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Structure of the Southern Patagonian Andes at 49ºS, Argentina

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ABSTRACT

This paper describes Late Paleozoic Gondwanan and Late Cretaceous to Early Cenozoic Andean structures in the Southern Patagonian Andes and an associated Extra-Andean region between lakes San Martín and Viedma. The study area encompasses a 200-km-long W-E section between the Patagonian icefield and the 72ºW longitude meridian, in Argentine Patagonia. The oldest structures are of Late Paleozoic age and developed through at least two deformation phases during the Gondwanan Orogeny. The first deformation phase (Dg_1) includes isoclinal and N-overturned WNW trending folds and associated thrusts, including duplexes. The second deformation phase includes NNE trending open folds (Dg_2). Deformation occurred in non-metamorphic to very low-grade metamorphic conditions. A spaced rough cleavage is found near the first phase fold hinges. The Eocene and Miocene Andean structural compression resulted in a N-S oriented fold and thrust belt. This belt is comprised of three morphostructural zones from W to E, with distinctive topographic altitudes and structural styles: Andean; Sub-Andean; and Extra-Andean zones. The first corresponds to the inner fold and thrust belt, while the last two are part of the outer fold and thrust belt. The Andean zone (3400–2000m above sea level) is characterized by N-S to NNE trending, E-vergent, Cenozoic reverse faults and associated minor thrusts. The northern part of the Sub-Andean zone (2000–1500m above sea level) consists of W-vergent reverse faults and some NNE open folds. The southern part of the Andean zone includes tight folds with box and kink geometries, related to thrusts at deeper levels. In the Extra-Andean zone, with maximum heights of 1500m, the deformation is less intense, and gentle folds deform the Upper Cretaceous sediments. An inherited Jurassic N-S extensional fault system imposed a strong control on this morphostructural zonation. Also the variation of the Austral Basin sedimentary thickness in the N-S direction seems to have influenced the structural styles of the outer fold and thrust belt. Those differences in sedimentary thickness may be related to S-dipping transfer zones associated to W-E Jurassic extension. In turn, the transfer zones may have been controlled by the N-vergent WNW, Dg_1, Gondwanan structural fabric.

KEYWORDS Inversion structures. Paleozoic Gondwanan structures. Andean structures. Fold and thrust belt. Southern Patagonian Andes.

INTRODUCTION

The study area provides an excellent location in which to investigate the current structural framework of the southern Andes, the influence of Paleozoic basement structures on the evolution of Mesozoic basins, and the Mesozoic fill of the Austral basin. It is located in the southern Patagonian Andes of Argentina at 49ºS latitude, where the Torre and Chaltén (Fitz Roy) peaks rise to 3128m and 3405m respectively and is near the eastern edge of the southern Patagonian icefield (Fig. 1A). This area includes part of the Extra-Andean region of the Santa Cruz province and occupies a 200km long E-W segment between lakes San Martín and Viedma. Geologically, this region is where the front of the Andean orogenic belt widens into the foreland reaching approximately 70ºW longitude (Fig. 1B). The area located east of 72º50'W (a region referred to as Sub-Andean) is key to understanding the structural behavior of the Cretaceous cover (thick-skinned *vs.* thin-skinned tectonics or strike-slip deformation).

The aims of this study were to determine the subsurface structure of the Extra-Andean zone, define geologic characteristics of structural/metamorphic zones, describe and interpret Paleozoic structures, and evaluate present structural morphology. To achieve this purpose, we present a regional structural interpretation based on a new geologic map of the area located between the Patagonian icefield and the 72ºW longitude meridian (Fig. 2). To the east, this study is based on exploration wells and seismic sections from the Piedra Clavada area. Data for this study were acquired while performing geological fieldwork for the 4972-III and 4975-IV 1:250,000 scale geologic map, El Chaltén (Giacosa *et al.*, 2011), and during the structural interpretation done for the nearby 4972-IV geological map, Tres Lagos (Cobos *et al.*, 2008) by one of the authors (RG).

We suggest a new interpretation for the deformation fabric of the Gondwanan basement and the influence this fabric had on the subsequent development of the structures that acted as transfer fault zones during Jurassic rifting. We also discuss the role that Mesozoic extensional structures may have played in the subsequent Andean compressional deformation, and indeed in the actual Patagonian Andes structure.

Previous studies on the structural geology and tectonics of this area were conducted by Nullo *et al.* (1978), Kraemer (1994), Coutand *et al.* (1999), Spikermann *et al.* (2000, 2006), Kraemer *et al.* (2002) and Fracchia (2002),

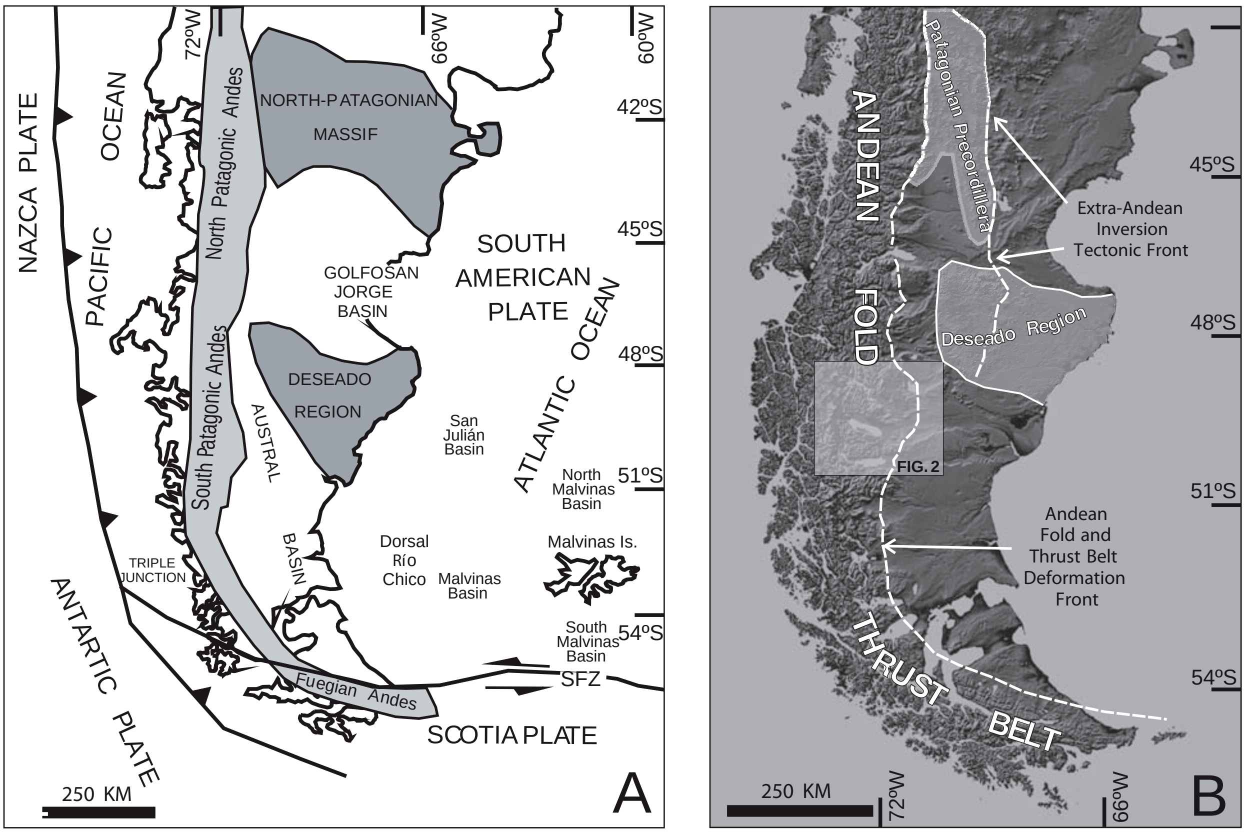

FIGURE 1 | A) Major geological provinces and tectonic setting of Patagonia. B) Image showing the Andean fold thrust belt deformation front (Kraemer *et al.*, 2002), and the eastern boundary of the Tertiary inversion tectonic front in the Patagonian foreland (Giacosa *et al.*, 2010).

whose contributions will be discussed later. Structural investigations conducted south of lake Viedma by Massabie (1990), Kraemer (1990, 1991, 1993) and Ghiglione *et al.* (2009) were used for comparison.

To the east, in the Extra-Andean zone, the most significant structural observations are those of Ferello (1955) describing the area of Piedra Clavada, and those of Casas (1957) describing the area of the anticlines of Mata Amarilla and Río Sehuén. Combining the findings of these authors with recent data from exploration wells and seismic sections allows a new interpretation of the subsurface structure in this sector.

With regard to the regional stratigraphy and tectonostratigraphic evolution, we followed the guidelines proposed by Arbe (2002) in a recent synthesis. Nonetheless, it should be noted that the field mapping of the sedimentary units, especially those of the Upper Cretaceous, remains problematic, despite generally good knowledge of the basin evolution (see Giacosa *et al.*, 2011). In this sense, the contribution of Kraemer and Riccardi (1997) is critical for the region between the Argentino and Viedma lakes.

GEOLOGICAL SETTING

The study region is characterized by the development of sedimentary and volcanic units associated with the evolution of the Austral Basin. The area includes three main tectono-stratigraphic units on Paleozoic basement (Fig. 3). They are a Jurassic syn-rift sequence, an Early Cretaceous thermal subsidence (sag) sequence

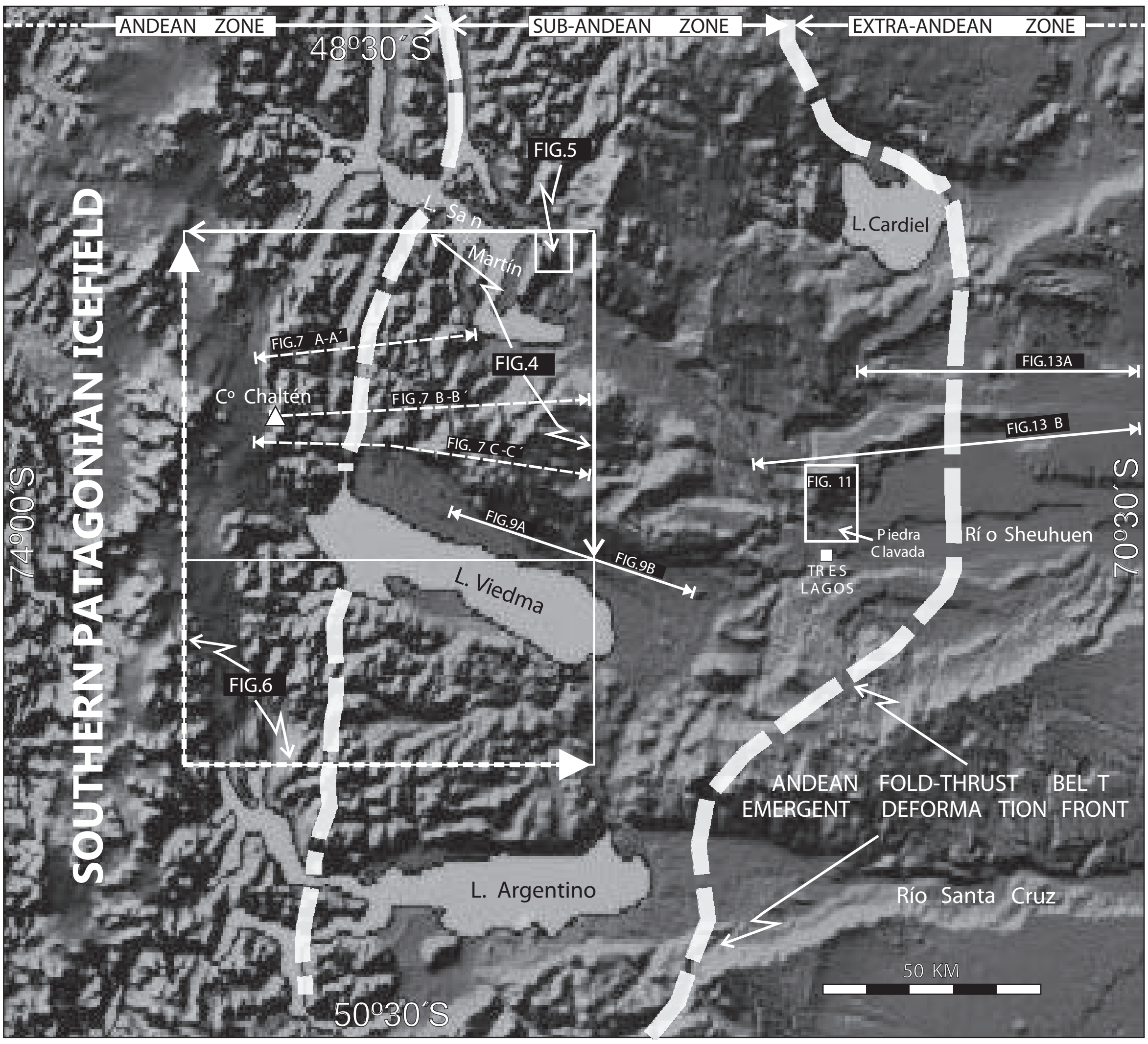

FIGURE 2 | Distribution of the morphostructural zones and location map of the subsequent figures. Figure 6 is the area of the 1:250,000 El Chaltén Geological Sheet (Giacosa *et al.*, 2011). The front of the fold and thrust belt is taken from Kraemer *et al.* (2002). Note the widening of the fold and thrust belt at Argentino and San Martín lakes latitude (compare with Fig. 1B).

and a foreland basin sequence that developed in the Late Cretaceous (Biddle *et al.*, 1986; Arbe, 2002; Kraemer *et al.*, 2002) (Fig. 3). The first two represent the Andean Cycle pre-orogenic succession and the last represents the syn-orogenic succession.

The Paleozoic basement of the southern Patagonian Andes consists of Upper Devonian and Lower Carboniferous sedimentary rocks of the Bahía de la Lancha formation and very low grade metamorphic rocks of the Río Lácteo formation. These rocks are composed of alternating sandy and shaly turbidite beds (Riccardi, 1971) with some diamictite facies (Poiré *et al.*, 1999) deposited on a passive continental margin (Augustsson and Bahlburg, 2003). The detrital material may have been derived from the Deseado massif (Hervé *et al.*, 2003) of crustal Grenvillan rocks located to the NE (Augustsson and Bahlburg, 2003). Westward, in Chile, these rocks contain large bodies of metabasites (Davidson *et al.*, 1987) that have chemical affinities with oceanic basalts (Godoy, 1980). The metabasites are interpreted as tectonic blocks developed during mélange formation in an accretionary prism resulting from subduction of the pacific plate (Hervé *et al.*, 1994).

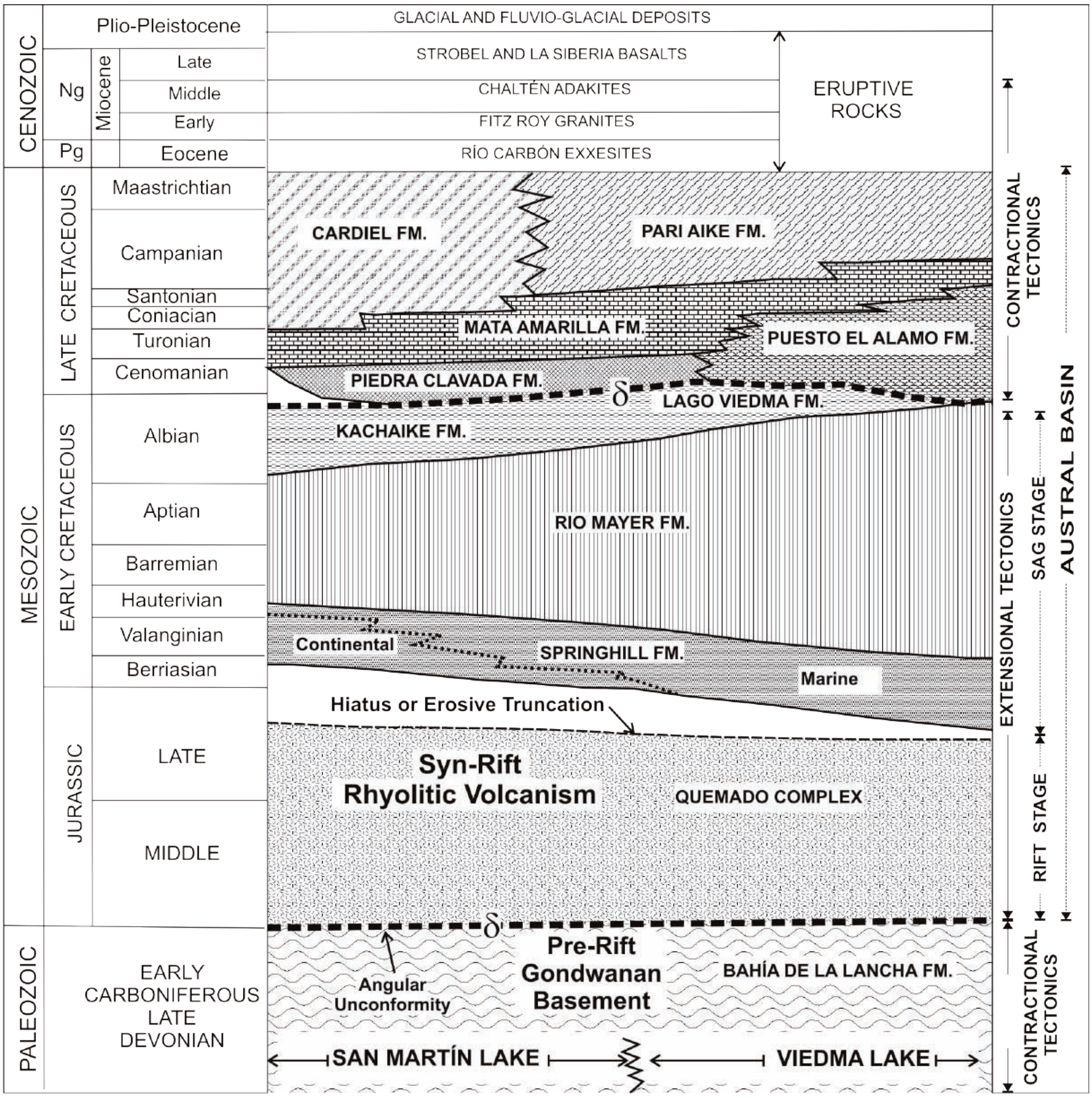

FIGURE 3 | Simplified tectono-stratigraphic sketch of the southern Patagonian Andes between the San Martín and Viedma lakes. Also shown the sedimentary sequences related to the Austral basin development. Based on Arbe (2002), Kraemer and Riccardi (1997) and Kraemer *et al.* (2002).

Radiometric dating by the SHRIMP method on zircons from the equivalent series of rocks in the nearby eastern Andes metamorphic complex (O'Higgins lake, Chile) indicate an older sedimentation age of 354±10Ma, near the Devonian-Carboniferous boundary (Sepúlveda and Hervé, 2000). In this series, a combination of U-Pb detrital zircon ages and fission track data led Thomson and Hervé (2002) to conclude these sediments were metamorphosed before the Late Permian under lower metamorphic conditions. This basement crops out extensively throughout the western sector of the study area and around San Martín lake (Fig. 4). It was also recognized in the subsurface to the north of Tres Lagos, at a depth of 758m below sea level (Giacosa and Márquez, 2002).

No evidence of metamorphism was found in the basement rocks of the study area. This situation is unlike that of the Paleozoic rocks located further north (Río Lácteo formation) and west (eastern Andes metamorphic complex), where metamorphic conditions reached lower greenschist facies (Giacosa and Franchi, 2001).

At these latitudes subduction began on the Pacific margin in the Jurassic, marking the beginning of the Andean orogenic cycle. The base of this cycle is represented by extensive volcanic accumulations and interbedded clastic sediments of the Middle to Upper Jurassic El Quemado complex. This sequence is interpreted as accumulating during the syn-rift stage (intracontinental extension) in grabens and half-grabens (Uliana *et al.*, 1989). As rifting continued, the Rocas Verdes back-arc basin (a part of the Austral basin) opened in the SW part of the South American continent (Dalziel *et al.*, 1974).

During the Berriasian-Valanginian and continuing until the Albian, volcanic activity and extensional faulting decreased and a thick siliciclastic sequence was deposited. The base of this sequence is composed of conglomerates, sandstones, and black shales of the Berriasian-Hauterivian Springhill Formation deposited in a coastal environment. From the Barremian onwards, shallow marine platform sediments of the Río Mayer formation alternated with deltaic deposits of the Kachaike and Lago Viedma formations representing the final infill of the Rocas Verdes basin (Biddle *et al.*, 1986). The Río Mayer, Kachaike and Lago Viedma formations together with the Springhill Formation are interpreted as a thermal subsidence sequence in a post-rift (sag) stage (Kraemer and Riccardi, 1997; Arbe, 2002). The equivalent series south of lake Viedma (Cerro Toro Formation) has a greater thickness suggesting this sector was more tectonically active.

Towards the Cretaceous-Paleogene boundary sedimentation reflects strong subsidence conditions related to tectonic loading (Biddle *et al.*, 1986). This loading started the retroarc foreland basin syn-orogenic succession, linked to the Andean Orogeny. Several units of the Upper Cretaceous in the area, *e.g.* Piedra Clavada, Puesto El Álamo, Mata Amarilla and Cardiel siliciclastic formations, represent sedimentation during this stage (Figs. 3, 4). This succession rests unconformably over the pre-orogenic succession.

During the Paleogene, foreland-basin sedimentation continued and intrusions of alkaline basic rocks, such as the Río Carbón Essexite, were common in the southern coast of San Martín lake (Riccardi, 1971). The Cerro Fitz Roy plutonic complex was emplaced in the Miocene (Kosmal and Spikermann, 2002; Ramírez de Arellano *et al.*, 2009) and includes four plutonic units of ultramafic, mafic, tonalitic and granitic rocks. These units are cut by micro-monzonitic and sub-volcanic dikes with ages ranging from 19 to 16Ma (Ramírez de Arellano *et al.*, 2009). At 14Ma the Chaltén Adakite intruded in the Sub-Andean sector (Ramos *et al.*, 2004). From the Late Miocene to Late Pliocene the Strobel and La Siberia Basalts (Ramos, 1982, Gorring *et al.*, 1997) flowed along a broad area (Fig. 4).

The Pliocene-Quaternary record is mainly represented by four glacial events, including glacio-fluvial and glacio-lacustrine deposits.

STRUCTURAL FRAMEWORK

The first orogenic event observed in rocks of the southern Patagonian Andes occurred during the Permian, in the context of the Gondwanan orogeny (Hervé, 1988). Later, between the Late Cretaceous and the Early Tertiary, the structures related to the Andean orogeny developed (Biddle *et al.*, 1986; Ramos, 1989). However, in the study area the Andean orogeny started later, in the Cenozoic.

The Andes mountain belt developed to the south of the Aysen Triple Junction (southern Patagonian Andes) and was mainly uplifted starting in the late Miocene, as a result of the collision of the Chile Ridge with the South American plate (Ramos, 1989; Hervé *et al.*, 2000), during the eastward subduction of the Antarctic plate.

Gondwanan Paleozoic structures

The structures deforming Paleozoic sedimentary rocks are better exposed in the Sub-Andean zone, in the eastern side of Bahía de la Lancha of San Martín lake (Fig. 4). Here the Paleozoic rocks crop out under the Jurassic volcanics of the El Quemado complex (Fig. 5A) and consist of massive

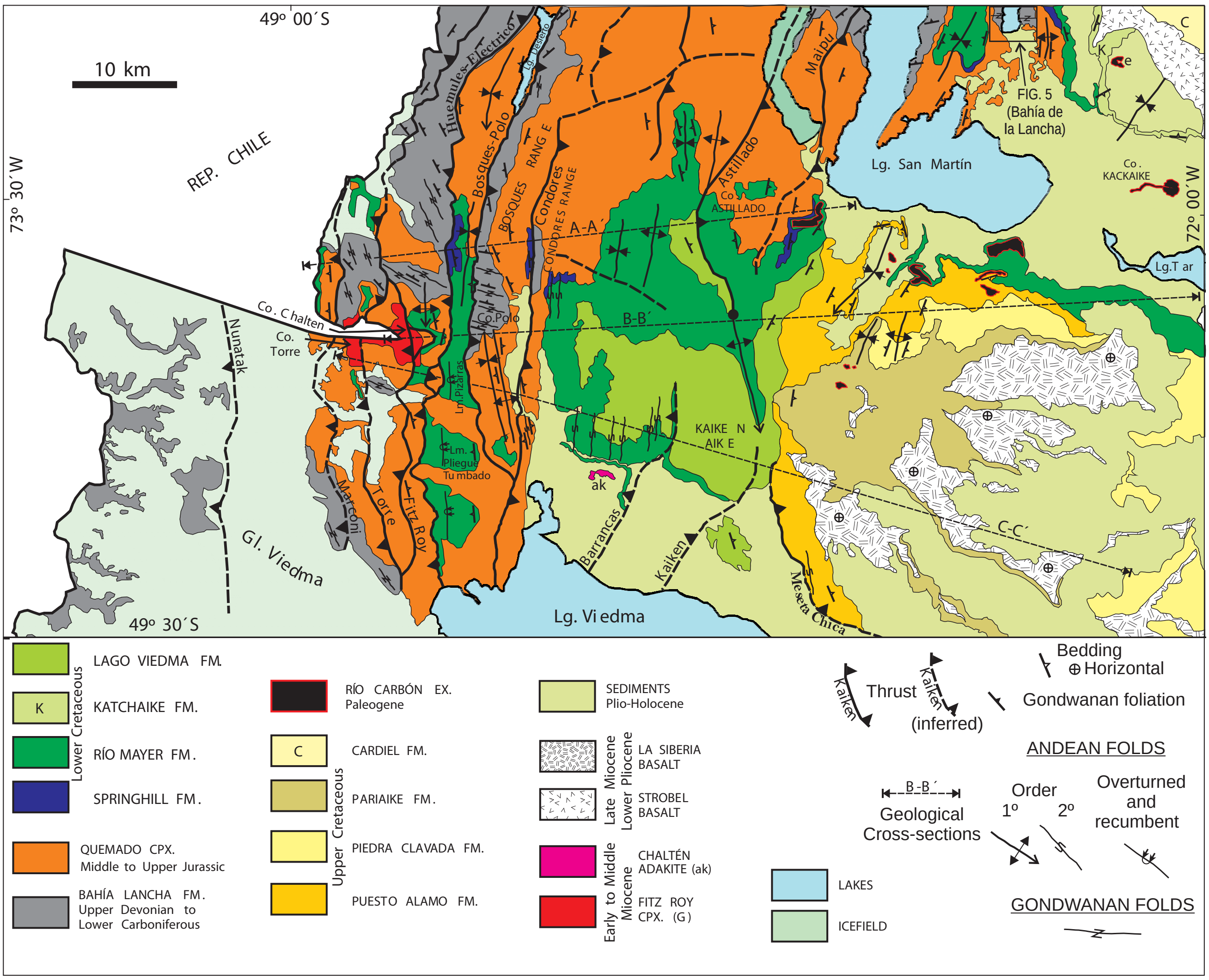

FIGURE 4 | Schematic geological map of the area North of Viedma lake, betwen San Martín and Viedma lakes, based on the 1:250,000 scale El Chaltén Geological Sheet (Giacosa *et al.*, 2011). Note the pre-rift basement rocks on the west, the rocks of syn-rift and sag stages in the central part and the foreland sequence to the east. Location is shown in Figure 2.

ortho-quartzites interbedded with highly deformed pelites (Figs. 5B, C). Paleozoic structures in this area are the result of at least two phases of deformation: Dg_1 and Dg_2.

The structural trend of Dg_1 is W-E to WNW (Fig. 5A). Dg_1 structure consists of tight, upright to isoclinal chevron folds. These folds have an incipient (rough) cleavage in the pelitic sediments (Fig. 5B). Northward, the structural style changes to N-vergent asymmetric folds associated with thrust faults that are interpreted as a N-vergent duplex system (Fig. 5C). The Dg_1 structures are deformed by southerly-trending open folds of the second deformation phase (Dg_2). The structures of both deformation phases are cut by normal faults, likely related to the Mesozoic extensional event.

The same set of structures can be seen in the Cancha Rayada peninsula, near the shore of the San Martín lake (Giacosa *et al.*, 2011). In this area, several W-E to WNW trending N-overturned folds (Dg_1 folds) with axial-plane cleavage near their hinges are exposed. Westwards, this structural trend is repeated in the Bosques range, in the Eléctrico river valley, and in the outcrops surrounded by the southern Patagonian icefield (Figs. 4; 6).

Because the compressional Andean deformation is more intense in the mountain ranges of the innermost Andean zone, the strike of the Gondwanan structures rotate from NW to NE (Fig. 4), to the W of the study area (see below).

Andean Cenozoic Structures

The Andean Cenozoic structure is characterized by the presence of a fold and thrust belt with eastward propagation. Three principal morphostructural zones

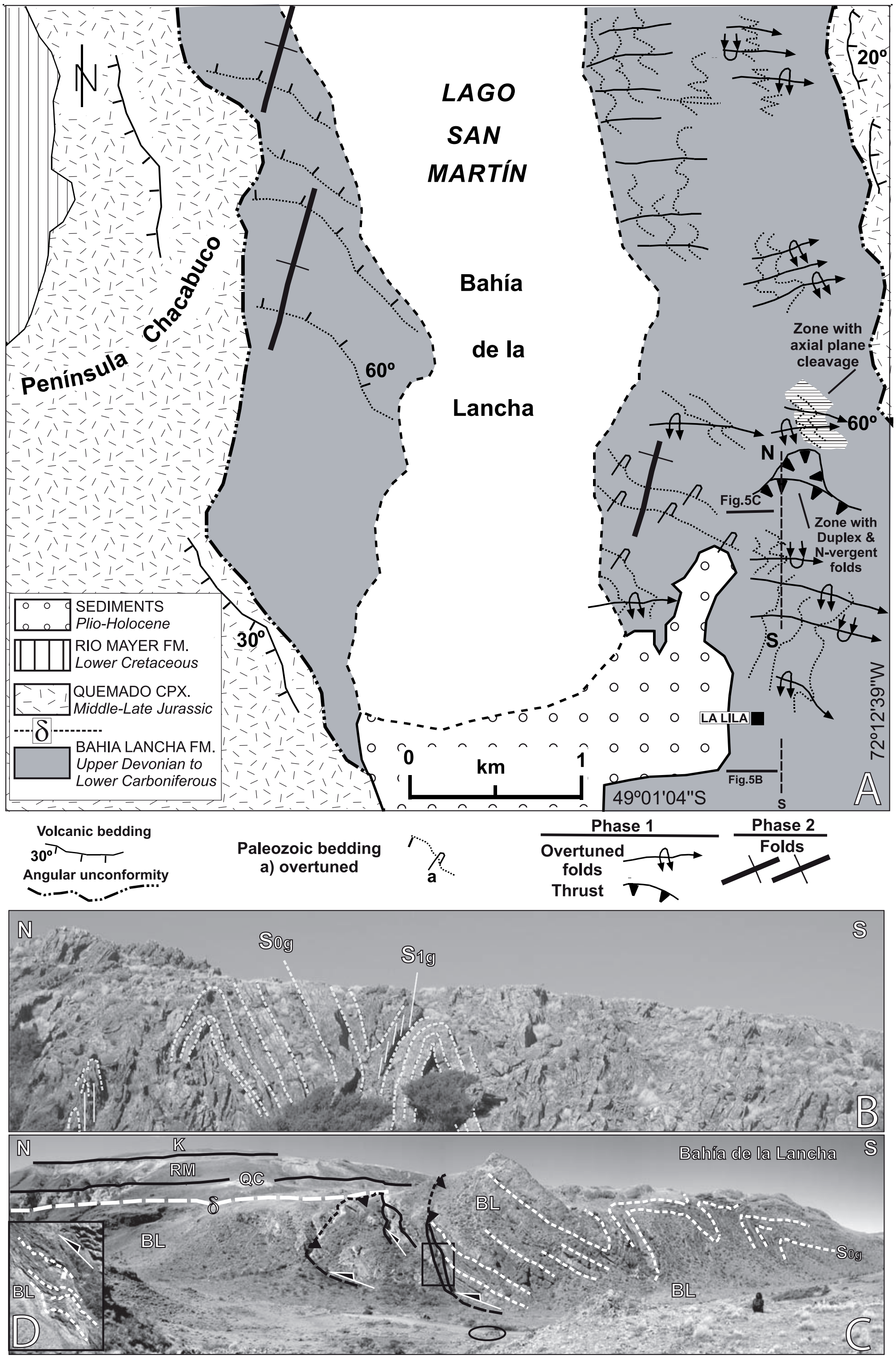

FIGURE 5 | A) Geological map of the Bahía de la Lancha in the San Martín lake, the classical site of Paleozoic rocks in the southern Patagonian Andes. Note the W-E strike and N-vergent Paleozoic structures of Phase 1 that are gently deformed by N-S folds of Phase 2. Location is shown in Figure 2. B) Bahía de la Lancha formation show W-E closed to isoclinal folds with vertical axial plane. Bedding is S_0g and S_1g is the Gondwanan incipient axial plane cleavage in shales. Arrow in Figure 5A shows the location of this picture. C) N-S structural section. Note the isoclinal and N-overturned WNW folds and north-vergent duplexes and the deformed Paleozoic rocks that underlay through a marked unconformity (d) to the Jurassic volcanites of El Quemado complex (QC). The Cretaceous Río Mayer (RM) and Kachaike (K) formations cover the volcanites. The bedding traces of the Paleozoic strata is referenced by S_0g. Arrow in Figure 5A show the location of this picture. D) W-E assymetric "S" drags microfolds in shales of the Bahía de la Lancha formation in the footwall block of N-vergent duplex.

of N-S trends, with different altitudes, topography and structural patterns were identified in the study area (Fig. 2). The first of these zones is the Andean zone, to the west. It is very rugged with heights over 2000m (Cerro Chaltén being the highest, of 3405m) and is characterized by 2 to 4km wide mountain ranges, developed on hard rocks of the Gondwanan Paleozoic basement and igneous rocks of the Mesozoic and Cenozoic. It was also named Basement Domain by Kraemer (1991) and Ghiglione *et al.* (2009) and the inner fold and thrust belt by Kraemer *et al.* (2002). The second morphostructural zone, to the east, is the 75km wide Sub-Andean zone, with summits between 1500 and 2000m. Its northern part is characterized by some mountain ridges, well defined by the abundance of hard Mesozoic volcanic rocks, and its southern part by a gentle morphology developed on Mesozoic sediments. The final morphostructural zone is the Extra-Andean zone, east of the 72ºW meridian, with a fairly smooth topography and heights less than 1500m. This zone only includes a few outcrops of pre-Tertiary rocks. The Sub-Andean and Extra-Andean zones correspond to the so-called outer fold and thrust belt from Kraemer *et al.* (2002) (Fig. 6). This subdivision is controlled by the Cenozoic structural framework and there exists a correspondence between the distribution of elevations in the Andean zone and the dominant structural styles. As shown in Figure 6, this structural zonation continues south of lake Viedma.

Structure of the Andean fold and thrust belt

In the study area the boundary between the inner and outer fold and thrust belt lies at the Cóndores thrust and to the south of lake Viedma at the Musters and Huemul thrusts (Fig. 6).

Figures 6 and 7 show the main structures of the fold and thrust belt (reverse faults and thrusts), triangle zones, and first- and second-order folds. The latter are in the Paleozoic rocks and also in the Río Mayer and Lago Viedma formations. Figure 6 also indicates the approximate eastern boundary of the axial-plane cleavage and pencil lineation front in the above-mentioned formations.

Inner fold and thrust belt

To the north of lake Viedma and towards lake San Martín (Figs. 4; 6), the inner fold and thrust belt extends from the international border to the Cóndores range in the East. Towards the western border of the belt the highest point is Cerro Chaltén or Fitz Roy peak (3405m), while south of lake Viedma the highest point is in the Masters range (2458m), located over the inner fold and thrust belt's eastern limit (Kraemer *et al.*, 2002).

From W to E, the inner fold and thrust belt is composed of several east-vergent thrusts and two easternmost back-thrusts. Kilometer-sized folds are associated with the thrusts (Figs. 4; 7). South of Viedma lake (Fig. 6) a similar geometry can be seen in the inner fold and thrust belt (Kraemer, 1991). The structures with an opposite vergence in the eastern inner fold and thrust belt produced the Vueltas and Masters Triangle zones, extending from north to south (Fig. 6). As suggested by Kraemer (1991) and Kraemer *et al.* (2002) the thrusts are possibly listric at depth and flatten at depth into a common basal thrust, slightly tilted to the west.

The structure of the Vueltas triangle zone varies from N to S (Fig. 4). In the northern part it is formed by the Vespignani syncline, a south-plunging open fold with a subvertical axial-plane that deformed the Jurassic volcanic rocks of the El Quemado complex (Figs. 4; 6). To the south, the main structure in the triangle zone is a large recumbent fold in the well-stratified sedimentary rocks of the Río Mayer Formation (Loma Pliegue Tumbado and Pizarras synclines) (Figs. 6; 8A). These synclines are characterized by an intense ductile deformation in the limb closer to the fault, produced during the tectonic inversion of a previous normal fault that separates different thicknesses of the El Quemado complex (Figs. 7C-C'; 8B). Along the Eléctrico river, the hanging-wall of the Huemul-Eléctrico thrust is made up of a large fold (Eléctrico anticline) that deforms the unconformity between the Paleozoic and Jurassic rocks.

In the north side of Polo hill, the trace of the Gondwanan structures describe a gentle arc of antiformal geometry, which is related to the hanging-wall of the Bosques-Polo Andean fault. Moreover, the superposition of Andean and Gondwanan folds are very well exposed near the fault trace of the Bosques-Polo Andean fault, at the Eléctrico river bridge (Fig. 10D).

Outer fold and thrust belt

The outer fold and thrust belt is characterized by the presence of thrusts, with less displacement than in the inner fold and thrust belt and associated folds, which are dominant to the south of lake Viedma and in the eastern part (Extra-Andean zone).

The western outer fold and thrust belt (Sub-Andean zone) has two well-differentiated sectors (Figs. 4; 6) and the presence of axial-plane cleavage and pencil lineation can still be recognized (Fig. 10A, B, C).

North of lake Viedma, W to SW of lake San Martín, there are W-vergent thrusts that cut the Jurassic volcanic rocks. These are interpreted as related to the partial inversion of the normal faults of the Jurassic rift (Cóndor and Maipú thrusts, Fig. 7A-A', B-B'). The western limb of the W-vergent thrust related fold (100 meter scale) is characterized by a short and very steep morphology, while the eastern limb is a gentle east-dipping surface (approx. 20º). Locally, near the inner fold and thrust belt limit, folds appear with 10 meter scale, which has an associated cleavage.

South of lake Viedma, the thickness increase of the Cretaceous sediments allowed fewer thrusts and hectometer to kilometer wavelength low amplitude folds, that compensate the displacement of the thrusts (Fig. 6; 7C-C'), resulting in a more flat topography. The Kaikén Aike fold belt, located in the northern shore of lake Viedma, is a set of detached folds developed in sediments of the Río Mayer and Lago Viedma formations (Figs. 4; 6; 8C) that mark the transition between these two sectors.

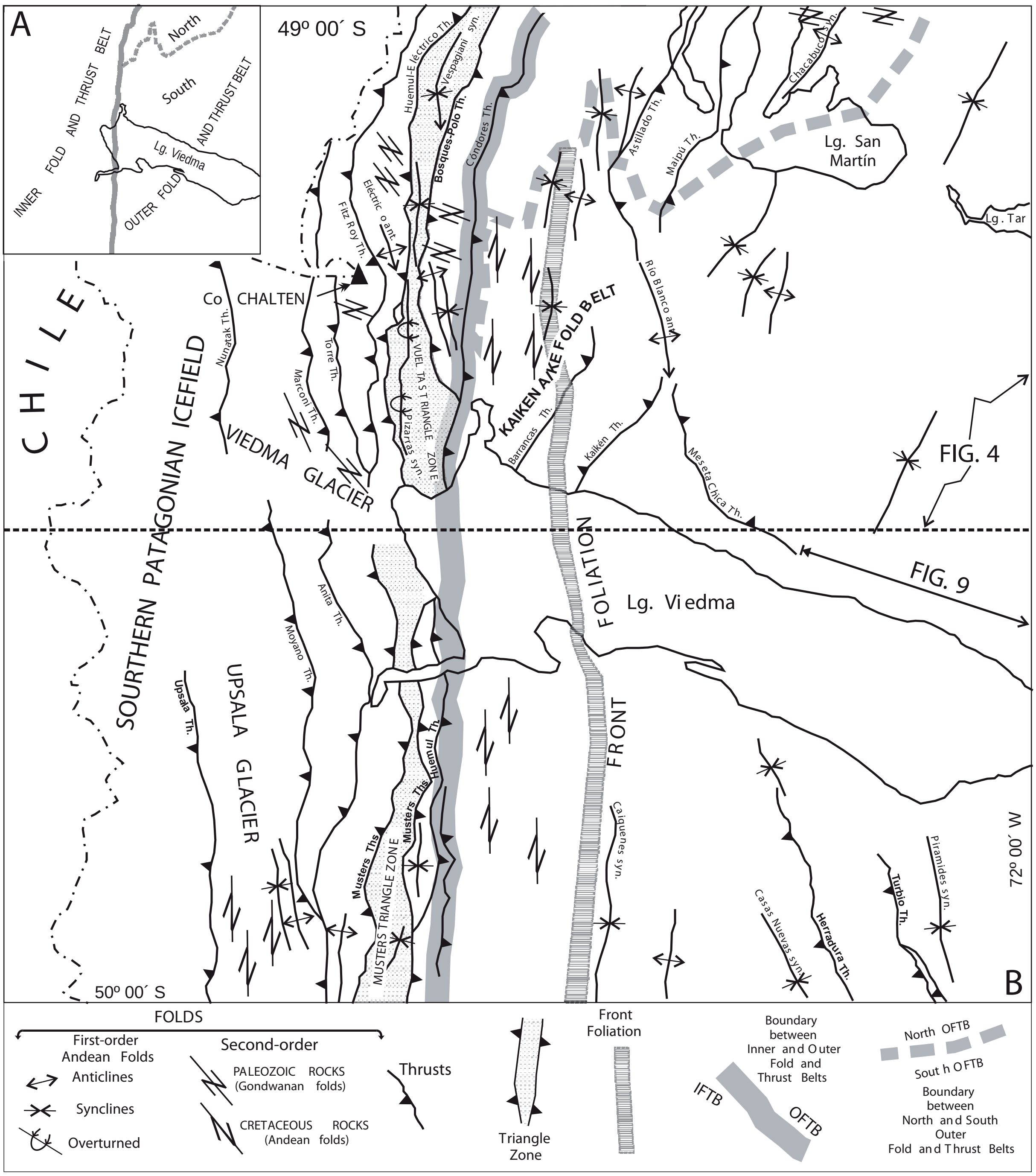

FIGURE 6 | Regional tectonic map of the 1:250,000 El Chaltén geological sheet (Giacosa *et al*., 2011) showing the study area (Fig. 4) and the structures south of Viedma lake (Kraemer, 1991). Note that no significant variations in the strike of the inner and outer fold and thrust belt and the location of front foliation on both sides of lake Viedma. Location is shown in Figure 2.

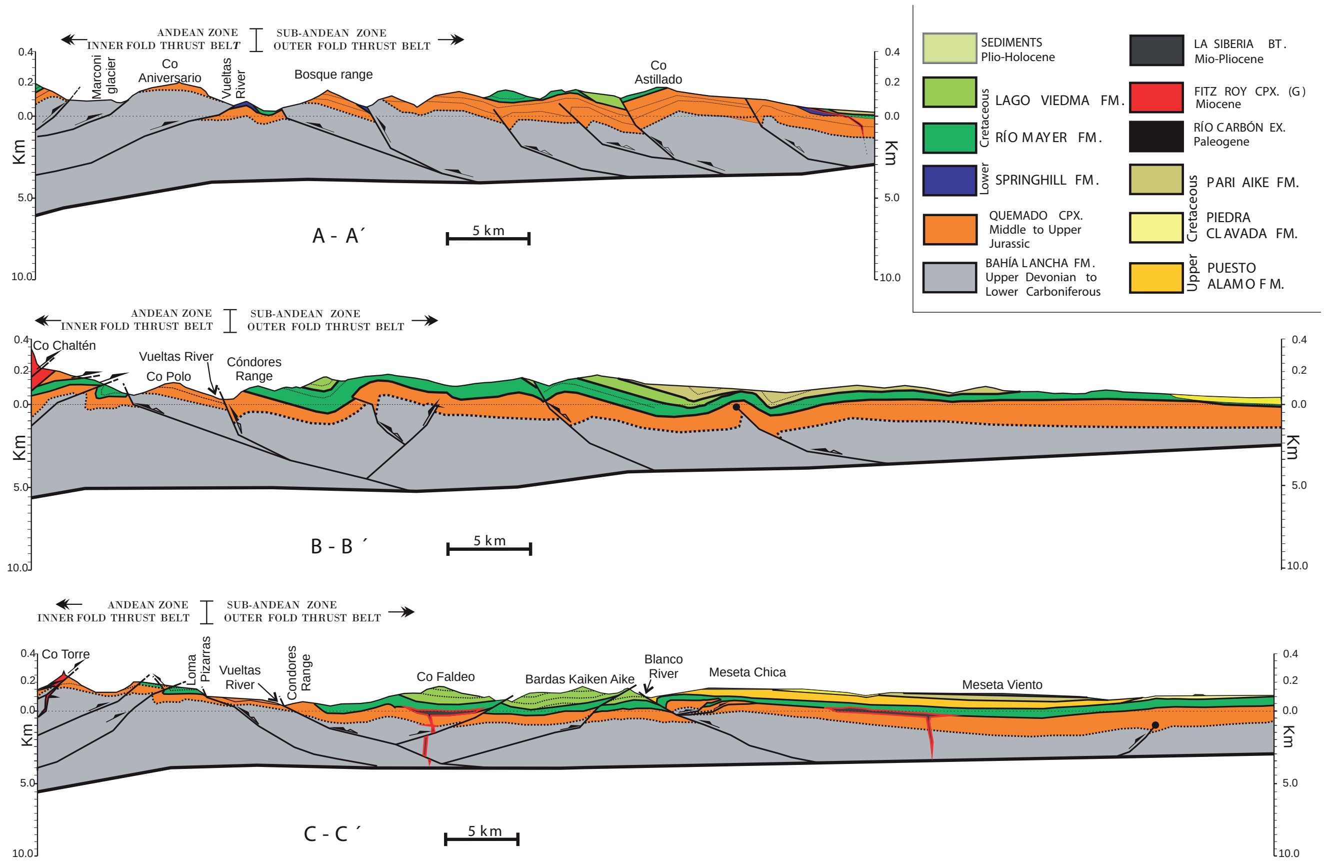

FIGURE 7 | Regional cross-sections (not balanced) between the San Martín and Viedma lakes. Seismic profile of Figure 9 is 10km south of section CC'. Location of sections lines is shown in Figure 4.

Towards the east, in the Extra-Andean zone, the deformation diminishes, and gentle folds deform the Upper Cretaceous syn-orogenic sediments (Figs. 4; 11 to 13). They are very open synclines with wavelengths of up to 10km and NNE to N-S subhorizontal hinges between 20 and 30km long, with intermediate narrow anticlines. They are interpreted as fault-propagation folds developed on the thrust that cut through the basement at depth. On the subsurface several high-angle normal faults are interpreted from seismic profiles, cutting the Jurassic volcanic rocks (Figs. 9B; 12; 13) and many thrusts resulting from the partial inversion of these normal Jurassic faults (Figs. 12; 13). The most conspicuous structure coincides with the Río Blanco. It is a fold associated with a W-vergent reverse fault and with two E-vergent thrusts (Fig. 9A), both of which are probably related to the deep propagation of the Kaikén and Meseta Chica thrusts to the north (Figs. 4; 7).

The deformation style of the outer fold and thrust belt in the Extra-Andean zone has its best surface expression in the surroundings of Tres Lagos and Piedra Clavada (Fig. 2). To the north of Tres Lagos and along the Chalía river, Ferello (1955) first identified a set of N-S to NNW trending folds in the Río Mayer, Piedra Clavada and Mata Amarilla formations, as part of a large anticline structure, covered by the horizontal flows of the Upper Miocene Strobel basalt. The Piedra Clavada anticline is a slightly asymmetric open fold with limbs dipping from 2º to 10º, and a set of faults parallel and normal to the axis, which Ferello (1955) called longitudinal and transverse faults, respectively (Fig. 11). Many of these faults are steep normal faults, dipping 70º to 80º with displacements from 18 to 50m (Figs. 11; 12) with some open drag folds. Their fault-surfaces show well-developed striations and abundant tensile fractures with calcite and silica (opal) fillings. Ferello (1955) provides an interesting description of a west-inclined south-directed structure he called a "pivotant fault". Its northern side is a 45º west-dipping reverse fault, while its southern side is a 80º west-dipping normal fault. This structure could be interpreted (Fig. 12) as a partially inverted extensional Jurassic fault passing to a thrust fault in the post-rift and syn-orogenic formations (Río Mayer and Piedra Clavada formations respectively). Toward the west, in the slightly asymmetric Waring anticline, its western limb displays longitudinal and transverse normal faults whose displacements reach up to 30 meters.

Casas (1957) described several slightly asymmetric folded structures to the north of Sehuén river, which he called the Vázquez and Ferrari anticlines, while to the south he identified the Amenida anticline and several fractures near Tres Lagos (Fig. 2). The main fractures are accommodation normal faults, many transverse to the folds. It is also interesting that disharmonic folding developed along the Piedra Clavada and Mata Amarilla formations.

The subsurface structures of this sector (Fig. 13A, B), are a group of half-grabens limited by west-dipping faults and gentle folds with concentric and kink geometries and have deformed

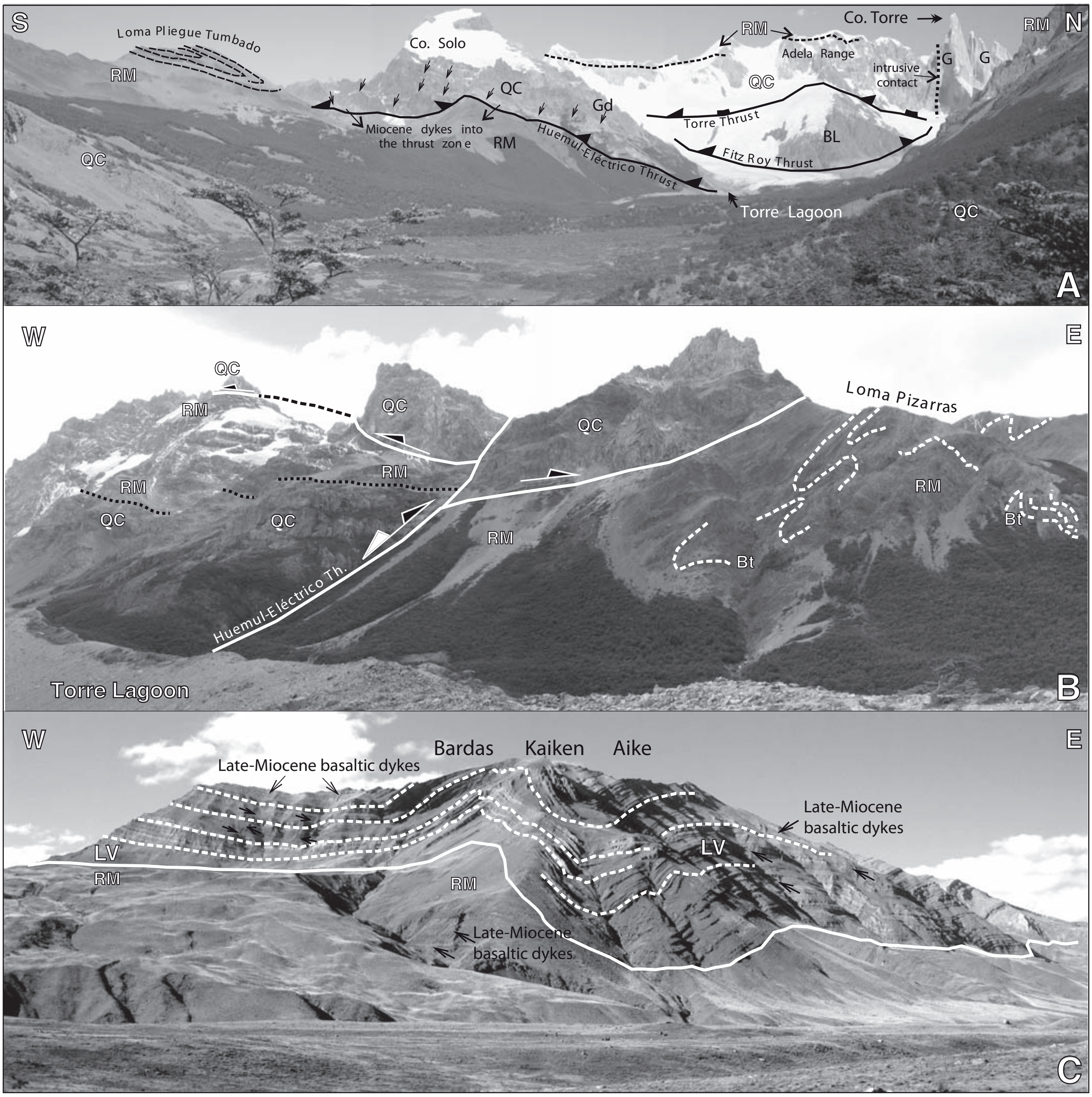

FIGURE 8 | A) View to the west of the Loma del Pliegue Tumbado, Solo hill, Adela range and Torre hill, showing the Huemul-Eléctrico, Fitz Roy and Torre thrusts and the recumbent folds in the pelites of Río Mayer formation (RM). Arrows show dykes (Gd) of Miocene Fitz Roy plutonic complex (G) above the fault plane. Note the vertical intrusive contact between the plutonic rock and the volcanites of the Quemado complex (QC). B) Torre glacier area. The Huemul-Eléctrico thrust and associated shortcuts thrust and (meso) folds in the Loma de las Pizarras. C) View of the Río Mayer (RM) and Lago Viedma (LV) formations in the Kaiken Aike fold belt (north of Viedma lake. Fig. 4). The fold belt is intruded (arrows) by vertical Late-Miocene (Strobel Basalt) dykes.

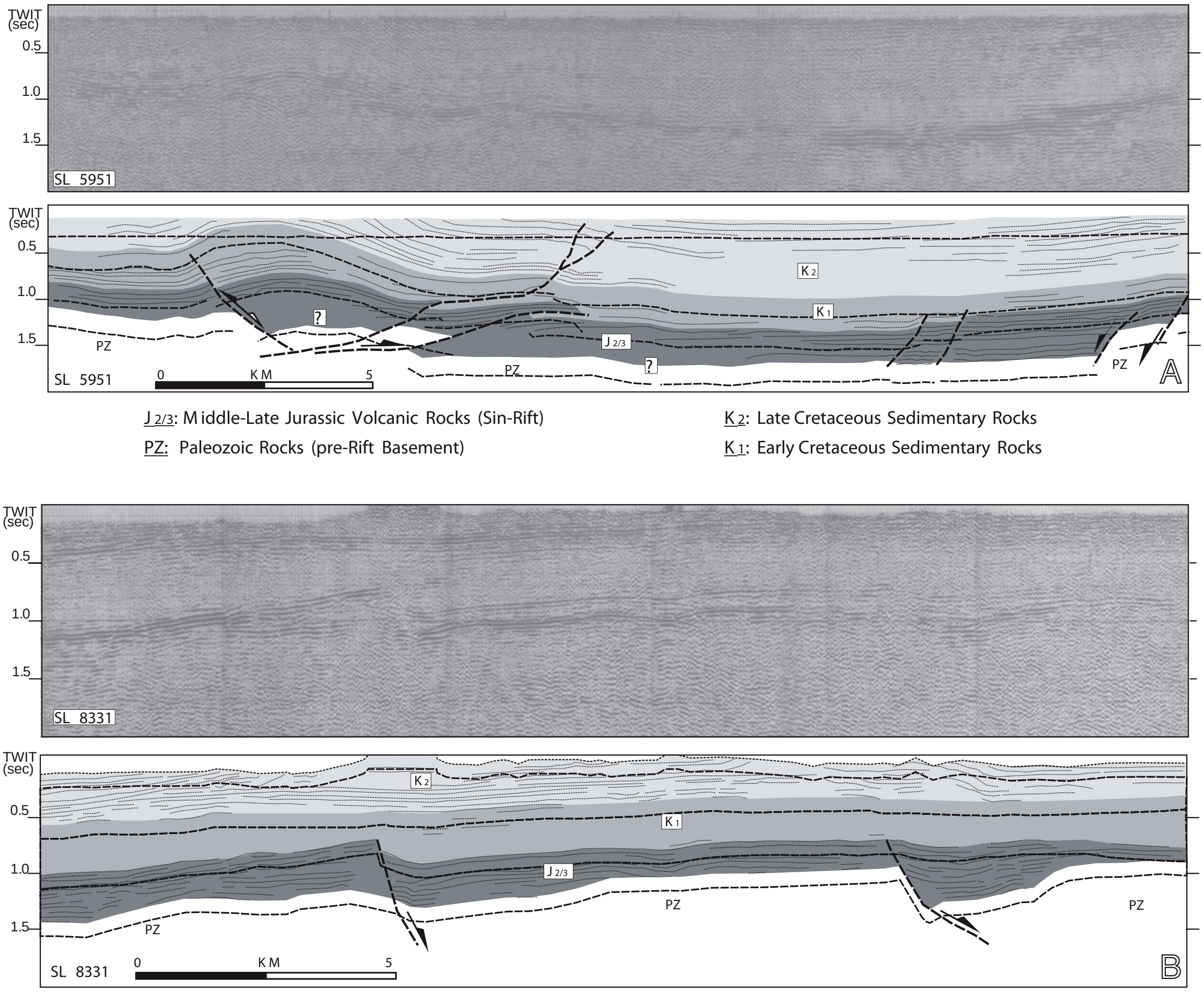

FIGURE 9 | A-B) Seismic profiles and their structural interpretations. In the Figure 9A (section 5951) the compressional structure in the subsurface is the Meseta Chica thrust (Fig. 4). Location of seismic lines is shown in Figure 2.

post-rift accumulations in their hanging-walls. These features may be interpreted as related to tectonic inversion (Fig. 13B) during the development of the outer fold and thrust belt. However, towards the east, the high-angle normal faults do not show evidences of tectonic inversion.

Evidence of Cenozoic compressional deformation is less frequent and present at a wider spacing towards the east of the study region, near 70ºW in the zone of La Pampa (Sylwan *et al.*, 1996).

Andean cleavage

Andean cleavage and pencil lineation in shales of the Río Mayer and Cerro Toro formations (Fig. 10A, C) can be found on both sides of lake Viedma along a 40-50km wide belt, between the Patagonian icefield and 72º45'W longitude (Kraemer, 1991; Fig. 6). These microstructures are a general feature of the entire inner fold and thrust belt (Andean zone) and locally in the highly-deformed western sector of the outer fold and thrust belt (Sub-Andean zone). They show a N-S strike and are associated with mesoscopic folds (wavelengths of 40-50m), which are sometimes very open, as in the south shore of lake Viedma at 49º40'08''S latitude–72º49'52''W longitude (Giacosa *et al.*, 2011).

In the Las Vueltas river lookout (Fig. 10B, C) the axial-plane cleavage is cut by andesitic dikes of the late stage Miocene magmatism of the Fitz Roy plutonic complex (Ramírez de Arellano *et al.*, 2009). These dikes are in turn displaced by Andean thrusts and were correlated with the 14Ma El Chaltén Adakite (Ramírez de Arellano *et al.*, 2009). This relationship, repeated in other sectors of the Cordillera (Kraemer *et al.*, 2002) suggests that the cleavage developed prior to the Miocene, very possibly during the Eocene. We interpret the eastern limit of the Andean cleavage (Fig. 6) as the ductile deformational limit in the Eocene orogenic wedge. This implies that the Eocene shortening caused internal deformation of the rocks reaching as far as 72º45'W and the estimated 11% of shortening in the outer fold and thrust belt, north of lake Viedma, mentioned by Coutand *et al.* (1999) should be regarded as a minimum value.

Andean tectonic evolution

The structural morphology of the southern Patagonian Andes at 49ºS is the consequence of Late Mesozoic-Early Cenozoic orogenic processes. However there is an inherited component derived from the anisotropy imposed by older extensional structures, which developed during the formation of the Austral basin (Figs. 8B; 9A; 12; 13). The effect of earlier structures of Paleozoic age is more uncertain and not clear. The Austral Basin evolved as a back-arc basin during the Late Jurassic and the Early Cretaceous and begins to close in the Late Cretaceous to Cenozoic (Biddle *et al.*, 1986). In this syn-orogenic setting, the sedimentary units from the foreland basin stage were derived from the north and west (Manassero, 1988). Because the progression of deformation and uplift is from the west toward the east (foreland propagation), the first important deformation in the study area started earlier in the Cenozoic (Biddle *et al.*, 1986). Normal faults, formed in the previous extensional stage, determined the structural zonation and the geometry of the structures in the region in subsequent events.

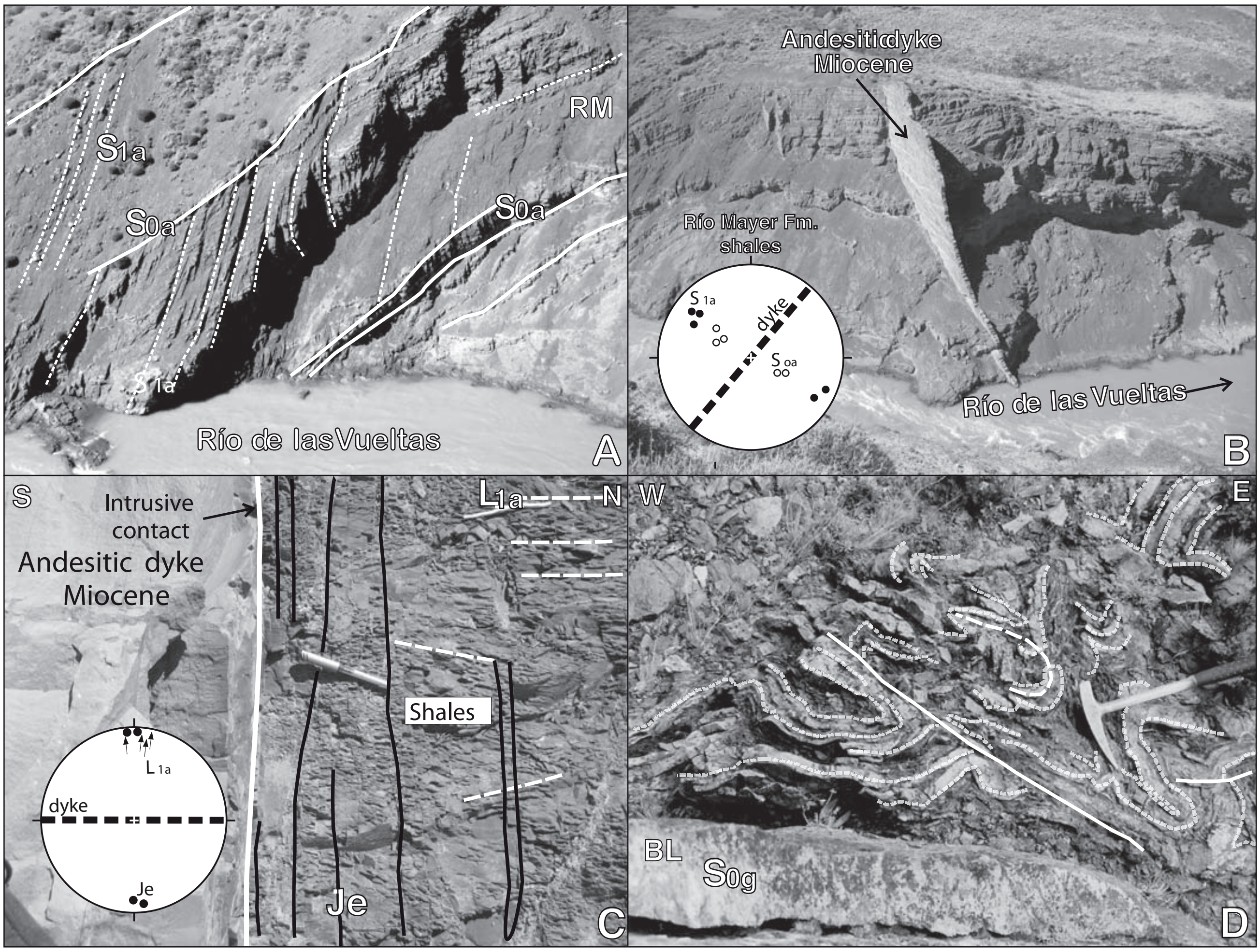

FIGURE 10 | A) The Río Mayer formation (RM) in the Vueltas river. Facies of black shales and laminated sandstones (bedding is S_0a) with Andean axial planar cleavage (S_1a). B) Vertical andesitic dyke, to the Miocene magmatism (Fitz Roy plutonic complex), intruded deformed shales of the Río Mayer formation (RM). Stereonet shows the relations between dyke strike, bedding (S_0a) and axial plane cleavage (S_1a). C) The contact zone between andesitic dyke and shales of the Río Mayer formation in the Vueltas river. Andesitic dyke and cooling joints (Je) cutting the pencil lineation (L_{1a}) in the shales. Stereonet shows the relationships. D) Faulting and refolding in massive ortho-quartzites and pelites of the Bahía de la Lancha formation (BL) in the bridge over Eléctrico river. Refolding is near the fault plane in the hanging-wall of Bosques-Polo thrust. Thin dashed lines indicate bedding traces, solid lines faults and the thick dashed line show the approximate position of the refolded Gondwanan folds.

The regional studies in the Austral Patagonian Andes in Argentina show two major compressive deformation phases during the Andean orogeny (Kraemer *et al.*, 2002; Marenssi *et al.*, 2002, 2003), a deformational phase in the Eocene (Incaic) and another in the Late Miocene to Early Pliocene (Quechua).

In the outer sector of the outer fold and thrust belt, in the Piedra Clavada-Tres Lagos area, the timing of the folding was constrained by the basalts in the Meseta del Bagual, which are correlated to the Upper Miocene Strobel basalt. A similar relation is indicated in the region of lake Cardiel by Ramos (1982), who used radiometric ages to constrain the age of the more pervasive deformation and uplift to before 8.6±0.6Ma (Late Miocene). Towards the foreland, at 70ºW in the area of the La Pampa anticline, the extensional structures are interpreted as being active until the deposition of the Río Mayer formation. The positive inversion of the anticline is interpreted as post-Middle Miocene, according to the level of structural parallelism between the bottom of the Patagonia formation and the Cretaceous strata (Sylwan *et al.*, 1996).

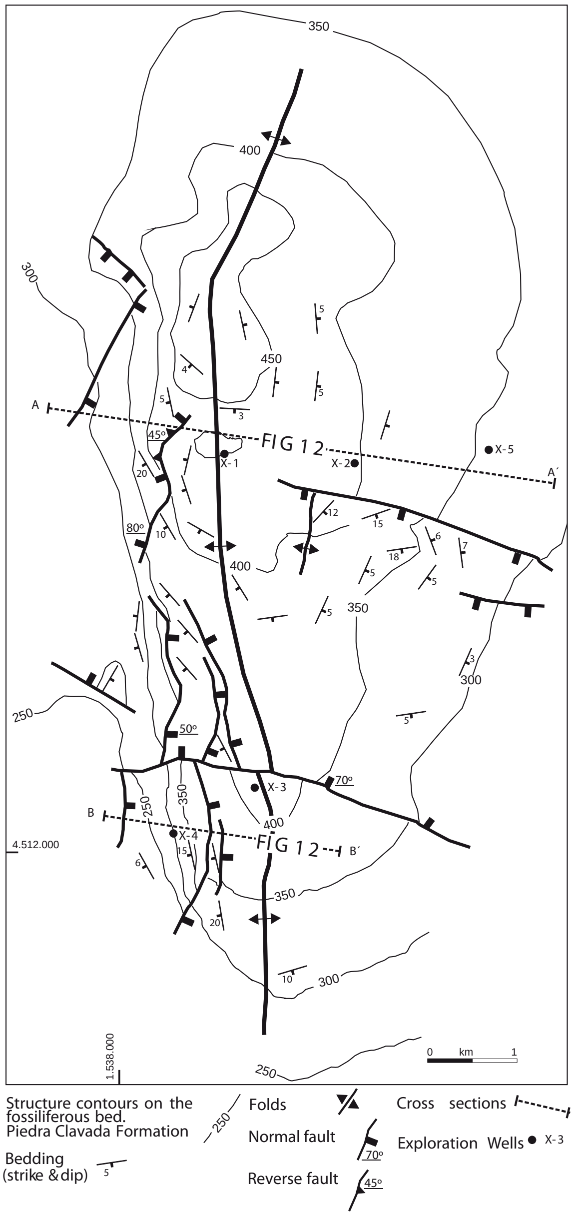

FIGURE 11 | Structural map of the Piedra Clavada anticline. Based on Ferello (1955) and data from YPF exploratory wells. Location is shown in Figure 2.

The Cenozoic evolution of the fold and thrust belt in Argentina was explained by Kraemer *et al.* (2002) as consisting of two phases. The first resulted from the progressive thickening of an orogenic wedge that incorporated foreland material at its apex as predicted in the critical wedge model of Dahlen (1990) and Williams *et al.* (1994). In the Eocene, the deformation propagated towards the foreland and the wedge thickened through brittle reactivation of some extensional Mesozoic faults in the inner fold and thrust belt. The final stage, which may have reached the Pliocene, was caused by the reactivation of Mesozoic extensional structures and preserved in the eastern distal sector.

An episode of sedimentation in a retroarc foreland basin is recognized between both deformation phases, represented by the Eocene sedimentary wedge (depocenter to the W), that originated from the erosion of the orogenic belt, located further west. As a result, the continental sediments of the Río Leona formation (Upper Eocene to Lower Oligocene) unconformably cover the Middle Eocene marine sediments of the Man Aike formation (Marenssi *et al.*, 2002, 2003).

Miocene intrusive rocks of the Fitz Roy plutonic complex were emplaced between 19 and 14Ma (Ramírez de Arellano *et al.*, 2009). Later, at 14Ma, the El Chaltén Adakite intruded (Ramos *et al.*, 2004).

From the Late Miocene to Pliocene, the Strobel and La Siberia basalts (Ramos, 1982, Gorring *et al.*, 1997) flowed along a broad area (Fig. 4). This magmatism was possibly related to the formation of an asthenospheric window, following the collision of the Chile Ridge against the Pacific subduction zone (Ramos and Kay, 1992), giving rise to a new compressive phase (Quechua) and the migration of the orogenic belt through the foreland.

DISCUSSION

Revision of the available structural and tectonic information, the new data from the regional geological mapping, and the reinterpretation of seismic sections (Cobos *et al.*, 2008; Giacosa *et al.*, 2011) suggests that several geologic features are repeated across the Patagonian Andes. The effects of the structures from previous orogenies determine the development of the Mesozoic rift systems, and how the following tectonic inversion controlled the morpho-structural zonation and the characteristic structural styles of the Cenozoic Andean belt (Figs. 8B; 9; 13).

Based on our observations we propose alternative interpretations for some geologic characteristics typical of the southern Partagonian Andes. This is the case with the major transverse structures in the Cordillera, coinciding with lakes San Martín, Viedma and Argentino, known in the geologic literature as the Mackenna, Viedma and Argentino lineaments. The significance of these structures have been discussed by different authors.

Nullo *et al.* (1978) associated these lineaments to "regmatic" structures that were reactivated as wrench zones during the Gondwanan orogeny. These authors indicated that the NNE trending (N05º-10ºE) folds were associated with the main Gondwanan deformation ("dominant Variscan style"), while the W-E trending folds were related to dragging during the subsequent transpression. However, our data indicate that the W-E structures in the Paleozoic rocks are much more extended in the region as it reaches areas distant from the Mackenna and Viedma lineaments. On the other hand, our interpretation, different from that of Nullo *et al.* (1978), considers the W-E fabric as the principal structure (Dg_1) of the Paleozoic rocks, while the NNE strikes are due to a later deformation (Dg_2) (Fig. 5A).

Kraemer (1994) has studied the influence of these lineaments during the Jurassic rifting and the development of the Austral basin. Kraemer indicates that they correspond to transfer zones with dextral to dextral-normal kinematics formed during the W-E regional extension through N-S normal faults.

According to our interpretation from the Paleozoic fabric in the surroundings of lake San Martín, it is possible to suggest that the transfer zones may have developed by reactivation of the N-vergent W-E Gondwanan faults. The N-vergence may have caused the southwards inclination of the transfer zones, and the progressive deepening of the basin in that same direction in the Mesozoic (Arbe, 1987; Kraemer, 1994; Ghiglione *et al.*, 2009).

In the Jurassic and in the Early Cretaceous, the heterogeneous distribution of the extension, separating distinct areas by transfer faults, plays a decisive role in the style and geometry of the structures developed during the compressional Andean episode. This deformation is conditioned by the different thickness and age of Late Cretaceous sediments to the north and south of lake Viedma. Apart from the dissimilar thicknesses of the pre-orogenic sedimentary deposits, it is also significant that an important unconformity (of some 10My) exists in the sediment representing a depositional lapse during the Albian-Cenomanian which is the age of the first syn-orogenic deposits south of lake Viedma (Aguirre Urreta, 1990; Arbe, 1987; Kraemer, 1994). During the Eocene, the ductile deformation that accompanied the thickening of the fold and thrust belt seems to have reached a similar position, as indicated by the front of tectonic foliation, near 72º42'W on both sides of lake Viedma (Fig. 6). Finally, except for some differences in the structural style due to the different thickness of the Cretaceous sediments, the Late Miocene deformation also produces a similar structural zonation on both sides of lake Viedma. All this suggests that the reactivation of these transfer extensional faults is pre-Eocene in the study area.

The area between lakes San Martín and Viedma records the influence of the previous extensional structures on the nucleation and evolution of the new structures. However this influence decreases gradually until the Miocene, when no significant changes are seen.

Regarding the presence of regional N-S strike-slip faults as described by some authors (*e.g.*, Coutand *et al.*, 1999, Spikermann *et al.*, 2006), our data support the hypothesis for local dextral transfer zones, which accommodate the W-E continental extension during

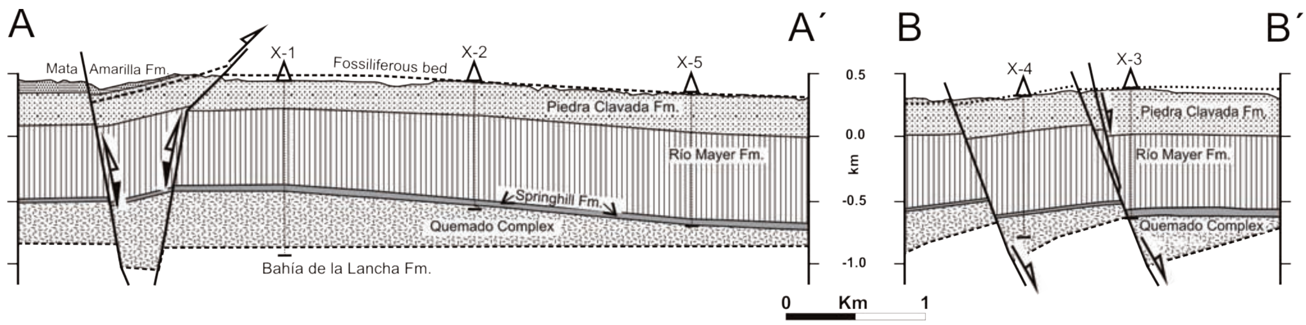

FIGURE 12 | Structural cross-section of the Piedra Clavada anticline. Based on Ferello (1955) and data from YPF exploratory wells X-1, X-2 and X-5. Location is shown in Figure 11.

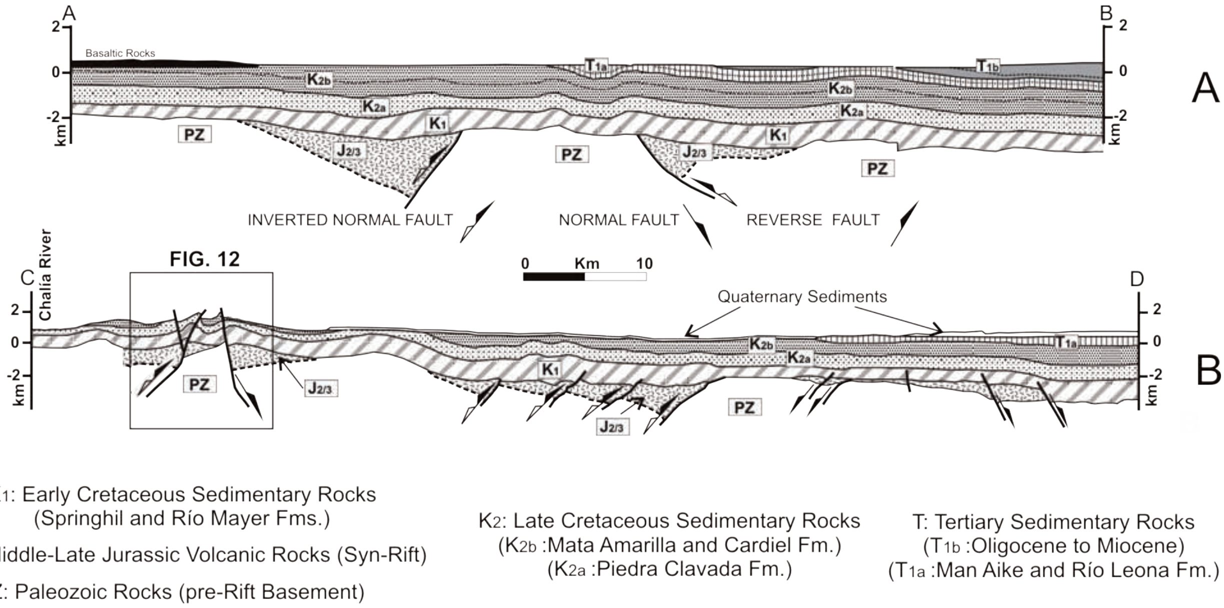

FIGURE 13 | A) AB cross-section (not balanced) based on seismic line BSCA 91-082. B) CD cross-section (not balanced) based on seismic line BSCA 90-002. Location is shown in Figure 2.

the Jurassic rifting. Later, these transfer zones are reactivated during the subsequent Andean compressional events, especially during the pre-Eocene deformation. Furthermore, it is possible to geometrically relate these transfer zones with the WNW penetrative fabric (Dg_1) of the Gondwanan orogeny.

Finally, rocks of the Fitz Roy Plutonic complex are close to the E-vergent Torre and Fitz Roy thrusts. Their syntectonic emplacement with thrusting was proposed by Coutand *et al.* (1999) because these rocks have solid-state deformation fabrics (Ramírez de Arellano *et al.*, 2009). For the non-deformed subvolcanic rocks of this complex, these authors propose a correlation with the El Chaltén Adakite (Ramos *et al.*, 2004) and suggest an intrusion under post-tectonic extensional conditions.

CONCLUSIONS

The structures developed during the Gondwanan orogeny (possibly Permian) in the southern Patagonian Andes of Argentina, between 49º and 49º30' S latitude, are isoclinal and overturned WNW trending folds and N-vergent duplexes (Dg_1), which are subsequently deformed by NNE open folds (Dg_2).

The pattern of the Gondwanan Dg_1 deformation may have controlled the WNW transfer extensional zones developed during the Jurassic rifting.

The style and geometry of the pre-Eocene structures and the thickness and age of first syn-orogenic sediments (Late Cretaceous) to the north and south of lake Viedma were controlled by the Jurassic extensional transfer zones.

The Andean structural organization that developed during the Eocene and Late Miocene-Pliocene compressive deformations resulted in a N-S thick-skinned fold and thrust belt. This belt shows, from W to E, three morphostructural zones: Andean, Sub-Andean and Extra-Andean. The first forms the inner fold and thrust belt, while the other two are part of the outer fold and thrust belt. Each morphostructural zone is characterized by specific topographic and structural features.

The inheritance of the N-S normal faults from Jurassic rifting is the main control of this structural zonation, while the structural styles of the Sub-Andean and Extra-Andean zones seem to be influenced by the different sedimentary thickness in the N-S sense, which are probably related to the extensional transfer zones.

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