STRUCTURE AND EVOLUTION OF THE AUSTRAL BASIN FOLD-THRUST BELT, SOUTHERN PATAGONIAN ANDES

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ABSTRACT

This study focuses on the evolution of the Southern Patagonian Andes fold-thrust belt and the adjacent non-deformed foreland of the Austral basin between 49°45' and 52°00'SL. This sector involves mainly Late Cretaceous sequences of the first regressive cycle (Lago Viedma Cycle) of the Austral basin foreland stage, and Campanian to Paleogene sequences associated with tectonic uplift of its western boundary. From a stratigraphic-sedimentary point of view, a first-order increase in the fill-thickness and depth to the basement exists from north to south including the presence of deeper depositional environments in the same direction. Furthermore, there are strong along-strike variations in width and lateral position of the structural domains following the same trend. Based upon previous interpretations, is concluded that the distribution of extensional depocenters from the early extensional phase of the basin controlled these important sedimentary and structural N-S contrasts. Furthermore, in our presented model, East-west oriented transition zones are interpreted as accommodation zones separating synrift sub-basins.

Keywords: *Austral basin, Foreland basin, Cretaceous, Extensional depocenters.*

RESUMEN: *Estructura y evolución de la faja plegada y corrida de la cuenca Austral, Andes Patagónicos Australes.* Este estudio se concentra en la evolución de la faja plegada y corrida de los Andes Patagónicos Australes y del antepaís adyacente no deformado de la cuenca Austral entre los 49°45' y 52°00'SL. Este sector involucra principalmente secuencias cretácicas superiores del primer ciclo regresivo (Ciclo Lago Viedma) de la etapa de antepaís de la cuenca Austral, y secuencias campanianas a paleógenas asociadas con el levantamiento tectónico de su límite occidental. Desde el punto de vista estratigráfico sedimentario, existe un incremento de primer orden de norte a sur en el espesor del relleno y la profundidad del basamento incluyendo la presencia de ambientes deposicionales más profundos en la misma dirección. Se han detectado fuertes variaciones a lo largo del rumbo en el ancho y la posición lateral de los dominios estructurales en la misma dirección. Siguiendo propuestas previas del sector norte de la zona estudiada, se interpretan estos importantes contrastes sedimentarios y estructurales N-S como controlados por los depocentros extensionales y, por lo tanto heredados de rasgos de una fase extensional previa de la cuenca.

Palabras clave: *Cuenca Austral, Etapa antepaís, Espesor, Cretácico, Depocentros extensionales.*

INTRODUCTION

The Austral (Magallanes) basin has been affected by eustatic sea level changes and different deformational regimes since Mesozoic times, resulting a complex tectonostratigraphic pattern (Figs. 1 and 2). In the sector under study the deformational regime has changed from a Middle Jurassic-Hauterivian extensional kinematics to a Barremian - Neogene overall compressional setting, although a significant diachronicity occurred through basin.
Mid to Late Jurassic basal sequences (known as Tobífera, El Quemado, Chon Aike or Lemaire Formations; Fig. 3), which constitute the lower structural package of the fold-thrust belt, were deposited in grabens, in a regional context of lithospheric thinning and continental rifting (Wilson 1991, Uliana *et al.* 1989). Upper Jurassic stretching was maximum at the western continental margin, where the Rocas Verdes marginal basin developed oceanic crust. This deepest sector was filled by distal turbidites (Fig. 1; Calderón *et al.* 2007).
Mechanic subsidence and stretching attenuated towards the eastern craton, as shown by the presence of shallower sequences, dominated by continental to hemipelagic sequences (Arbe 1989; Manassero 1988). The synrift sequences are uncomfortably overlie by extended lower Cretaceous sag deposits of the arenaceous Springhill (Zapata- Río Mayer infe-

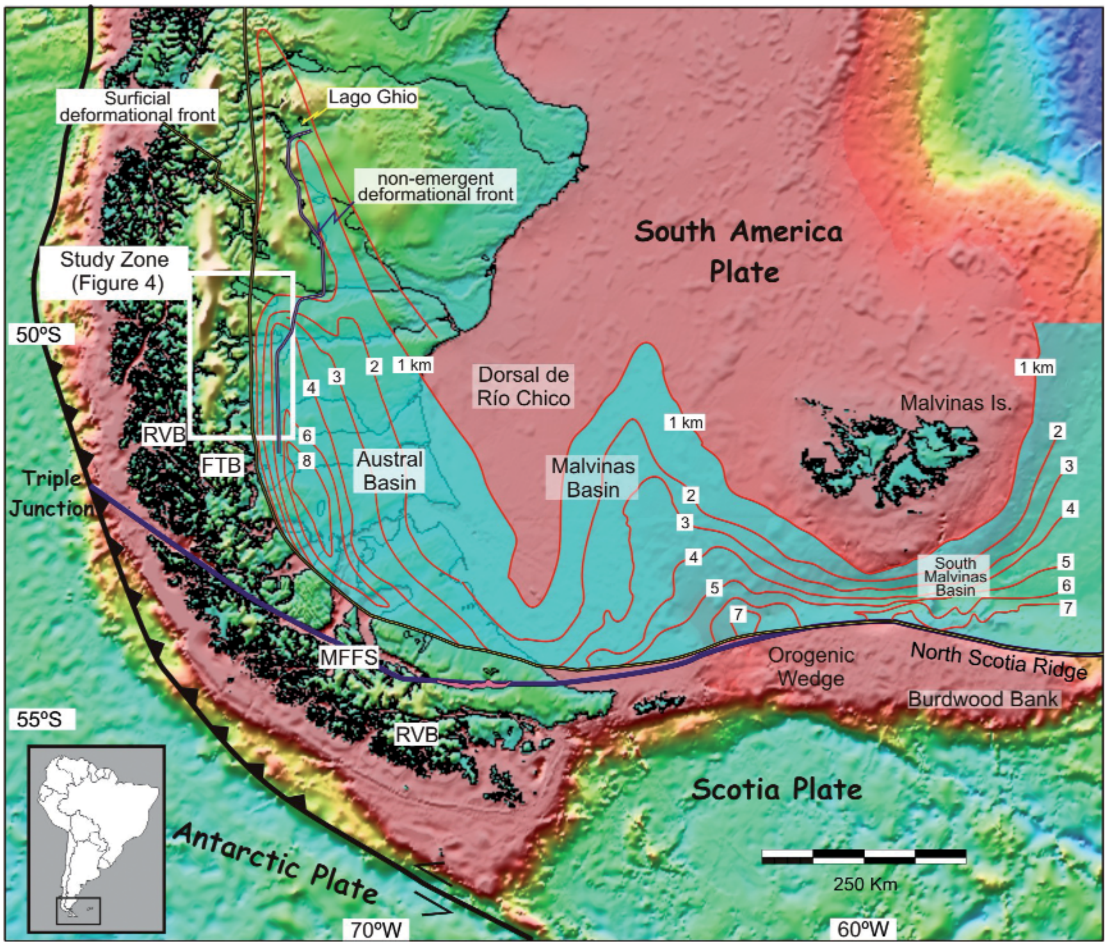

Figure 1: Location of study zone showing main morphostructural units from Austral and neighboring basins. Contours indicate foreland sediment thickness within the undeformed depocenters in kilometers. FTB - fold-thrust belt; RVB - Rocas Verdes Marginal Basin.

rior) and pelitic Palermo Aike (Inoceramus inferior, Pampa Rincón) formations (Fig. 3) recognized, respectively, as the main petroleum source and reservoir rock of the Austral Basin ("Sistema Inoceramus inferior - Springhill"; Pedrazzini and Cagnolatti 2002, Zilli *et al*. 2002). Synrift and Sag sequences were overlie by Upper Cretaceous regressive sequences of the first foreland-basin stage coming from the north and west, developing angular unconformities (Coutand *et al*. 1999) since Aptian (Arbe 1989; Kraemer 1998, 2003) or Turonian times (Fildani *et al*. 2003).

Over the ensuing 100 Myr, contractile deformation propagated eastward, generating at least four orogenic sequences with an important westward provenance of sediments from the mountains towards the undeformed foreland (Arbe 1989, 2002, Kraemer 2003). The coarser proximal facies of these sequences, probably representing pulses of accelerated uplift and propagation of the deformational front, are now involved in the fold-thrust belt, where they are separated by paraconformities or angular unconformities representing long hiatuses (Lago Argentino and Western Austral basin in figure 3). Their foreland-distal equivalents, consisting of medium to fine grain sediments, are separated by paraconformities with shorter hiatuses and some of them represent Upper Cretaceous to Paleocene reservoirs (Piedra Clavada, Mata Amarilla, Campo Boleadoras, María Inés, Zona Glauconítica; known as the "Sistema Inoceramus inferior - Magallanes inferior "; Marinelli 1998, Cagnolatti and Miller 2002, Zilli *et al*. 2002, Limeres and Dellapé 2005).

Although most of the working petroleum and gas systems are located in the stable slope and platform of the basin, important gas reservoirs are associated with the fold-thrust belt such as the Tranquilo (Chile) and Glencross (Arg.) gas fields (Fig. 2). There also exists a number of detected resources that have not been tested properly due to technical limitations, for example, wells Cerro Palique.es-1 (Paso Furh block) and Cancha Carrera.es-1 (Tapi Aike block) (Fig. 2) stressing the promising potential of the fold-thrust belt.

The present work focuses on the Patagonian Andes fold-thrust belt and the adjacent non-deformed foreland of the Austral basin between 49°45' and 52°00 'SL (Figs. 1 and 4), including the exploratory blocks Paso Fuhr, Tapi Aike and Río Turbio (Fig. 2). The studied sector involves mainly Late Cretaceous sequences of the first regressive cycle (Lago Viedma Cycle), and Campanian to Paleogene se-

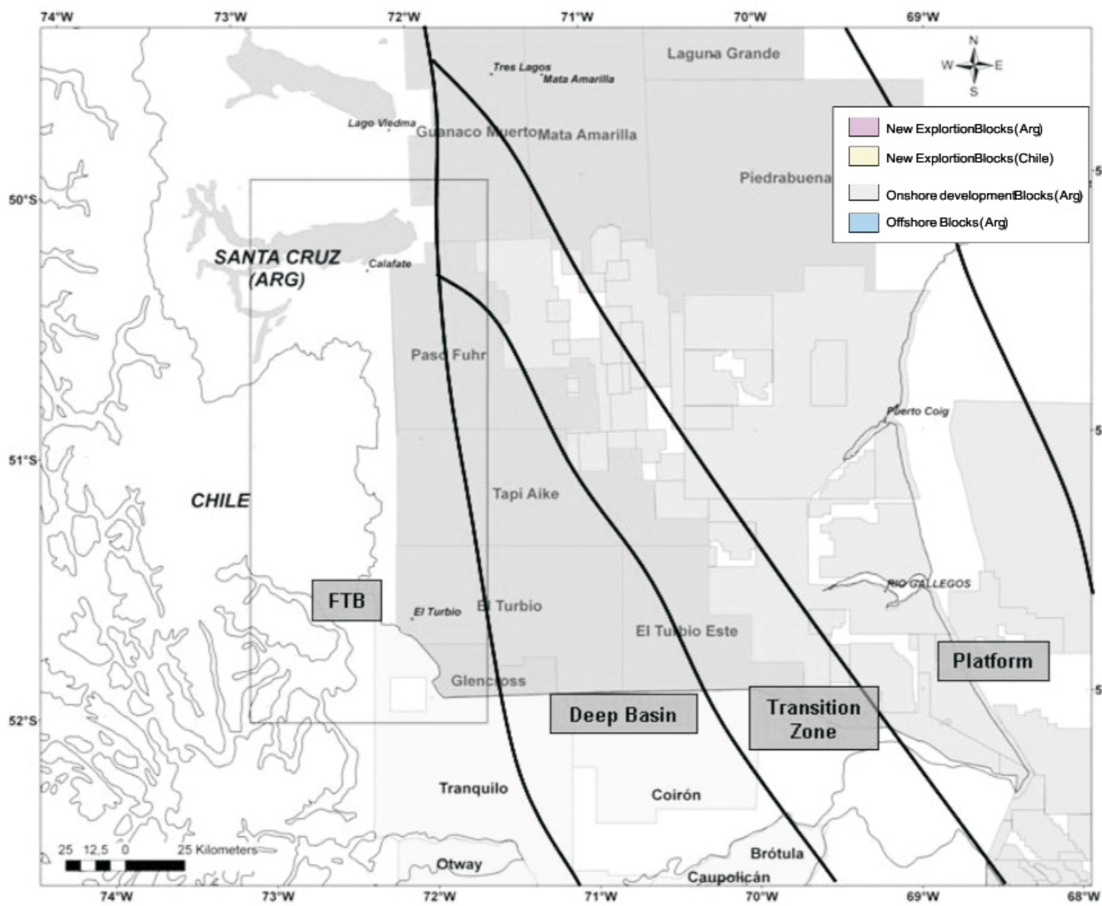

Figure 2: Oil and gas blocks of Austral basin in Santa Cruz Province (Argentina) and Chile, showing main morphostructural units and studied exploratory fields. FTB - Fold and thrust belt.

quences associated with tectonic uplift (Arbe 1989, 2002, Kraemer and Riccardi 1996, Malumián *et al.* 2000).

From a stratigraphic-sedimentary point of view, the sector includes a first-order increase in the fill-thickness and depth to basement from north to south including the presence of deeper depositional environments in the same direction. We detected strong along-strike variations in width and lateral position of the structural domains in the same trend (Fig. 4). According to an idea first proposed by Arbe (1989) and followed by Kraemer and Riccardi (1996) and Kraemer (1998) for the northern sector of the study zone, these important sedimentary and structural N-S contrasts are interpreted as being controlled by the distribution of extensional depocenters from the early extensional phase of the basin.

An account of the structural and stratigraphic features of the region under study is given, while the relation between compressional faulting and previous extensional depocenters is discussed with the aim of exploring the presence of petroleum-gas systems.

GEOLOGICAL SETTING

Due to to the fact that is surrounded by evolving tectonic boundaries (Fig. 1), the Austral basin was affected by extension and rifting during Gondwana break-up (Biddle *et al.* 1986, Uliana and Biddle 1988, Uliana *et al.* 1989), and was subsequently influenced by Andean compressional uplift as a result of the interaction between the subducting oceanic plates from the Pacific basin (Farallon-Aluk-Nazca-Antarctic plates) and the overriding South America plate (Ramos 1989, Yrigoyen 1989, Coutand *et al.* 1999, Diraison *et al.* 2000, Somoza and Ghidella 2005, Ghiglione and Cristallini 2007).

The metamorphic basement of the region, located along the pacific archipelago (Fig. 1), was generated from late Paleozoic to early Mesozoic times as an accretionary prism developed along the Panthalassic (Pacific) margin of Gondwana (Dalziel, 1981, Hervé *et al.* 1981, Mpodozis and Ramos 1990). The western Basement domain is composed of the Paleozoic Eastern Andes Metamorphic Complex, including polideformed metaturbidites of Late Devonian to Late Permian age (Calderón *et al.* 2007).

Initial subsidence began in almost all of the Patagonian hydrocarbon-producing basins during the Triassic-Jurassic continental rifting of southern South America (Uliana *et al.* 1989). As a consequence, one of the largest known silicic igneous provinces (LIP) was formed in Patagonia, dominated by rhyolitic ignimbrites, which form a bimodal association with minor mafic and intermediated lavas

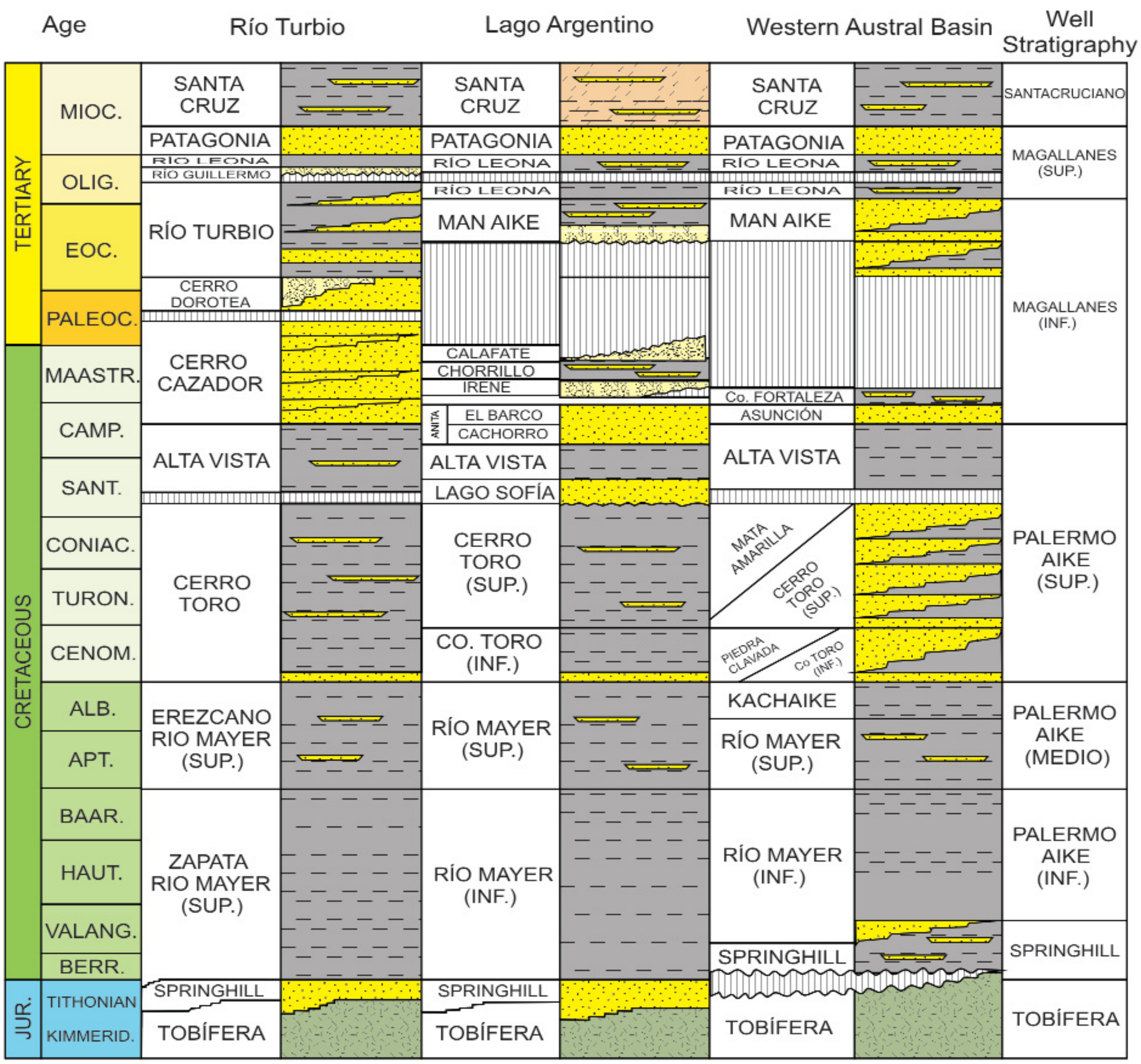

Figure 3: General chronostratigraphic diagram for Austral (Magallanes) basin taken from Ambrosio (2003) after Arbe (1989).

(Pankhurst *et al.* 1998, 2000). A clear diachronism is recognized between the Early-Middle Jurassic volcanism of eastern Patagonia (Marifil and Chon Aike formations) and the Middle-Late Jurassic volcanism of the Andean Cordillera (El Quemado and Tobífera formations; Fig. 3), showing a regular decrease of ages from the ENE (187 Ma) to the WSW (144 Ma) along 650 Km (Pankhurst *et al.* 1998, 2000, Féraud *et al.* 1999). This progressive stretching culminated towards the SSW with the generation of oceanic crust in the Rocas Verdes marginal basin along the Pacific margin of the continent during Late Jurassic times (Dalziel 1981, Mukasa and Dalziel 1996). The northern remnants of the sea floor and bimodal magmatism of the marginal basin are grouped into the Sarmiento Ophiolite Complex, located SW from the study zone (Fig. 1) active between 152 and 142 Ma (Calderón *et al.* 2007).

The Late Jurassic extensional event, which was dominant in the Austral and Malvinas basin, produced several depocenters controlled by normal faulting (Biddle *et al.* 1986, Diraison *et al.* 2000), filled up by an heterogeneous suite of siliceous volcanic and volcaniclastic rocks called Lemaire Formation in Argentina (Caminos *et al.* 1981, Yrigoyen 1989) or Tobífera Formation in Chile (Thomas 1949). In the Austral basin, these rocks are absent on some basement highs, but can reach over 2000 m in constrained extensional depocenters (Biddle *et al.* 1986). The dominant trend of the early Mesozoic rifting was mainly NW to NNW as shown in the eastern Austral basin by seismic lines from the undeformed foreland depocenter (Biddle *et al.* 1989, Uliana *et al.* 1989). Towards the west, the Late Jurassic rocks form elongated outcrops with a N to NNE trend that represent an inverted main extensional depocenter (Fig. 4).

An uppermost Jurassic-lower Cretaceous

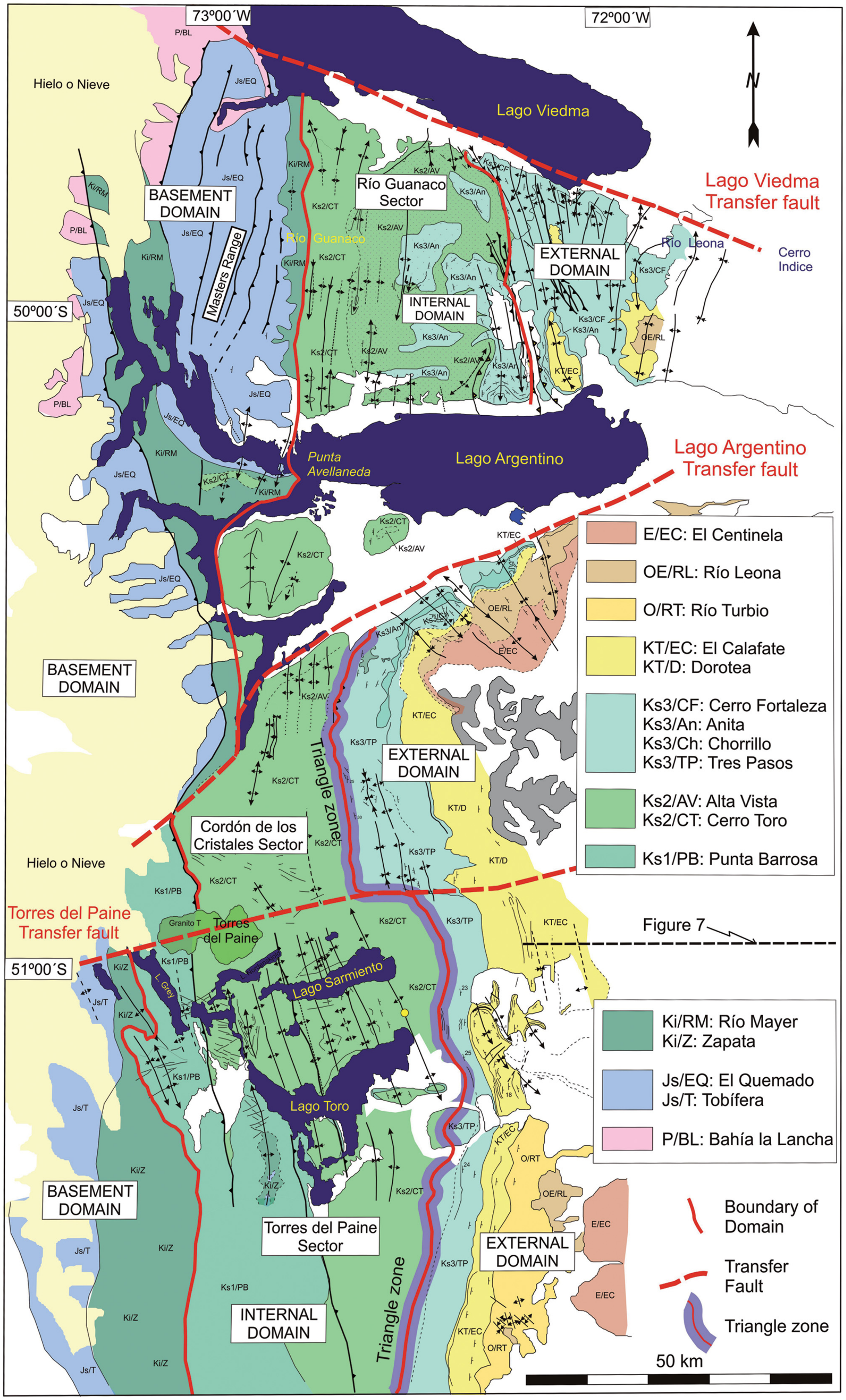

Figure 4: Geological map of the study zone from collected field data and after SERNAGEOMIN (1982), Kraemer (1996, 2003), Malumián *et al.* (2000).

transgressive siliciclastic wedge represented by the Springhill and Pampa Rincón Formations (Fig. 3; Arbe 1989, 2002, Kraemer *et al.* 2002) follows the Upper Jurassic rift-related section. These retrogradational sedimentary sequences took place while the basin passively subsided during the sag phase, characterized by minimal faulting through the Early Cretaceous (Uliana *et al.* 1989, Ramos 1989). The Springhill Formation is a sandstone succession of retrogradational fluvial, shoreline, and shallow-marine sandstones that represents the major hydrocarbon reservoir of the Austral and Malvinas basins (Biddle *et al.* 1986).

A typical foreland-phase started during the early Cretaceous, dominated by flexural subsidence and cratonward migration of sedimentary depocenters related to Andean uplift and expansion (Yrigoyen 1989, Kraemer 2003). Late Cretaceous to Tertiary units were derived from the north and west, show a progressive onlap geometry from west to east (Biddle *et al.* 1986, Manassero 1988) and development of synsedimentary structures since Late Cretaceous (Coutand *et al.* 1999). Hinterland uplift and erosion caused the deposition of coarse clastic sediments that indicates the onset of a foreland phase in the Austral basin evolution (Biddle *et al.* 1986). The age of this first coarse clastic infill in Torres del Paine (Wilson 1991) is not older than Turonian (92 ± 1 Ma), on the basis of detrital zircon provenance analysis from the Patagonian Andes (Fildani *et al.* 2003). However, tectonic uplift could have started earlier, during late Hauter-Barremian, to the northwest of our study zone, as shown by an angular unconformity between Springhill and previously deformed Aptian sequences in Lago Ghio (Fig. 1, Arbe 1989, 2002). Afterward, the offsetting effects of constant basement uplift in the hinterland and forward imbrication in the thin-skinned fold-thrust belt sustained the progression of deformation (Kraemer 2003, Ghiglione and Ramos 2005, Ghiglione y Cristallini 2007). Compressional deformation have been associated with a major component of right lateral wrenching parallel to the Cordillera (Coutand *et al.* 1999).

GEOLOGY AND STRUCTURE OF THE PATAGONIAN ANDES FOLD-THRUST BELT

On the basis of mechanical stratigraphy, the lithostratigrafic units of the belt can be divided into four main structural packages; from bottom to top these are (Figs. 3 and 4): (1) Paleozoic metamorphic rocks (Bahía La Lancha and Río Lácteo Formations) intruded by Tertiary plutonic and volcanic rocks from the Patagonian batholith, which constitute the crystalline basement; (2) Upper Jurassic marine synrift sequences; (3) Lower Cretaceous platform sequences from the sag stage (Springhill Formation); and (4) Upper Cretaceous to Neogene continental and marine strata from the foreland basin stage.

The structure of the region under study can be divided into three tectonomorphic zones, including from west to east (after Kraemer *et al.* 2002; Fig. 4): the Basement thick-skinned brittle domain, the Internal ductile fold-thrust belt and the External fold-thrust belt.

Basement domain

The Basement domain is bounded to the east by the irregular Upsala thrust with eastern vergence (Fig. 4-6), while its west limits shows predominately a westward vergence (Kraemer 1998). The Late Jurassic synrift deposits uncomformably overlie the Paleozoic basement near its eastern boundary, while all the sequence is intruded by Jurassic to Neogene calc-alkaline continental margin magmatic arc rocks from the Patagonian Batholith (Calderón *et al.* 2007). The Late Jurassic rocks form elongated outcrops with a N to NNE trend that represent an inverted main extensional depocenter, thrusted towards the east over the fold-thrust belt (Kraemer 1998, Pizzio *et al.* 2008).

Some early Cretaceous cover of this depocenter is concentrated near the eastern boundary. The best outcrops showing partially to totally inverted depocenters are located between Argentino and Viedma lakes, in the western margin of Río Guanaco (Kraemer 1998) and in Punta Avellaneda (Fig. 4). In this sector there are westward verging back-thrusts along the Masters Range uplifting eastward-thinning jurassic synrift deposits, indicating the total inversion of the westward boundary of an extensional depocenter (Kraemer 1998).

Internal fold-thrust belt

The internal fold-thrust belt is composed of ductile structures, characterized by N-S trending thrusts, backthrusts and folds (Fig. 4-6). This domain is bounded to the west by the Upper Jurassic positively inverted and exposed depocenters. The structural packages involved are mainly Late Cretaceous sequences of the first regressive cycle associated with tectonic uplift (Lago Viedma Cycle), composed from north to south of the formations Puesto El Moro, Piedra Clavada-Mata Amarilla, Lago Viedma-Puesto El Alamo and Cerro Toro (Fig. 2), belonging to the Mata Amarilla subcycle (Arbe 2002).

There are strong along-strike variations in width of this ductile domain that take place in discrete ~E-W transition zones (transfer faults from Fig. 4). In our study zone, at least three transition zones are recognized, the two northern zones coinciding with Viedma and Argentino lakes, while the southern one is located at ~50º55`LS, just north of Sarmiento lake. These transition zones or transfer faults are limiting the Río Guanaco, Cordón de los Cristales and Torres del Paine sectors (Fig. 4). From north to south, the internal domain get increasingly wider and an overall westward shift of its position take place (Fig. 4-6).

A radical change in the Late Cretaceous-early Tertiary sedimentary facies also takes place along the same N-S trend. This change involves a southward shift from prograding continental and litoral facies to marine and deep marine facies that occurs at the latitude of Lago Viedma (Río Leona-Cerro Indice; Fig. 4) (Arbe 1989,

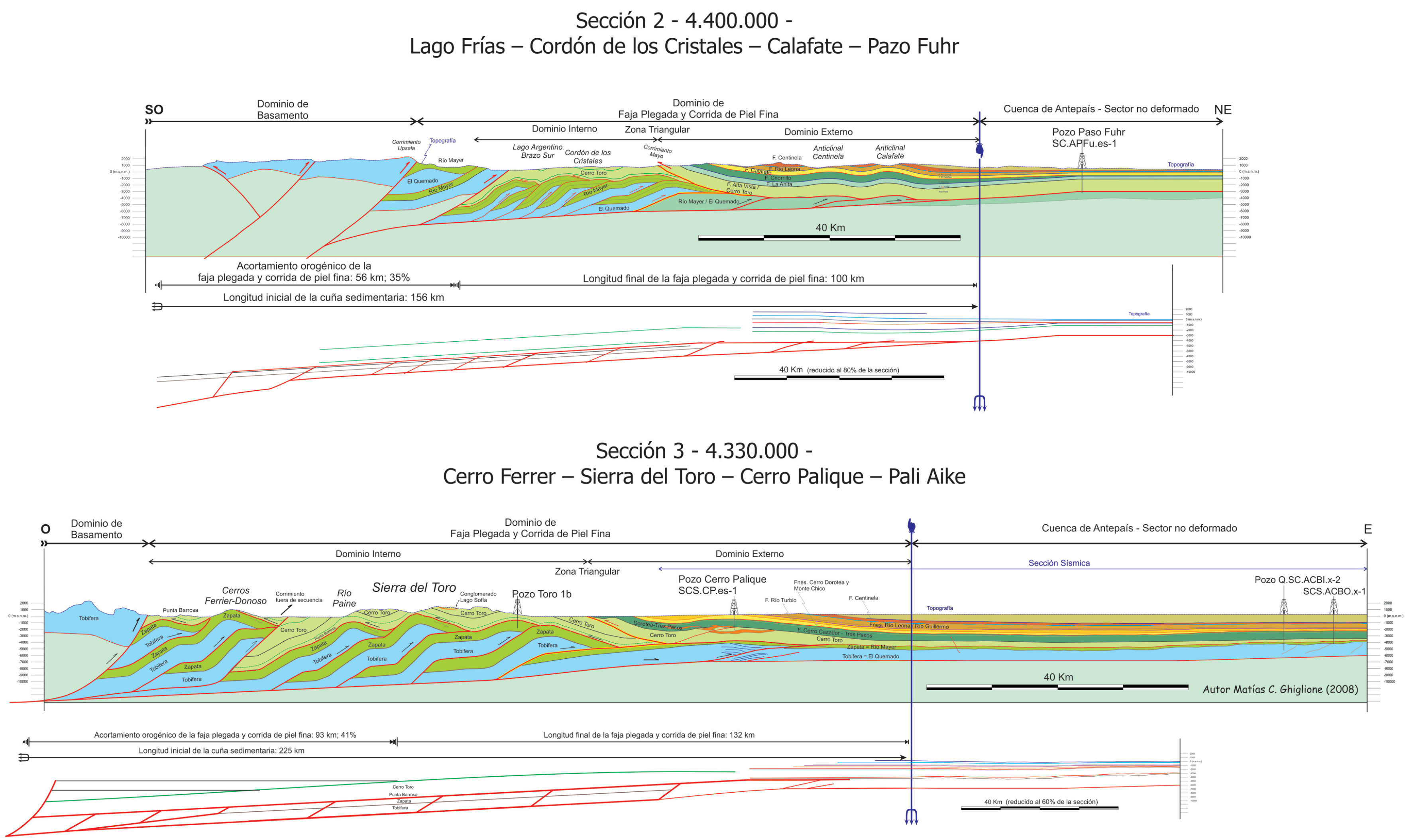

Figure 5: Structural sections (see figure 4 for location and figure 6 for fault correlation).

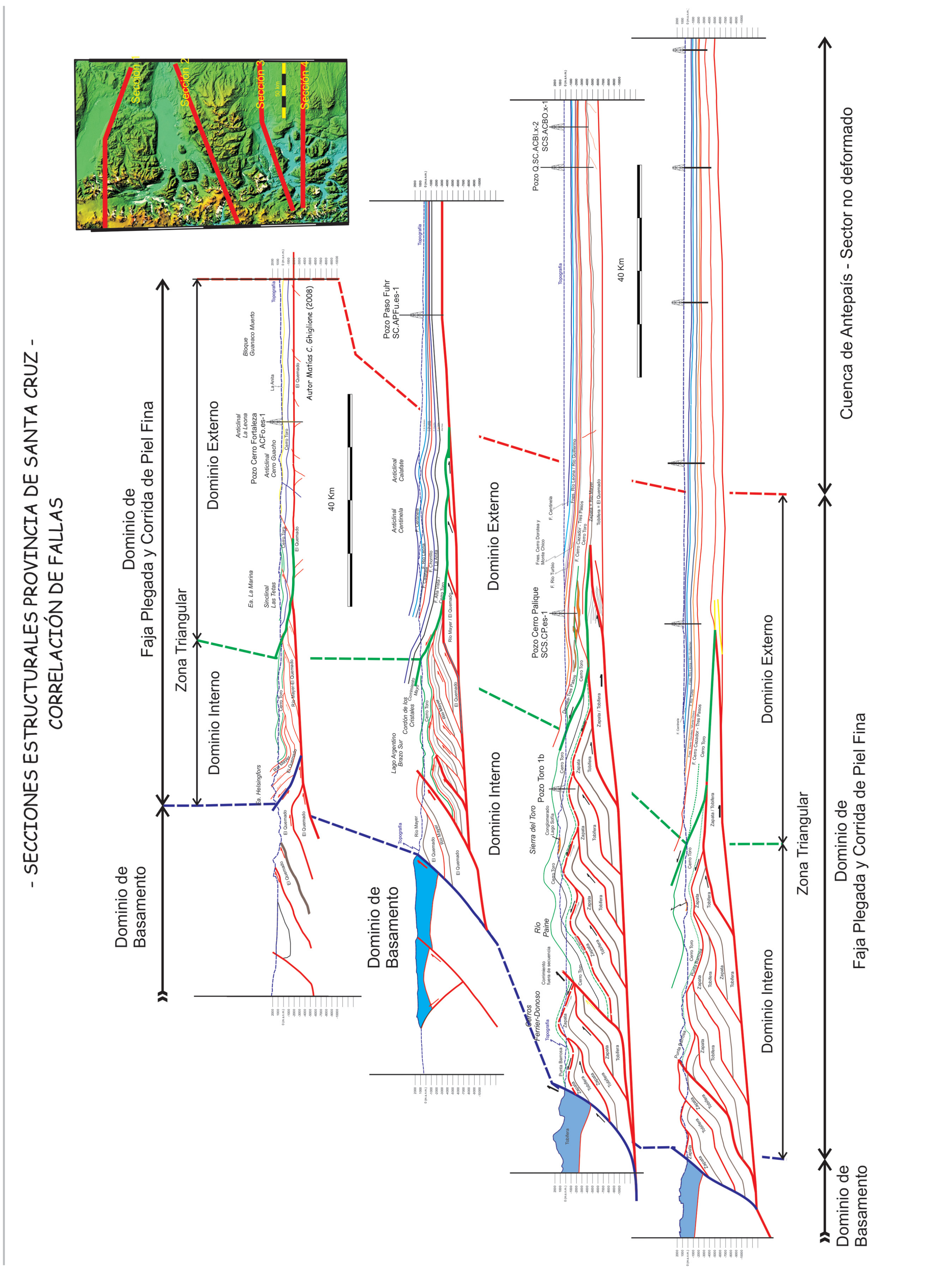

Figure 6: Fault correlation, see figure 4 for location.

2002). Total sedimentary thickness and depth to basement also shows a strong increase towards the south around this sector (Figs.1 and 6).
Further north, in the northern sector of the basin, the Internal domain as defined here losses expression, and is replaced by a triangle zone where the Paleozoic basement interact with Late Jurassic to Tertiary deposits (Ramos 1989). In this northern sector marine sequences are replaced by much thinner equivalent continental deposits of the Río Tarde and Cardiel Formations (Ramos 1989).

External fold-thrust belt
The external thin-skinned domain, involving Campanian to Paleogene sequences (Arbe 1989, 2002, Kraemer and Riccardi 1996, Ambrosio 2003, Marenssi *et al.* 2005; Fig. 3), is thrusted with westward vergence forming a frontal monocline, while thin-skinned folds and thrust with eastward vergence are developed to the east (Figs. 4 and 5). The external domain bounds with the Internal domain to the west (Fig. 4-6), while its eastern limits is the non-emergent deformational front (Fig. 1). The external domain also presents strong north-south changes in width (Figs. 1 and 4), that consistently take place around the same transfer faults that affect the Internal domain (Figs. 4 and 6).
The structural style of the external domain is that of a monocline developing a triangle zone, where Maastrichtian to Tertiary sequences are thrusted to the west over a Late Cretaceous epidermic wedge (Figs. 5 and 6). North of Río Turbio, there is a series of elongated N-S anticlines located east from the triangle zone (Figs. 4 and 5) where seismic data shows a strong interaction between faults affecting the synrift deposits of Tobífera Formation and shallow anticlines (Figs. 6 and 7).

Along strike changes in the fold-thrust belt
Given the above-mentioned observations, it was examined if the N-S changes in the structural domains are somehow connected with the observed changes in sedimentary facies and thickness in the same direction as proposed by Kraemer (1998). Our data is in agreement with the possibility that the Late Cretaceous-early Tertiary sedimentary facies could be reflecting a paleobathymetry-topography inherited from Late Jurassic extensional times. In this manner, the southward shift from prograding continental and litoral facies to marine and deep marine facies that occurs at the latitude of Lago Viedma would be reflecting the passage from a sector with minimum stretching to a deep basin generated during the extensional phase (Arbe 1989). The N-S axial direction from Lago Sofia conglomerates is probably reflecting the same control as well.
These changes wich take place in discrete ~E-W transition zones can be interpreted as the result of inverse reactivation of synrift depocenters located beneath the tertiary structures (Figs. 8 A and B). East-west oriented transition zones can be interpreted as accommodation zones separating synrift sub-basins (Figs. 8 A and B). While the deepness (Latest Jurassic paleobathymetry) of these depocenters controlled facies arrangement and total thickness of Late Cretaceous to Tertiary sequences, their dimensions controlled the width and length of future compressional structural domains (Figure 4). These assertions are in agreement with the migration of extensional depocenters from the ENE to the WSW along 650 Km (Pankhurst *et al.* 1998, Féraud *et al.* 1999; Fig. 8C). This progressive stretching culminated towards the SSW with the expansion of the Rocas Verdes marginal basin along the Pacific margin of the continent during Late Jurassic times (Dalziel 1981, Wilson 1991, Mukasa and Dalziel 1996, Calderón *et al.*, 2007; Fig. 8C).
In the presented model, the eastern boundary of the basement domain represents total inversion and exhumation of extensional depocenters, while inversion and exhumation decreases progressively towards the Internal and External domains (Fig. 8C).

DISCUSSION AND CONCLUSIONS: EVOLUTION OF THE PATAGONIAN ANDES FOLD AND THRUST BELT AND EXPLORATION OPPORTUNITIES

Evolution of the fold and thrust belt
Our study highlights several key points regarding the structural style and tectonostratigraphy of the Southern Patagonian Andes fold-thrust belt.
1- Along-strike variations in width of structural domains that take place in discrete transition zones seems to be reflecting the control of positive inverted extensional depocenters as previously proposed (Arbe 1989; Kraemer 1998). East-West oriented transition zones can be interpreted either as ancient transfer faults or accommodation zones separating synrift sub-basins.
2- The earlier uplift of the sector located to the north of the study zone is one of the most important conditioners of the evolution of the basin, and unveiling its causes would be important for understanding deformational processes and the present tectono-sedimentary pattern.
The substratum of the Patagonian fold-thrust belt consists of at least three adjacent, approximately N-NE oriented, elongated extensional depocenters. These depocenters show a westward increase in the degrees of inversion and exhumation: The first, completely inverted and exposed depocenter is represented by the eastern sector of the Basement domain. The Inner fold thrust belt comprises the second inverted depocenter. This depocenters is less inverted and synrift sequences are not uplift up to superficial levels, however all of the compressional structures are dissected. A third depocenter is interpreted to be beneath the external fold-thrust belt. This sector is the northern expression of the Tranquilo-Glencross trend, and therefore has a promising potential for the Mesozoic-Tertiary petroleum system.

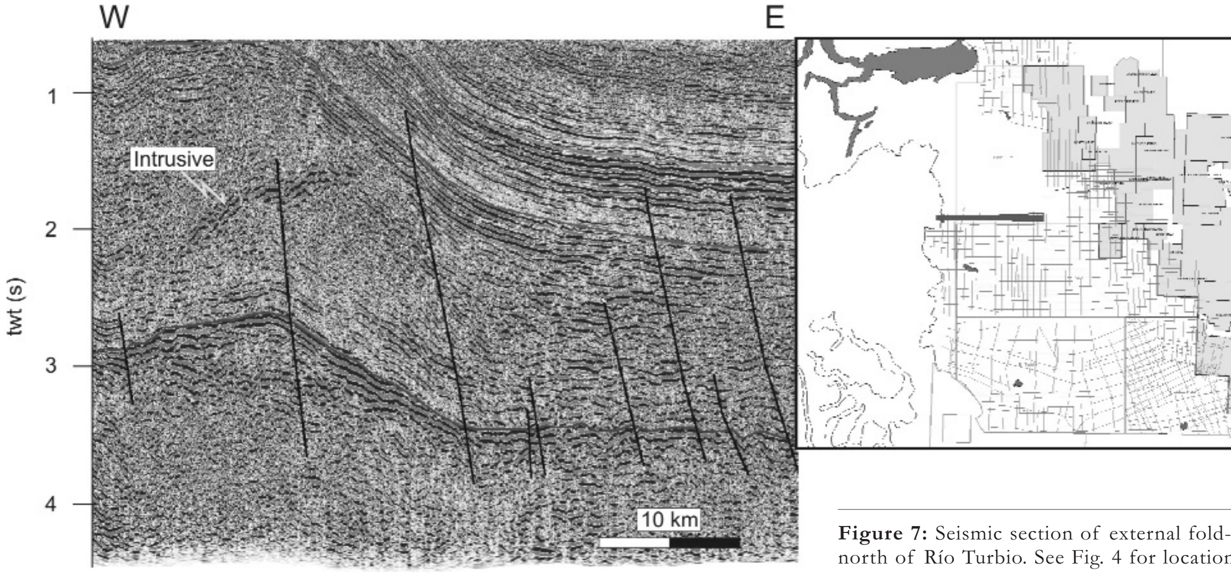

Figure 7: Seismic section of external fold-thrust belt, north of Río Turbio. See Fig. 4 for location.

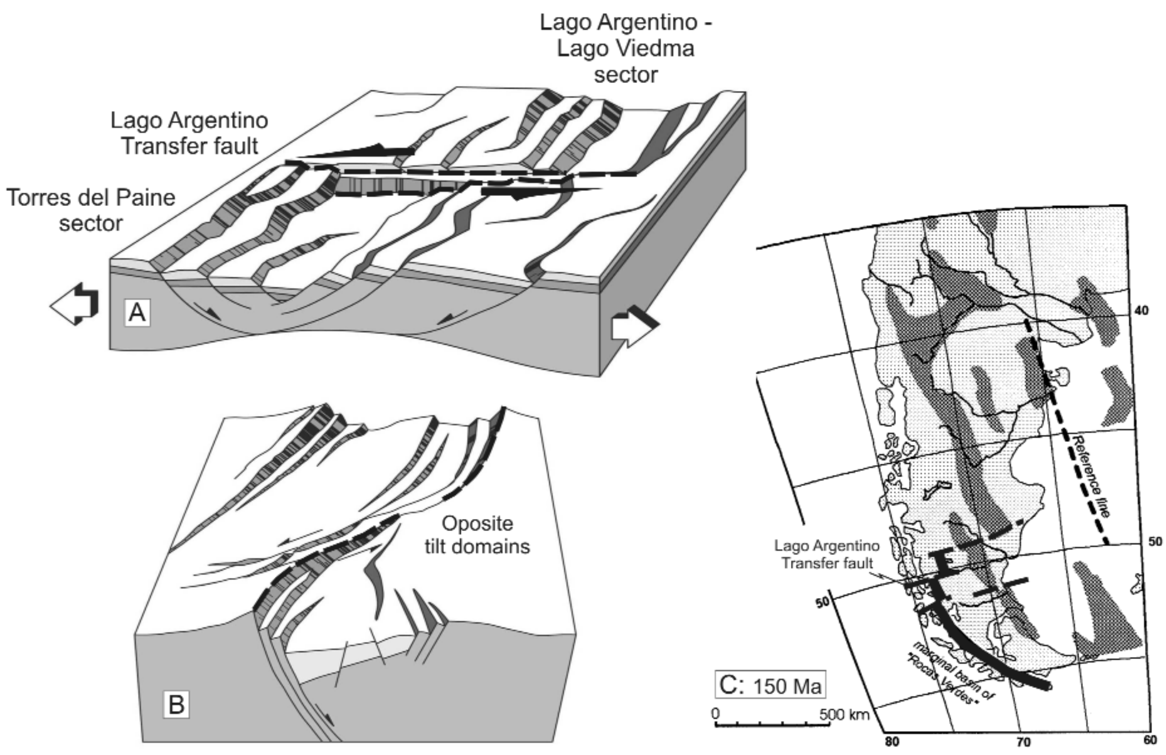

Figure 8: a and b) Sketches (modified from Barredo *et al.* 2007) showing rifting patterns of extensional depocenters separated by strike-slip or transfer faults as proposed for the studied zone (see text for discussion). Referen-ces are shown to illustrate the extensional stage of the hypothetical Lago Argentino transfer fault (a and b). c) Pa-leogeographic reconstruction of southern South America illustrating troughs and sags, after Uliana *et al.* (1988). Half-grabens defining the main Jurassic tectonic structure of the region controlled the Cretaceous bathimetry and sedimentation, and the Tertiary structural geometry (see discussion in the text).

Exploration Opportunities

The Austral or Magallanes basin is one of the less explored basins of Argentina and Chile. Although most of the proved petroleum and gas systems are located in the stable slope and platform of the basin, there also exists an important potential for the presence of oil or gas reservoirs in the deep basin and fold and thrust belt (Fig. 2) that remains in the frontier of exploration. To revert this situation, Argentina and Chile have recently bid new exploratory blocks in the region.

The best precedent related to the fold-thrust belt found in Argentina is associated with Tertiary gas reservoirs from the Magallanes formation in the Glencross field (Fig. 2) operated by Petrobrás Energía. The Tranquilo field (Fig. 2), discovered in 1960, is the most promising example from Chile, where Tertiary clastic sequences (Loreto and Leña Dura Formations) are gas productive reservoir in structural traps.

There are also other antecedents within the study zone such as the Paso Fuhr.es-1 well from the Paso Fuhr block, where the presence of gas have been tested and dry-gas was found. Other neighboring wells have had manifestations of gas in Tertiary and Cretaceous reservoir, although technical difficulties due to inexperience resulted in abandonment of wells without further testing.

Exploratory efforts are now being concentrated in the potential presence of late Cretaceous-Tertiary reservoirs in structural traps along the external fold-thrust belt (Figs. 2 and 4). The petroleum systems to be evaluated could be similar to other known late Cretaceous-Tertiary reservoirs located in the slope sector (Zilli *et al.* 2002, Cagnolatti and Miller 2005, Limeres and Dellapé 2005). Results from the present study show the existence of pervasive positive inversion of extensional depocenters during the Andean compressional deformation of the fold-thrust belt (Fig. 8). This structural model includes structural faulting connecting the main known source rock of the basin with potential sand reservoirs in structural (anticlines) and possibly stratigraphic traps.

While sedimentological studies are being conducted to understand the distribution and location of potential reservoirs. There also exist non-conventional plays to be evaluated, such as fractured basement rocks (for example Lago Mercedes field in Chile) or igneous reservoirs (sills in Paso Fuhr; Figs. 2 and 7), coal bed methane (Río Turbio field; Fig. 2), and tight sands from deltaic sequences (Marinelli 1998). Although past experiences seem to indicate that gas is the hydrocarbon most likely to be found in significant concentrations, there are also some promising oil antecedents such as the Morro Chico x1 well from Glencross field (Fig. 2), which encourages us to continue studying the source rock distribution and maturity.

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