendicular lithospheric weaknesses in the upper plate such as sutures or previous extensional basins, creating orogen-perpendicular extensional/transtensional systems (Sengor, 1995; Mats and Perepelova, 2011; Ingersoll, 2012).

In central Patagonia, strong compression achieved in late Early Cretaceous times was responsible for the broken foreland formation (San Bernardo FTB) mainly through inversion of NNW structures (Fig. 14A). Taking into account the general trend of the inverted structures, we speculate that the orientation of the main contractional axis could have been roughly ENE. We suggest that such compression could have reactivated extensionally the most favorable E–W and other minor WNW structures of the Neocomian rift, mainly at the eastern San Jorge Gulf Basin. At a smaller scale, these reactivations mimicked the mechanics of impactogene basins (Fig. 14A). Hence, the Neocomian rift suddenly reconfigured into an extensive E–W trending tectonic depression, with its main active zone displaced to the east

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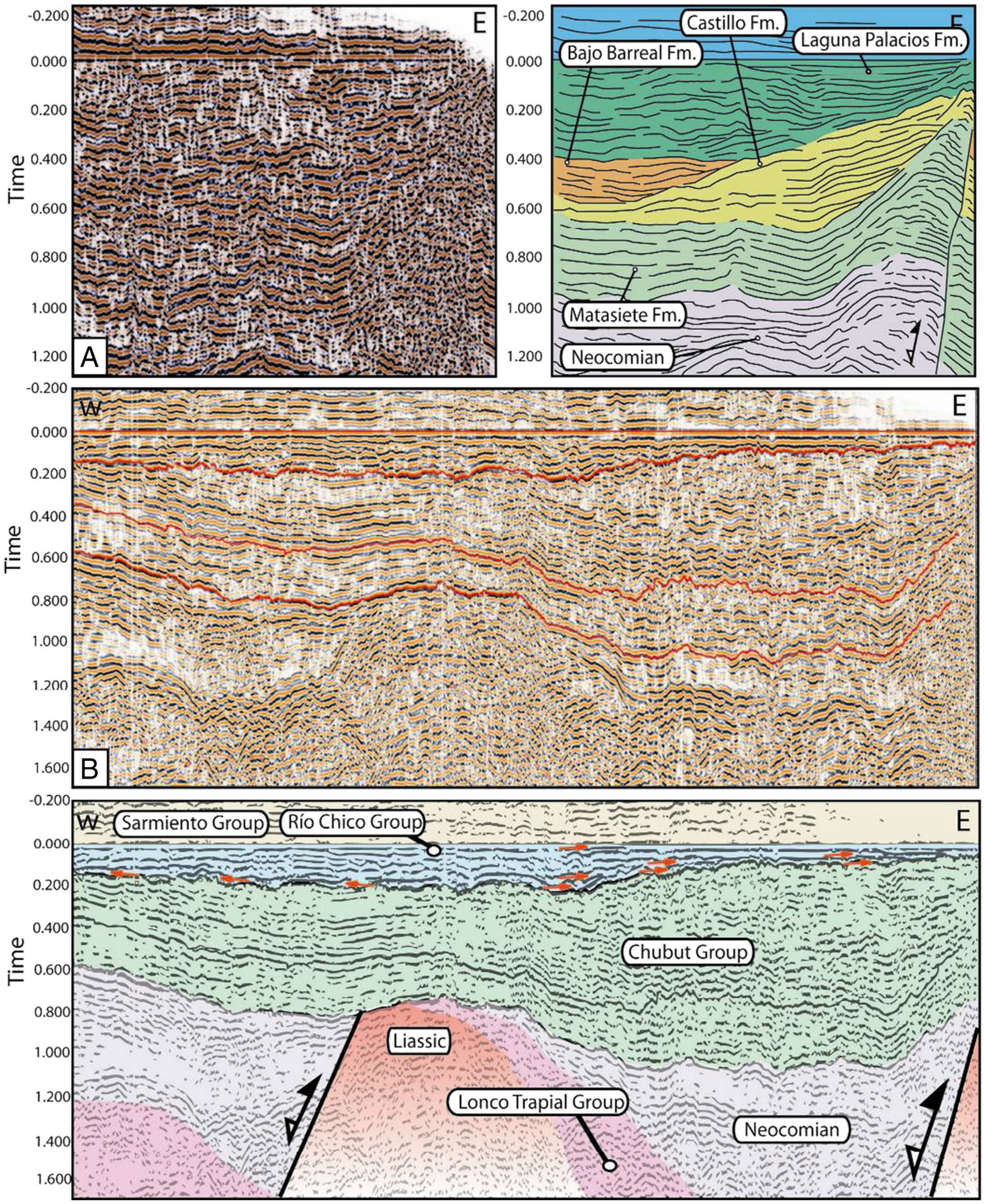

Fig. 12. A) Flattening to the top of the Laguna Palacios Fm. showing syn-contractional deposition of the Chubut Group at the back limb of an anticline associated with an inverted fault (see inset in Fig. 12 for location). B) Flattening to the top of the Paleocene Río Chico Group showing its syn-tectonic character. Red arrows indicate onlapping reflectors against the backlimb and forelimb of two Cretaceous–Paleocene anticlines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where the Chubut Group filled synextensionally (Uliana et al., 1989; Chelotti, 1997; Figari et al., 1999) (Fig. 14A). This process may have also operated in Danian times, as evidenced by coeval marine synorogenic deposition in the foreland area (Lefipan Fm.) and synextensional deposition of the Salamanca Fm. in the San Jorge Gulf Basin (Ruiz et al., 2005; Foix et al., 2012) (Fig. 2).

A similar syncontractional stage has been proposed for the Baikal rift by Mats and Perepelova (2011), where properly oriented depocenters with respect to the contractional stress field were reactivated during the collision of India.

A quantitative relation between shortening and extension is not established here, since no total estimations of the Cretaceous shortening are available for the Patagonian Andes, where most of shortening was probably accommodated.

9.2. Cretaceous plate tectonic context of Central Patagonia: causes of contractional stress field

Orogeny in mid-Cretaceous times affected most of the South American margin, possibly controlled by an acceleration of the continent during its westward drifting (Somoza and Zaffarana, 2008). However, our data point to a more pronounced deformation in Central Patagonia, in the place where South America collided against two oceanic ridges during its westward drifting (Seton et al., 2012). The

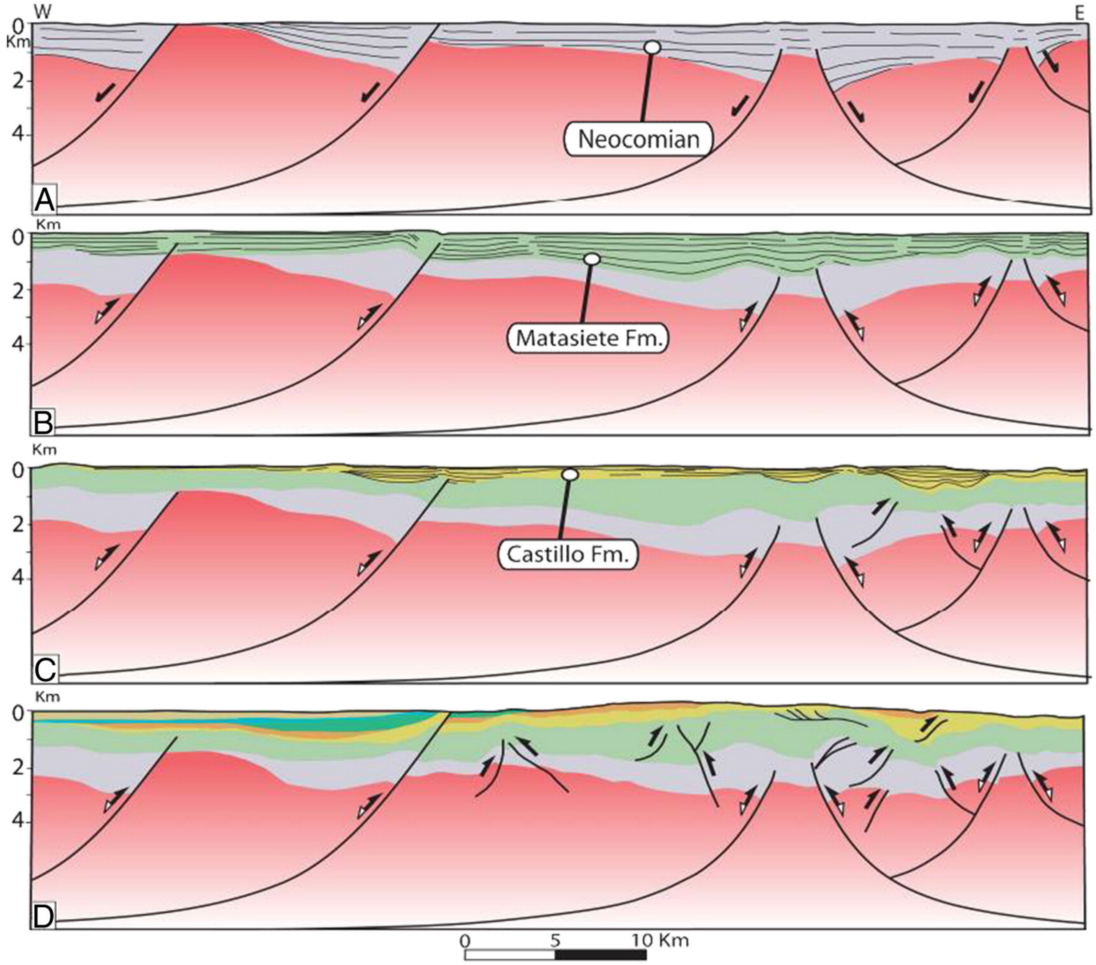

Fig. 13. Schematic diagrams showing the evolution of the San Bernardo FTB and inversion of the adjacent Río Mayo Basin. These diagrams are based on seismic profiles shown in Figs. 12 and 13 restored at different horizons by applying the flexural slip unfolding algorithm (Griffiths et al, 2002) with the Move® software (Midland Valley Ltd.). A) Initial stage corresponding to the extensional structures associated with synextensional deposition of Neocomian units. B) Early tectonic inversion and syntectonic deposition of Matasiete Fm. C) Tectonic inversion during deposition of Castillo Fm. D) Final contractional event during the middle to late Miocene. Below 5 km, geometry is schematic.

kinematic plate model of Seton et al. (2012) included the emplacement of the mega-LIP Ontong Java–Manihiki–Hikurangi in the Panthalassic ocean (Taylor, 2006). The eruption of this mega-LIP led to the break-up of the Phoenix plate into four other minor plates that led in turn to the creation of the Chasca and Catequil plates and a series of mid-ocean ridges that subducted beneath the South American margin (Fig. 14B). Recently, Maloney et al. (2013), based on this plate model, calculated variable convergence velocities, absolute overriding plate velocities (Fig. 14C), and subducted slab ages along the South American trench from 170 Ma to the present. Then these subduction parameters were compared with the main deformational stages of Andean evolution, concluding that trench-normal convergence above 4 cm/year constitutes a critical value above which orogenesis is triggered. However, Maloney et al. (2013) underestimated, and consequently excluded from this analysis, Early Cretaceous contractional deformation developed at the South Central and Patagonian Andes.

We used Maloney et al. (2013) data (averaging Point 43 at 40°30′S and Point 49 at 49°S in this work) (Fig. 14A and C) to represent the average trench normal convergence and absolute velocity of South America since 140 Ma to the present (Fig. 14C). In their model, positive values of trench normal absolute velocity indicate trenchward motion of the overriding plate, whereas negative values reflect motion away from the trench. Thus, positive trench normal convergence velocities indicate effective convergence between plates, whereas negative values indicate divergence. Based on this model, during the latest stages of western Gondwana break-up, in the Late Jurassic–Earliest Cretaceous, South America had a displacement away from the trench, when extensional basins developed in Central Patagonia (Figs. 14A, C and 15A). Afterwards, approximately at ~132 Ma (Early Cretaceous), seafloor spreading initiated at the South Atlantic (Eagles, 2007). As the absolute motion of South America reached a stationary state (~125 Ma), a sudden acceleration in trench normal convergence rate took place, reaching a maximum value of ~9 cm/year. This anomalously high convergence lasted (with decreasing intensity) until soon after 120 Ma. At ~120 Ma the Chasca/Catequil midocean ridge collided against the South American margin (Fig. 14B and C). As collision proceeded, a rapid increase in trench-normal convergence and absolute motion of South America occurred at ~118 Ma (Fig. 14C). Thus, this process would have caused an effective collision of the South American margin against Chasca/Catequil mid-ocean ridge from ~120 to ~93 Ma (Figs. 14B and 15B). Then, this triple joint plate boundary rapidly migrated northwards, when the Farallon/Antarctic mid-ocean ridge began to collide obliquely against the continental margin almost at the same latitudes at ~86 Ma (Fig. 14B). Since collision of the first ridge, the magmatic arc front, previously located next to the Present Pacific coast at ~135 Ma, broadened towards the foreland area between 42°S and 48°S, stabilizing at this eastern position from ~120 Ma to 75 Ma (Fig. 4). In the Patagonian Andes Cretaceous arc migration had been previously attributed to a shallowing of the subducted slab (Barcat et al., 1989; Suárez et al., 2009a; Folguera and Ramos, 2011). In this context,

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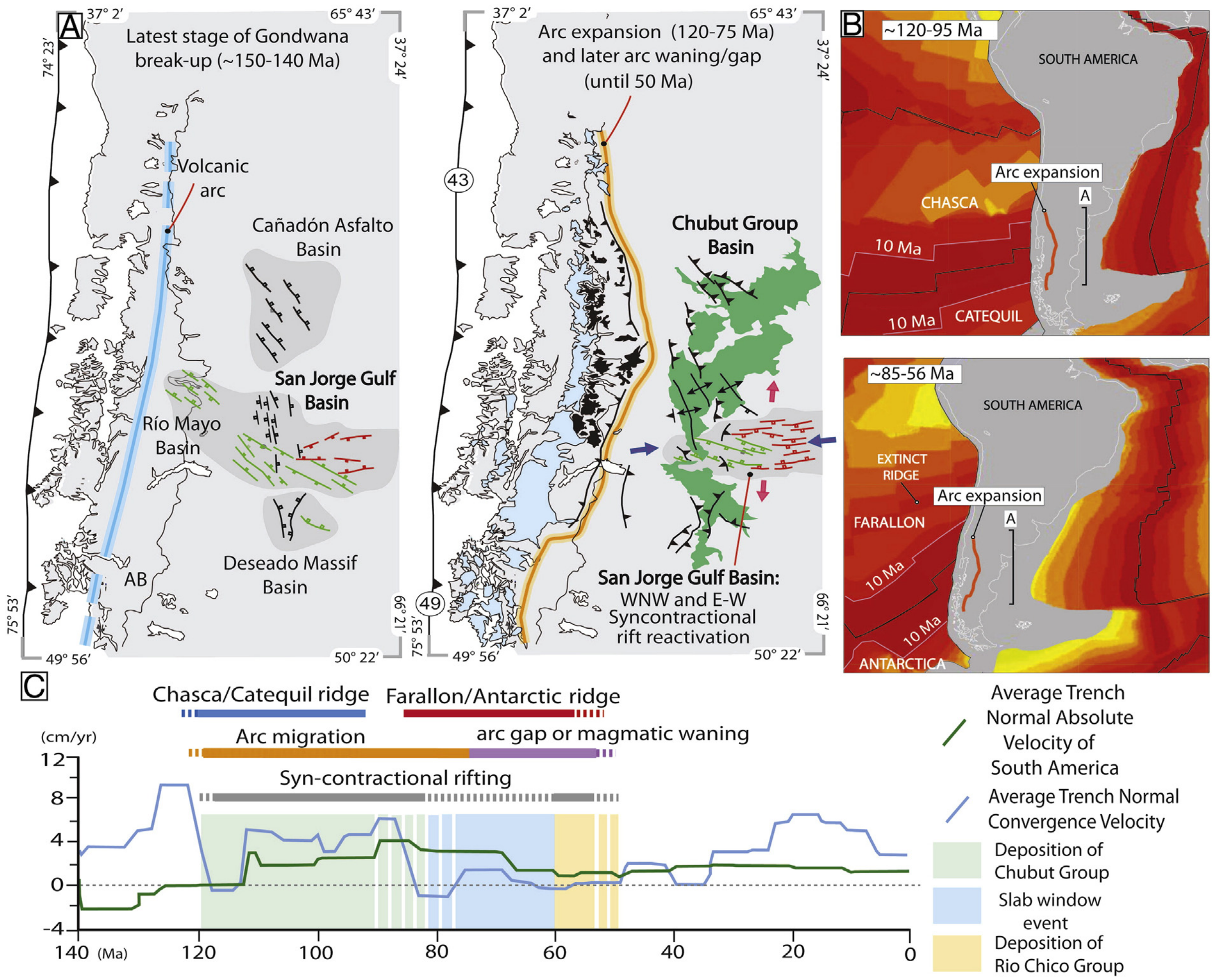

Fig. 14. A. Schematic cartoons showing the evolution of Central Patagonia during the Late Jurassic–Early Cretaceous (150–140 Ma) to Late Cretaceous times (120–75). The 150–140 Ma extensional stage was dominated by three general structural trends: NNW (black lines), WNW (green lines) and minor E–W (red lines). Later, since ~120 Ma, a slab shallowing event is suggested by magmatic arc expansion at the time of development of a broad broken foreland. At this time compression reactivated the E–W and WNW structures of the San Jorge Gulf Basin in a syncontractional mode (modified from Folguera and Ramos, 2011). B. Plate reconstruction taken from Seton et al. (2012) showing mid ocean ridge collisions during Cretaceous times in Patagonia: First Chasca/Catequil ridge collision from ~120 to 93 Ma and then Farallon/Antarctica ridge collision from 86 to 56 Ma. Note the spatial relation between young lithosphere subduction (depicted by 10 Ma isochrones) and development of arc expansion C. Average trench normal absolute and convergence velocities constructed with data taken from Maloney et al. (2013) (averaged for points 49 and 43 in A) and timing of different geological events.

it is worth noting the close spatial and temporal relation between the broken foreland sector, the development of the Chubut Group Basin, the magmatic arc migration and the series of mid ocean ridge collisions (Fig. 4 and 14).

All these processes appear to have converged to enhance orogeny as indicated by synorogenic sedimentation described in Sections 6 and 7. Thus, regional compression progressively caused early Andean mountain building, broken foreland formation, fragmentation of a distal sector of the foreland (inversion of offshore basins) and syn-contractional foreland rifting in the San Jorge Gulf Basin (Fig. 14A and 15B and C).

The deformational effects produced by collisions of mid ocean ridges have been recognized for a long time (Palmer, 1968). In most cases, subduction of mid-ocean ridges is associated with overriding plate extension enhanced by the development of slab windows (Thorkelson, 1996). However, subduction of oceanic lithosphere younger than ~10 Ma attached to midocean ridges can constitute positively buoyant anomalies that tend to resist subduction (Cloos, 1993). Thus, in these specific cases, subduction of midocean ridges may even lead to shallow subduction configurations (Nelson and Forsythe, 1989). Based on Seton et al. (2012)'s reconstruction, subduction of less than ~10 Ma ocean lithosphere, generated in two subsequent midocean ridges, is coincident with the described arc-magmatic expansion between ~120 and 75 Ma (Fig. 14B). A shallow slab angle attained at this time may have favored regional compression, as the interplate contact expanded between the overriding and subducting plates. It is worth noting that slab shallowing may have been further sustained by the trenchward motion of the overriding plate and/or high convergence (Heuret et al., 2007) (Fig. 14C). Hence, collision of these two mid ocean ridges against South America, when the continent accelerated towards the trench and/or the two plates converged, could have had dramatic consequences in Central Patagonia, deforming the whole South American Plate from the Andes to the offshore area of the Atlantic passive margin (Figs. 1 and 15C). On the other hand, thermal weakening of the upper plate imposed by prolonged mid-ocean ridge subduction may have facilitated deformation (Ramos, 2005).

Parada et al. (2001) argued that around the Aysen area, rocks associated with the late Early Cretaceous arc activity were locally influenced by an upwelling asthenospheric source that justified the anomalous arc signature and an elevated gradient as evidenced by a thermal metamorphic event (See location in Fig. 4). We speculate that asthenosphere locally leaking through the Chasca/Catequil mid-ocean ridge may have been responsible for influencing the chemistry of the volcanic arc at that area. A fully open slab window event could have been inhibited by the highly oblique collision of this mid-ocean ridge (60°<), as

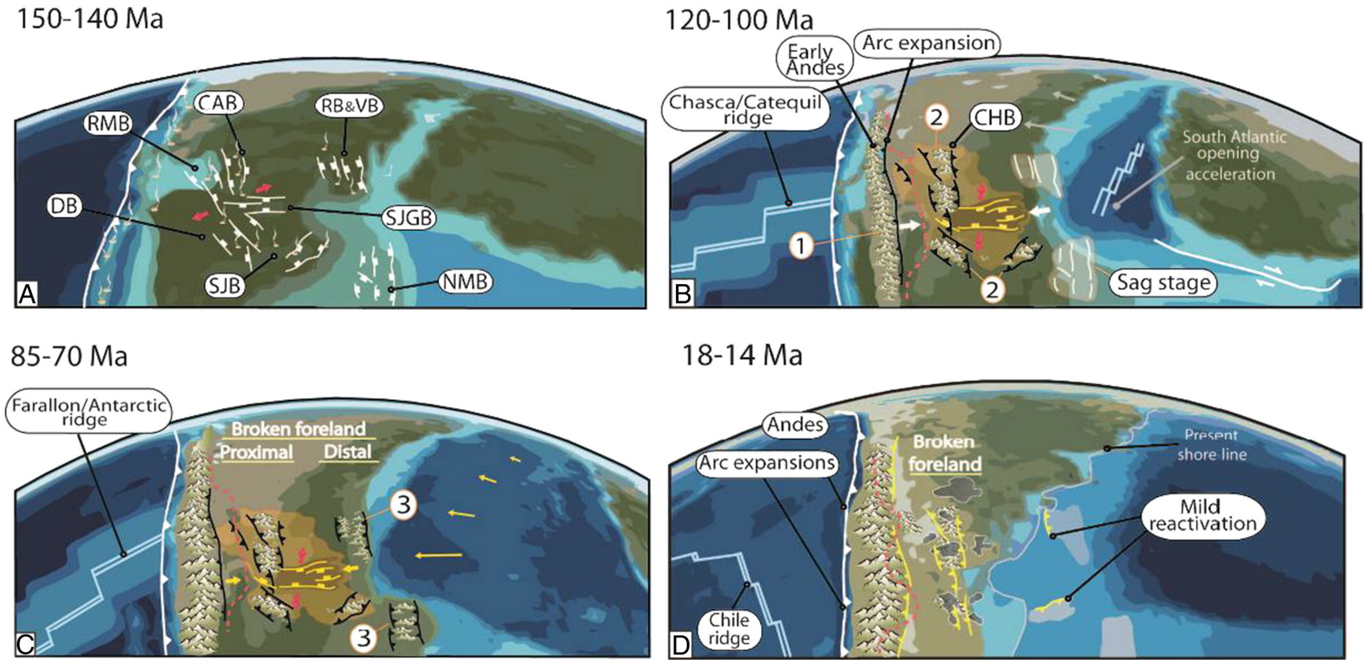

Fig. 15. Evolutionary model of the foreland and offshore regions of Central Patagonia in Mesozoic and Cenozoic times. A. Upper Jurassic–Lower Cretaceous extensional basins of the Patagonia and offshore regions. B. Opening of the South Atlantic ocean in late Early Cretaceous times, collision of Chasca/Catequil ridge, initial proximal and distal (San Julian Basin) broken foreland deformation and syncontractional foreland rift reactivation at San Jorge Gulf Basin. C. Collision of Farallon/Antarctica ridge, continued slab shallowing, full development of distal broken foreland (inversion of offshore basins) and further syncontractional rifting in Late Cretaceous. D. Final development of the broken foreland during the middle Miocene. Paleogeographic reconstructions modified from Blakey, R., Hronusov, V. Global Paleogeographic Views. Red dashed line represents arc position at the different times. Abbreviations are as in Fig. 1. Numbers represent the relative uplift order of the different morphostructural systems. See text for further details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

recently modeled by Quevedo et al. (2013) (Fig. 14B). Contrastingly, during the collision of the Antarctic/Farallon mid-ocean ridge since Late Cretaceous to the Paleocene, due to a more favorable oblique angle (60°>), a slab window would have opened responsible for the eruption of volcanic plateaus in the foreland area (Figs. 4 and 14B).

This is supported by a number of studies that point out to the development of a slab window event during the Late Cretaceous to Paleocene (Ramos, 2002; Demant et al., 2007). At around 75–72 Ma, scarce arc-related products at the western slope of the Andes are partially synchronous to Morro Negro/Alto Río Senguer retroarc basalts, interpreted as derived from an asthenospheric source (Demant et al., 2007) (Figs. 2 and 4). These authors described over the Chilean side of the Andes at these latitudes volcanic rocks with adakitic signature erupted at ~75 Ma. East of the Andes, basalts considered as equivalents of the Morro Negro/Alto Río Senguer retroarc basalts (81–77 Ma) and the Upper Cretaceous–lower Paleocene Mercedes basalts were similarly interpreted as related to a slab window event (Ramos, 2002) (Fig. 2). During a similar period, poorly differentiated rocks of Tres Picos Prieto Fm. (80–62 Ma) and Pre-Salamanca Fm. (64–62 Ma) were erupted at the retroarc area (Franchi and Page, 1980; Marshall et al., 1981) (Figs. 2 and 4).

Based on our dataset of available radiometric ages in arc-derived rocks, ~74–50 Ma time interval shows to be not well represented (Fig. 4). This could be a consequence of either the development of an arc gap as well as a decrease in magmatic activity at that time. Suárez and De La Cruz (2001) had already identified a magmatic arc gap at 45–48°S within this lapse (69–48 Ma), that could be extended from 42°S to as far as 48°S to the south based on the dataset displayed in Fig. 4. It is worth noting, that the abovementioned retroarc basalts were closely erupted at the time of the proposed volcanic arc gap or magmatic waning event period (~74–50 Ma) (Fig. 14C). This scenario is a common process described during collision of mid-ocean ridges where the volcanic arc shuts off and mafic magmatism appears at the foreland area associated with a slab window (Ramos and Kay, 1992; Ramos, 2005).

In late Eocene to early Miocene, vast portions of the San Bernardo FTB were covered by volcanic plateaus whose origin is still debated (Kay et al., 2006; Bruni et al., 2008). During this time, trench-normal absolute velocity of South America remained particularly low (Fig. 14C) (Maloney et al., 2013). However, plate convergence increased again at 23 Ma (above 4 cm/year), with a peak of 6 cm/year from ~20 to 15 Ma (Fig. 14C) (Pardo-Casas and Molnar, 1987; Maloney et al., 2013). This peak velocity is coincident with the latest stages of Andean deformation and broken foreland reactivation during the Neogene (19–14.8 Ma) (Bilmes et al., 2013) (Figs. 14C and 15D). However, this last event may have not been as strong as the Cretaceous/early Paleocene event. This could be inferred from mild reactivation of localized structures far into the foreland zone in the offshore area during Cretaceous times (Continanzia et al., 2011; and Micucci et al., 2011) (Figs. 2 and 15D).

This Neogene broken foreland admits no simple explanation, since no general arc expansion in Neogene times is reported from 43°30′S to 46°30′S along the arc front (Hervé et al., 2000, see Fig. 6), which precludes the possibility of a long-standing flat-slab segment, a conclusion to which Bilmes et al. (2013) had already arrived. We suggest that the restructuration of this broken foreland in the middle Miocene would have been mainly controlled by the presence of western Gondwana break-up related heterogeneities, such as basin edges, that were reactivated during high convergence periods (above 4 cm/year) (Fig. 14C). Throughout the Andean evolution of the Patagonian foreland, extensional basins have acted as anisotropies focalizing strain effectively during compression (Fig. 15). In this process, localized sectors of the foreland area were deformed (inverted basins). These are separated by relatively non deformed areas as the sector between the San Bernardo FTB (broken foreland) and the inverted offshore basins (distal broken foreland) (Figs. 3 and 15). Such a control on upper plate

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deformation during Andean orogenesis had been reported previously at a continental scale for the South American plate (Cobbold et al., 2007).

Future work is needed trying to test through mechanical modeling the evolution of this broken foreland basins when varying far-field convergence rates and three-dimensional rheological properties.

Conclusions

In summary from the above data and discussion, a series of conclusions can be drawn:

1. Analysis of surface and subsurface data at the San Bernardo FTB and the Río Mayo basin suggests a synorogenic character of the Cretaceous Chubut Group and probably the late Paleocene Río Chico Group. However, further detailed studies focused on the last unit are needed to confirm its synorogenic character.
2. The Chubut Group Basin is associated with the development of a broad broken foreland system. The distal part of this system may have extended into the offshore area in Cretaceous times.
3. The Patagonian Broken foreland interferes with a transversely oriented extensional depression (San Jorge Gulf Basin). This basin, could have responded to Cretaceous compression reactivating and nucleating new extensional structures, likely aided by favorable structure orientation, defining a general E–W rift. This is supported by a close spatial–temporal relation between foreland fragmentation and basin rifting that defined contrasting tectonic controls on the deposition of the Chubut Group. Hence, this is interpreted as a synorogenic foreland rift stage coexisting with the development of the San Bernardo FTB to the west.
4. Since the late Early Cretaceous to the late Paleocene contraction could be explained by a combination of changes in trench normal convergence, absolute velocity of South America and collision of mid-ocean ridges that would have conferred a shallower angle to the subducted lithosphere, as denoted by magmatic arc expansion and subsequent arc gap/waning. Thermal weakening of the upper plate caused by prolonged mid-ocean ridge subduction may have facilitated deformation.
5. Mesozoic extensional basins may have played a key role in focalizing contractional strain in the foreland area during periods of regional compression.

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