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Geodynamic context for the deposition of coarse-grained deep-water axial channel systems in the Patagonian Andes

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Abstract

We present field and seismic evidence for the existence of Coniacian-Campanian syntectonic angular unconformities within basal foreland basin sequences of the Austral or Magallanes Basin, with implications for the understanding of deformation and sedimentation in the southern Patagonian Andes. The studied sequences belong to the mainly turbiditic Upper Cretaceous Cerro Toro Formation that includes a world-class example of conglomerate-filled deep-water channel bodies deposited in an axial foredeep depocenter. We present multiple evidence of syntectonic deposition showing that the present internal domain of the fold-thrust belt was an active Coniacian-Campanian wedge-top depozone where deposition of turbidites and conglomerate channels of Cerro Toro took place. Cretaceous synsedimentary deformation was dominated by positive inversion of Jurassic

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extensional structures that produced elongated axial submarine trenches separated by structural highs controlling the development and distribution of axial channels. The position of Coniacian-Campanian unconformities indicates a ~50-80 km advance of the orogenic front throughout the internal domain, implying that Late Cretaceous deformation was more significant in terms of widening the orogenic wedge than all subsequent Andean deformation stages. This south Patagonian orogenic event can be related to compressional stresses generated by the combination of both the collision of the western margin of Rocas Verdes Basin during its closure, and Atlantic ridge push forces due to its accelerated opening, during a global-scale plate reorganization event.

INTRODUCTION

Although foreland basin systems may show a sediment transport directed perpendicular to the topographic front (DeCelles & Giles, 1996; Ford, 2004), axial sediment dispersal patterns typically develop in multiple sedimentary systems in response to an abrupt tectonic uplift and tilting within the wedge-top depozone. There are examples such as deep-water sequences of the Austrian molasse basin (Hubbard *et al.,* 2009), turbidite deposits in the easternmost Mediterranean (McCay & Robertson, 2012), and fluvial deposits in NW Argentina (Carrapa *et al.,* 2012). This kind of interaction between sedimentary and tectonic processes can produce a completely different distribution of accommodation space when compared with that predicted by conventional models, and may lead to difficult interpretations.

A peculiar feature of the northern Austral foreland basin system, also known as the Magallanes Basin, is a strong north to south axial sediment dispersal pattern with a deepening of the accommodation space in the same direction (Scott, 1966; Winn & Dott, 1979; Aguirre-Urreta & Ramos, 1981; Dott *et al.,* 1982; Macellari *et al.,* 1989; Aguirre-Urreta, 1990; Fildani & Hessler, 2005; Crane & Lowe, 2008; Hubbard *et al.,* 2008, 2010; Romans *et al.,* 2009, 2010; Jobe *et al.,* 2010; Bernhardt *et al.,* 2011) expressed in an increase in total sedimentary thickness and depth to basement towards the south, from a few hundred meters at Lago Posadas (47°) up to 8 km between 51° and 54°SL (Fig. 1). A remarkable scenario occurred in the Coniacian - Campanian foredeep depozone within the study zone, where a submarine slope and deltaic depositional system north of Lago Argentino prograded towards a deep water marine N-S trough developed to the south and filled by abyssal turbidites of the Cerro Toro Formation (Figs 2 and 3; Scott, 1966; Arbe, 1989, 2002; Hubbard *et al.,* 2008). In early Coniacian time (ca. 87 Ma, Bernhardt *et al.,* 2012) the abrupt inception of coarse-grained deep-water strata up to 400 m thick occurred along the pelitic marine trough, incising the abyssal platform (Winn & Dott, 1979; Dott *et al.,* 1982; Arbe & Hechem, 1984; Jobe *et al.,* 2010). A 4 to 8 km wide by >100 km long deep-water Sierra del Toro axial channel system and secondary channels located to the west were active until the Santonian-Campanian (Fig. 2) with southward transport along the axis of the trough extending from Laguna 3 de Abril in Brazo Sur of Lago Argentino to Seno Última Esperanza and further south (Fig. 3; Arbe & Hechem, 1984; Crane & Lowe, 2008; Hubbard *et al.,* 2008; Bernhardt *et al.,* 2012).

There is a conceptual understanding that an inherited tectonic relief and structural geometry from the Middle to Late Jurassic rift phase created this relict N-S trough ~2000 m depth, that influenced the sedimentary distribution patterns and structural evolution during the foreland phase (Wilson, 1991; Arbe 1989, 2002; Kraemer, 1998; Romans *et al.,* 2009; Fosdick *et al.,* 2011; Likerman *et al.,* 2013). However, important aspects of this singular foreland basin scenario remain poorly constrained, such as which factors triggered the abrupt inception of deep-water conglomerate channel systems, and which additional aspects may have controlled their north to south axial sediment dispersal pattern (Fig. 3). Recently, important structural and sedimentary indications of confinement and synsedimentary tectonic uplift for the western secondary axial channel systems have been discovered (Crane & Lowe, 2008; Gonzales & Aydin, 2008; Bernhardt *et al.,* 2011), although the proposed regional geodynamic models for the region (Wilson, 1991; Fildani *et al.,* 2008; Kraemer, 1998;

Ghiglione *et al.,* 2009; Romans *et al.,* 2009; Fosdick *et al.,* 2011) do not account for generalized synsedimentary uplift in the area of the channel systems during its deposition.

We present new, direct and independent field and seismic evidence for the existence of Coniacian-Santonian syntectonic angular unconformities within the Cerro Toro Formation, coinciding in time with the abrupt inception and development of submarine conglomerate channels in the abyssal platform. We conclude that the deposition of the Cerro Toro conglomerates was probably tectonically triggered in a wedge-top depozone dominated by positive inversion of N-S oriented Jurassic extensional structures that shaped the peculiar geometry of the depocenter. The structural geometry of basin inversion produced a bathymetry consisting of elongated axial submarine trenches separated by structural highs that may be a paradigmatic case for other foreland basin systems. The linking between deformational and sedimentary processes allows for an outstanding dating and distribution of thrusting, and a thoughtful discussion of the global geodynamic implications of the presented data.

GEOLOGICAL SETTING

The metamorphic structural basement of the region, outcropping along the Pacific archipelago (Fig. 1), is mainly composed of low-grade metasedimentary rocks interpreted as late Paleozoic subduction complexes intruded by Mesozoic-Cenozoic granitoids of the Patagonian Batholith (Ramos *et al.,* 1982; Hervé *et al.,* 2007).

Initial extensional subsidence began in Patagonia during the Triassic-Jurassic continental rifting of Gondwana (Uliana *et al.,* 1989), characterized by a bimodal association of rhyolitic ignimbrites with minor mafic and intermediated lavas (Pankhurst *et al.,* 2000; Féraud *et al.,* 1999). The Late Jurassic extensional event produced several N-S oriented synrift depocenters (Biddle *et al.,* 1986, Diraison *et al.,* 2000), filled up by a heterogeneous suite of siliceous volcanic and volcaniclastic rocks called El Quemado Complex in Argentina (Riccardi & Rolleri, 1980), and Tobífera Formation in Chile (Fig. 2; Thomas, 1949) that yielded zircon U–Pb SHRIMP ages of ca. 152–142 Ma in the Sarmiento Complex (Figs. 1 and 4C; Calderón *et al.,* 2007; Hervé *et al.,* 2007). Outcrop orientation and seismic information show that the early Mesozoic rift was mainly NNW to N-S trending in the Austral Basin (Biddle *et al.,* 1986, Uliana *et al.,* 1989, Ghiglione et al., 2013). Stretching was maximum along the Pacific margin and produced oceanic crust in the Rocas Verdes Basin during Middle to Late Jurassic time (Dalziel, 1981). The northern remnants of the pillow lavas sea floor and interfingered bimodal magmatism are grouped into the Sarmiento Ophiolite Complex located SW of our study zone (Figs 1 and 4C; Stern & DeWitt, 2003; Calderón *et al.,* 2007). Lower Cretaceous sag deposits composed of distal turbidites from the Río Mayer and Zapata Formations, with detrital zircons indicating a maximum Hauterivian age of sedimentation (Calderón *et al.,* 2007), cover the synrift units (Figs 2 and 4; Thomas, 1949; Wilson, 1991).

Uplift of the southern Patagonian Andes initially involved closure of the Rocas Verdes Basin ocean floor during the Late Cretaceous (Dalziel *et al.,* 1974), and obduction of its oceanic crust (Cunningham, 1995; Stern & de Witt, 2003; Calderón *et al.,* 2007, 2012; Klepeis *et al.,* 2010; McAtamney *et al.,* 2011). Subduction inception within the Rocas Verdes Basin and the ensuing ophiolitic obduction in the Cordillera Sarmiento occurred at ca. 85 Ma, as shown by means of combined zircon U–Pb and phengite $^{40}Ar/^{39}Ar$ age data representing cooling synchronous with mica crystallization (Calderón *et al.,* 2012). Further south, along the Beagle channel (55°SL, Fig. 1), closure of Rocas Verdes Basin and ocean floor obduction occurred also prior to 86 Ma (Cunningham, 1995; Klepeis *et al.,* 2010). Geobarometric considerations suggest that between ca. 85 and 80 Ma fast uplift rates of ca. 1–2 mm/yr prevailed during progressive deformation of the accretionary wedge in Cordillera Sarmiento (Calderón *et al.,* 2012). The basement domain experienced continuous uplift and denudation during the rest of the Cretaceous and Cenozoic (Thomson, 2002), while maintaining the critical taper of the fold-thrust belt that experienced multiple episodes of deformation (Kraemer, 1998; Ghiglione & Ramos, 2005; Fosdick *et al.,* 2011). The Patagonian fold-thrust belt experienced well-documented Cenozoic deformation, including at least two principal compressional events of Eocene and Miocene ages related to episodes of fast subsidence or ridge collision (Ramos, 1989, 2005; Kraemer, 1998, 2003; Suarez *et al.,* 2000; Ghiglione & Ramos, 2005; Ghiglione & Cristallini, 2007; Lagabrielle et al. 2009), enhanced by fast erosional denudation due to unroofing of the labile fine-grained Upper Cretaceous sequences (Fosdick et al., 2013).

Hinterland uplift and erosion caused the deposition of coarse clastic sediments on top of the sag units, indicating the onset of a foreland phase in the Austral and related basins of southernmost South America (see Ghiglione *et al.,* 2010 and references therein). A key-point in the development of the foreland phase of the northern Austral Basin is a first-order southward increase in the fill-thickness of the main Late Cretaceous depocenter, including the presence of deeper depositional environments in the same direction (Fig. 1; Aguirre-Urreta & Ramos, 1981; Aguirre-Urreta, 1990; Wilson, 1991; Arbe, 2002; Romans *et al.,* 2009). The first sequence associated with tectonic uplift between the Viedma and Argentino lakes is the lower section of the upper Albian - lower Campanian Cerro Toro Formation overlaying the sag deposits of the Rio Mayer Formation (Fig. 2; Arbe & Hechem, 1984; Kraemer & Riccardi, 1997). East of Lago Viedma the Albian Piedra Clavada Formation is the lateral equivalent of Cerro Toro Formation, and is overlaid by fluvial and estuarine deposits of Mata Amarilla Formation with tuff layer yielding a U-Pb concordia age of 96.23 ± 0.71 Ma (Varela et al., 2012).

South of Lago Argentino (Fig. 3) the first coarse clastic infill is represented by turbiditic sandstones of the Punta Barrosa Formation (Fig. 2) overlaying the sag deposits of the Zapata Formation (Wilson 1991), that yielded a maximum Turonian age of sedimentation (92 ± 1 Ma), on the basis of detrital zircon analysis (Fildani *et al.,* 2003). The onset of turbidite sedimentation coincided with the partial obduction of the Rocas Verdes basaltic floor, as shown by clastic composition of Punta Barrosa Formation (Fildani & Hessler, 2005; Romans *et al.,* 2010; Fosdick *et al.,* 2011; McAtamney *et al.,* 2011). Sandstone petrography, detrital zircon geochrononology, and mudstone geochemistry indicate that Punta Barrosa sediments (Fildani & Hessler, 2005; Fildani *et al.,* 2008), and equivalent units in Peninsula Brunswick 250 km to the south (Fig. 1, McAtamney *et al.,* 2011) were derived from uplifted Paleozoic metamorphic basement complexes, the Sarmiento ophiolitic complex, and a juvenile volcanic arc. Fosdick *et al.*(2011) dated a volcanic ash at the Zapata/Punta Barrosa formations transition zone (Fig. 2) yielding a late Albian U/Pb zircon age of 101 ± 1.1 Ma showing that incipient thrust belt formation was under way as early as the latest Albian.

The Punta Barrosa Formation is overlain by up to 2000 m of mudstone, sandstone, and conglomerate of the Cerro Toro Formation (Fig. 2). South of Lago Argentino, the Cerro Toro Formation includes large, conglomerate-filled submarine channels embedded within a predominantly thin-bedded mudstone and sandstone sequence deposited by low-density turbidity currents (Fig. 2; Katz, 1963; Winn & Dott, 1979; Hubbard *et al.,* 2008; Crane & Lowe, 2008; Bernhardt *et al.,* 2011; Jobe *et al.,* 2010). The ca. 87-84 Ma abrupt inception (Bernhardt *et al.,* 2012) of coarse-grained deep-water strata up to 400 m thick took place along a deep water marine trough (Figs 2 and 3). A 4 to 8 km wide by >100 km long deep-water "Sierra del Toro" axial channel system with transport southward along the axis of the trough (Fig. 3) was active since 84 Ma (Hubbard *et al.,* 2008; Bernhardt *et al.,* 2012). The secondary Silla syncline channel system started earlier (87 Ma) to the west, separated by a bathymetric high from the axial channel system (Fig. 2; Bernhardt *et al.,* 2011, 2012). Both systems were partially coeval and lasted up to early Campanian time (82 Ma, Bernhardt *et al.,* 2012); the main channels were confined to the west by the uplifted basement front and subsidiary splay thrusts (Fig. 3), and although they were separated by a high for most of their trace, they were probably interconnected at some points where the conglomerate channels linked (Winn & Dott, 1979; Dott *et al.,* 1982; Arbe & Hechem, 1984; Hubbart *et al.,* 2009). Recently, important sedimentary indications of confinement produced by active faulting and uplift during deposition of the western channels allowed Gonzales & Aydin (2008) and Bernhardt *et al.* (2011) to interpret that the bathymetric highs separating the channel systems were the product of synsedimentary tectonic uplift.

Progradational packages on top of the Cerro Toro Formation at this latitude are represented by the turbiditic Tres Pasos Formation and deltaic Dorotea Formation (Fig. 2; Katz, 1963; Natland *et al.,* 1974; Macellari *et al.,* 1989; Armitage *et al.,* 2009; Covault *et al.,* 2009; Romans *et al.,* 2009, 2010; Hubbard *et al.,* 2009), which are overlain by Paleogene shallow marine, estuarine and lagoonal environments followed unconformably/paraconformably by upper Eocene-Oligocene fluvial syntectonic sediments of Río Turbio-Río Leona Formations (Fig. 2; Manassero, 1988; Malumián *et al.,* 2000).The former are cover by marine deposits of a major Miocene transgression affecting Patagonia, known as *Patagoniano* (Centinela/Estancia 25 de Mayo Formation; Parras et al., 2008; Cuitiño & Scasso, 2010). Fast infilling of the accommodation space created by Miocene uplift and deformation resulted in progradation of fluvial deposits of the Santa Cruz Formation over the *Patagoniano* beds (Cuitiño et al., 2012).

INTEGRATED STRUCTURE FROM 49º30´ to 50º30´ SL

We present a detailed geologic map not previously published on an international journal (Fig. 3) that integrates structures and stratigraphic units in an area of ~21,000 km^2 between Lago Viedma in Argentina and the Última Esperanza region in Chile (Fig. 1). The integrated geology of the study zone allowed the construction of four new serial cross sections (Fig. 4) based on collected field data (Figs 3 and 8), previously unpublished well and seismic data (Figs. 5, 6A and 6B) and previous studies. Seismic data are illustrated in two-ways-time sections, although time to depth conversion was used for the calculation of vertical distances discussed in the text. Age of seismic horizons was correlated from available exploratory wells (Fig. 3).

The region under study can be divided into three structural domains including, from west to east (after Kraemer, 1998; Kraemer *et al.,* 2002; Ghiglione *et al.,* 2009, 2010; Giacosa *et al.,* 2012; Figs 3 and 4): (i) The basement thick-skinned domain, and the fold-thrust belt subdivided into a (ii) western internal domain and an (iii) eastern external domain.

(i) Basement Domain

The regional basement domain recognized on the western flank of the Patagonian-Fuegian Andes, is the responsible for transferring shortening to the fold-thrust belt by means of the basement thrust front (Fig. 1; Kraemer, 2003; Ghiglione & Cristallini, 2007). Uplift and structural consolidation of this crystalline domain started during early to late Cretaceous time as a consequences of the final closure of the Rocas Verdes Basin ocean floor and consequent collision of its west margin against the South America craton (Kohn et al., 1995; Cunningham, 1995; Calderón et al., 2011). Ensuing pulses of Late Cretaceous-Cenozoic tectonic basement uplift preceded deformation of the sedimentary cover (Ghiglione & Ramos, 2005; Klepeis et al., 2010). The subduction of Rocas Verdes ocean floor was supposedly directed to the west and south from the cratonward margin during its closure, and it actually constitutes a major fault system with basinward vergence recognized within the basement domain along the Beagle channel (Cunningham, 1995; Klepeis et al., 2010) and in the eastern flank of Cordillera Sarmiento (Fig 4C; Calderón et al., 2011). Therefore, from a mechanical point of view, the Canal Beagle sector can be correlated with the Cordillera Sarmiento since they both transferred shortening to the fold-thrust belt, and as will be discussed later, they both experienced similar ages of ocean basin closure and resulting cratonward uplift of the oceanward margin of Rocas Verdes Basin on top of the South America craton.

In the Lago Viedma - Ultima Esperanza sector, the thick-skinned basement domain is constituted by Paleozoic-Triassic metamorphic rocks intruded by Tertiary plutonic and volcanic rocks from the Patagonian batholith, and totally inverted grabens exposing Upper Jurassic synrift deposits of Tobífera-El Quemado (Figs 3 and 4). The northernmost ophiolitic remnants of Rocas Verdes Basin are located within this domain, in the Sarmiento Complex (Figs 1 and4C).

Major outcrops of the Tobífera and El Quemado Formations are concentrated along the eastern belt (Figs 3 and 4). These Upper Jurassic rocks form elongated outcrops with a N to NNE trend that represent an inverted main extensional depocenter, bounding to the east with the fold thrust belt by the Zapata-Perito Moreno thrusts (Figs 3 and 4). Some of 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 the Punta Avellaneda (Fig. 3). In these sectors there are westward verging back-thrusts uplifting eastward-thinning Jurassic synrift deposits, indicating the total inversion of extensional depocenters. In the Última Esperanza region, the eastern boundary of the basement domain presents a series of backthrusts superposing the Zapata Formation over the Tobífera hinterland thrusts and duplex, such as the Zapata thrust, located west of Lago Grey (Figs 3, 4C, D; Wilson, 1991; Fosdick *et al.,* 2011).

Fold-thrust belt

The fold-thrust belt exposes Upper Cretaceous to Neogene deep-marine to nonmarine strata from the foreland basin stage (Figs 2, 3 and 4). It shows predominantly folding, with few outcropping thrusts from partially inverted structures. The structure is primarily dominated by partial positive tectonic inversion of Jurassic rifts in the western internal domain (Figs 4, 5 and 6; Kraemer, 1998; Ghiglione *et al.,* 2009; Giacosa *et al.* 2012; Fosdick *et al.,* 2011). Inversion tectonics coexists with a shallow detachment surface to the east, producing thin-skinned folds and thrust sheets in the external domain (Figs 4, 5 and 6). A similar structural configuration is recognized along the study zone (Figs 3 and 4), while north of Lago San Martin (Fig. 1) the internal domain progressively narrows and gives way to an eastward advance of the basement domain (Ramos, 1989; Kraemer et al., 2002; Giacosa *et al.,* 2012).

(ii) The Internal Domain is characterized by partial inversion of Jurassic depocenters between Lago Argentino and Lago Viedma as show by seismic data (Figs 5 and 6; Coutand et al. 1999), and a similar configuration is valid in the Última Esperanza region (Soffia *et al.,* 1988; Harambour, 2002). This western sector of the fold-thrust belt is composed of N-S trending thrusts, back-thrusts and folds with eastward vergence (Figs 3-6). The eastern boundary is interpreted as the tectonic inversion of a westward-dipping, eastern boundary of a main Jurassic depocenter, represented by the Simon thrust, based on the analysis of seismic reflection data (Figs 5 and 6). In the Torres del Paine region, the main frontal structure of the internal domain is the Toro anticline, cored by westward-dipping, high-amplitude reflectors in seismic-reflection data showing the presence of a basement-seated Toro thrust fault that soles out within the Paleozoic metamorphic basement (Harambour, 2002; Fosdick *et al.,* 2011) interpreted as produced by the tectonic inversion of a Jurassic rift boundary (Likerman *et al.,* 2013). The latter proposal is strengthen by drill data from Toro 1b exploratory well, showing that synrift deposits of the Tobifera Formation uplifted with respect to its regional level are located on the core of the Toro anticline (Figs 3 and 4C). We interpret that the westward dipping, positively inverted normal fault, induces the development of a backthrust and an eastward dipping frontal monocline when its tip-point reaches the base of eastern foreland sequences (Fig. 4C-D). This interpretation was validated throughout kinematic forward modeling (Fig. 7). Alternative interpretations explain the frontal structure without a backthrust (Fosdick *et al.,* 2011), although they do not account for the presence of a conspicuous frontal monocline between the Río Turbio and El Calafate localities (Figs 3 and 4).

The eastern boundary of this domain has an irregular trace, interpreted as the trace of a westward dipping boundary of a N-S extensional depocenter (Ghiglione *et al.,* 2009; Likerman *et al.,* 2013; this work). From north to south, the internal domain increases its width and an overall westward shift of its position takes place (Figs 3 and 4). Strong along-strike variations in width of this structural domain take place in discrete ~E-W transfer zones showing inflexions of the domain boundaries (Fig. 3). At least three transfer zones are recognized in the study zone, the two northern zones coinciding with Viedma and Argentino lakes, while the southern one is located at ~50º 55`LS, north of Lago Sarmiento (red dotted lines in Fig. 3). According to an idea first proposed by Arbe (1989) and followed by Kraemer (1994, 1998) and Kraemer & Riccardi (1997) for the sector north of Lago Argentino (Figs 1 and 3), these important structural N-S contrasts are here interpreted as being controlled by the distribution of extensional depocenters from the early extensional phase of the basin. In agreement with Arbe (1989), the east-west oriented transfer zones are currently interpreted as the surficial expression of ancient extensional accommodation zones separating Jurassic grabens (Kraemer, 1994; Ghiglione *et al.,* 2009).

From this conceptual understanding, it has been suggested that adjacent extensional depocenters with different widths reflecting variables degrees of extension would produce this map-view geometry during tectonic inversion, without involving significant strike-slip displacement (Ghiglione *et al.,* 2009). Recently, a work from Likerman et al. (2013) produced an analog modeling designed to test this hypothesis, creating two rift-segments with different extension separated by a transfer zone. A strong variation in width and lateral position of main thrusts during the compressional stage of the model occurred near the transfer zone, similar to those found on the Patagonian fold-thrust belt (Fig. 3; Likerman *et al.,* 2013).

(iii) The External Domain involving outcrops of Campanian to Paleogene sequences (Arbe 1989, 2002; Kraemer & Riccardi, 1997; Marenssi *et al.,* 2005), is thrusted westward over a Lower Cretaceous to Paleogene wedge forming a frontal monocline, while thin-skinned folds and thrusts with eastward vergence are developed to the east (Figs 3, 4 and 5). Its eastern limit is the blind deformation front (Figs 3 and 4). The structural style of the western external domain is that of a triangle zone developing a monocline, where Maastrichtian to Tertiary sequences are thrusted to the west over a Upper Cretaceous wedge (Figs 3, 4 and 5). A series of low amplitude elongated N-S broad anticlines and synclines located east of the monocline (Figs 3 and 4) are produced by tectonic inversion, as show by the strong interaction between faults affecting synrift deposits of Tobífera Formation and shallow structures (Figs 5 and 6).

STRUCTURAL MODEL

The Patagonian Jurassic fault array was prone to reactivation under small amounts of compression or extension orthogonal to their orientation during Mesozoic-Cenozoic time (Ghiglione *et al.,* 2013). Our structural model hinges on the idea that positive inversion of Upper Jurassic rift depocenters delineated the development of the internal domain, as was recently demonstrated throughout analog experiments (Likerman *et al.,* 2013).

In the presented model, the eastern boundary of the basement domain represents total inversion and exhumation of extensional depocenters, while exhumation decreases progressively towards the internal and external domains (Figs 4, 5 and 6). Our serial ~E-W structural sections are in general agreement with previous works (Kraemer, 1998; Giacosa *et al.,* 2012; Fosdick *et al.,* 2011), and point out the lateral continuity of structural domains and their boundary thrusts (Figs 3 and 4; Kraemer *et al.,* 2002).

The structural model was kinematically tested by forward modeling of Section 4C Cerro Ferrier – Pali Aike (Fig. 7) using the *2D Move* software (© Midland Valley Exploration Ltd). The superficial structures and seismic data were mimicked successfully, including the backthrust between the internal and external domains, and the resulting monocline (compare Figs 4 and 7). The obtained shortening parameter of 29 km (20%), is in accordance with previous palinspastic geometrical restorations indicating 35 km (26%) of retroarc shortening between the Argentino and Viedma lakes (Kraemer, 1998) and of ~32 – 40 km (~19%–23%) in the Última Esperanza region (Fosdick *et al.,* 2011).

While late Cretaceous horizontal shortening was mainly concentrated on the basement domain up to Campanian time (Fosdick *et al.,* 2011; Calderón *et al.,* 2012), subsequent deformation migrated into the fold-thrust belt, were shortening was maximum during the Miocene (Ramos, 1989; Kraemer, 1998). We calculate around 600 m of late Coniacian to Santonian basement uplift above the Simon thrust based on thickness of syntectonic sediments onlapping the basement high (Fig. 6A). Although we propose generalized fault inversion across the internal domain of the fold-thrust belt during the Coniacian-Campanian, it could have been achieved with less than a 5% shortening (measured from Figure 7a of Likerman *et al.,* 2013).

LATE CRETACEOUS SYNTECTONIC UNCONFORMITIES

Syntectonic angular unconformities and synkinematic sequences are recognized from outcrop and seismic data across the fold-thrust belt in the region of the Viedma and Argentino lakes, and can be divided according to their ages in two groups: (i) Coniacian-Santonian syntectonic angular unconformities within the Cerro Toro Formation and (ii) lower Campanian syntectonic angular unconformities between the Alta Vista Formation and the Asunción Member of the Anita Formation.

In the Ultima Esperanza region (Fig. 3) the first coarse clastic infill indicating the onset of the foreland stage is represented by the 250-400 m thick turbiditic sandstones of the Punta Barrosa Formation (Fig. 2; Win & Dott, 1979; Wilson 1991; Fildani *et al.,* 2008). On that region, foreland sedimentation continues with the Cerro Toro Formation composed of mudstone and thin-bedded sandstones representing deposition from low-density turbidity currents intercalated with lenticular conglomeratic units up to 400 m thick (Katz, 1963; Winn & Dott, 1979; Hubbard *et al.,* 2008; Crane & Lowe, 2008; Bernhardt *et al.,* 2011; Jobe *et al.,* 2010). The conglomerates are interpreted as deposits of a low-sinuosity, axial channel belt that served as a conduit for turbidity currents transporting coarse clastic detritus (Winn & Dott, 1979; Hubbard *et al.,* 2008).

At its type locality on the NE slope of Sierra del Toro (Fig. 3), the Cerro Toro Formation reaches ca. 1300 m, whereas the entire formation has a cumulative thickness of ca. 2000-2200 m on the Última Esperanza region (Winn & Dott, 1979; Hubbard *et al.,* 2008), and of 1050 m between Argentino and Viedma Lakes (Kraemer & Riccardi, 1997).

On the basis of fossil content in Ultima Esperanza, the Punta Barrosa Formation was given a late Albian to Cenomanian age, while the Cerro Toro Formation was interpreted as Cenomanian to Campanian (Katz, 1963; Scott, 1966; Natland *et al.,* 1974; Dott *et al.,* 1982; Winn & Dott, 1979). The age span of these two units has been the subject of intense geochronological U/Pb dating of zircons from volcanic ashes and sandstones over the last decade, yielding an age range for Punta Barrosa Formation from 101 ± 1.1 to 90.7 ± 2.5 Ma - late Albian-Turonian (Fig. 2; Fildani *et al.,* 2003; Fosdick *et al.,* 2011). The northern outcrops from Cerro Toro Formation in Ultima Esperanza spans a Turonian to Campanian interval (ca. 90–82 Ma) whereas the formation top, 70 km to the south, is as young as ca. 76 Ma (see review from Bernhardt *et al.,* 2012).

At the type locality of the Cerro Toro Formation, fossil content collected by Hauthal in 1905 and classified by Wilckens (1907) was characterized mainly by *Inoceramus steinmanni* (Fig. 2) associated with *Inoceramus andinus,* covering a range of many hundred meters in the stratigraphical column. On the NE slope of Cerro Toro where the base of the formation is not exposed, *Inoceramus steinmanni* still was encountered on top of a 700-m thick shale section (Katz, 1963). The northernmost known outcrop of conglomerate channels from Cerro Toro Formation is located in Laguna 3 de Abril in Brazo Sur of Lago Argentino (Fig. 3), and *Inoceramus steinmanni* was recollected on top of the section (Fig. 2; Arbe & Hechem, 1984; Pizzio, 2009). Both species are also widespread in the upper member of Cerro Toro

Formation between the Argentino and Viedma lakes and Kraemer & Riccardi (1997) assigned it to the upper Santonian - lower Campanian.

The first sequence associated with tectonic uplift between the Viedma and Argentino lakes is the upper Albian - lower Campanian Cerro Toro Formation overlying the sag deposits of the Rio Mayer Formation (Fig. 2; Arbe & Hechem, 1984; Kraemer &Riccardi, 1997). Two members CT1 and CT2 composed of turbiditic mudstones and sandstones separated by an unconformity and laterally corresponding paraconformity can be differentiated in the Cerro Toro Formation (Figs 2 and 6A; Arbe & Hechem, 1984; Kraemer & Riccardi, 1997; Kraemer, 1998; Arbe, 2002). The turbidites facies of the Cerro Toro Formation extensively outcrop between the Viedma and Argentino lakes and have an abundant fossil content including age-diagnostic ammonites and inoceramids. The fossil content of its lower member CT1 indicates a late Albian to early Coniacian age and can be correlated with the Punta Barrosa Formation (Kraemer & Riccardi, 1997). The upper member CT2 of early middle Coniacian to late Santonian age is contemporaneous with the deposition of deep-water conglomeratic channels to the south of Lago Argentino (Fig. 2; Arbe & Hechem, 1984; Kraemer & Riccardi, 1997; Riccardi, 2002). *Inoceramus steinmanni* associated with *Inoceramus andinus,* and *Sphenoceramus cf. lingua* have been found in the upper member of Cerro Toro Formation on the SWshore of Lago Viedma (Kraemer & Riccardi, 1997), a similar fossil association to that described for the Sierra del Toro locality (Wilckens, 1907; Katz, 1963).

(i) Cerro Toro Coniacian Syntectonic Angular Unconformity

The Lago Argentino Coniacian syntectonic angular unconformity is evidenced by the westward onlap and thinning of seismic reflectors within the Cerro Toro Formation as seen in seismic sections YPF 8124 and 8125 (CoU in Fig. 6A). This unconformity was first described by Kraemer & Riccardi (1997) and Kraemer (1998), and interpreted as the product of a Late Cretaceous isolated basement uplift. These authors only had the eastern portion of the seismic section available, and the nature of the whole structure under tectonic inversion was not visible. When considered on its totality it can be noted as an inverted Jurassic rift depocenter (Fig. 6A). Kraemer (1998) based on correlation between outcrop and seismic information indicated an early Cenomanian to early Coniacian age for the top of pre-kinematic CT1, and an early middle Coniacian to late Santonian - early Campanian age for syntectonic CT2, bracketing the age of the syntectonic angular unconformity (CoU in Fig. 6) between the early and middle Coniacian. Furthermore this syntectonic angular unconformity can be correlated westward with its equivalent paraconformity on the Arroyo La Sola Section (Fig. 3; Kraemer & Riccardi, 1997).

We calculate a 600 m thickness for the upper Coniacian to Santonian onlapping sediments, that thins until disappearance against the frontal limb of basement uplift (Fig. 6A). Although the unconformity is only recognized in the eastern flank of this ~30 km long inverted symmetrical depocenter (Fig. 6A), we can deduce that it represents the positive inversion of the whole structure, as deformation was transmitted from west to east (e.g. Fig. 7). To the north, a similar structural configuration of tectonic inversion can be recognized in seismic lines along Lago Viedma (Figs 5A, B). In our view, the syntectonic unconformity is the product of the relative uplift produced by tectonic inversion of the whole internal domain along the northern shore of Lago Argentino, and most probably up to Lago Viedma.

Other important features along seismic line YPF 8124 are the development of small synclines between inverted normal faults (PPC in Fig. 6A), that seem to lose expression up section as if they were partially filled by syntectonic sediments, and are interpreted here as probable structurally controlled paleochannels actives at the time of the Cerro Toro Formation deposition.

Our data independently supports further interpretations for the syntectonic deposition of the oldest channel-lobe complex in the Silla syncline area during the Coniacian ca. 87 Ma (Fig. 3; Crane & Lowe, 2008; Bernhardt *et al.,* 2011, 2012). Thinning and disappearance of these units along the eastern limb of the syncline reflect confinement of the flows to a narrow trough or mini-basin bounded to the east by a tectonic high (Bernhardt *et al.,* 2011). Deposition of the coarse-grained units of the Silla syncline took place in a structurally defined depression controlled primarily by thrust faults flanking the syncline (Gonzales & Aydin, 2008). However, papers by Beaubouef (2004) and Campion et al. (2011) show data that does not align with an interpretation of topographic confinement of channels in the Silla syncline, but rather high-relief levee build-up.

Other equivalent syntectonic unconformities within the Cerro Torro Formation are described by Coutand *et al.* (1999) on the northern shore of the Lago Viedma in the same structural position, i.e. on the eastern boundary of the internal domain (Fig. 3). In this place, reverse faults are associated with thick depocenters in footwall synclines and condensed sequences over hanging wall anticlines, showing that folding and faulting were ongoing during Albian to Campanian sedimentation of Cerro Toro Formation (Coutand *et al.,* 1999).

(ii) Alta Vista / Anita Formations Campanian Syntectonic Angular Unconformity

Another unconformity showing eastward onlap of seismic reflectors is located 10 km east from the Paso Charles Fuhr exploratory well (Fig. 6B). The age of involved stratigraphic horizons was obtained from micropaleontologic content of foraminifera and ostracods from the Paso Charles Fuhr well (Ronchi & Viñas, 1985) and lateral correlation of reflectors. A westward-dipping monocline, produced by the Paso Charles Fuhr thrust, involving up to Santonian-Campanian levels can be clearly recognized (Fig. 6B). The basal onlapping sequences including the unconformity are assigned to the *Gaudryina healyi* foraminifera zone of Malumian & Masiuk, (1975) and can be assigned to the Campanian-lower Maastrichtian (Ronchi & Viñas, 1985).

A second monocline is located westward from the Paso Charles Fuhr well, and affects the same pre-kinematic sequences, underlying older syntectonic onlapping sequences (Fig. 6B).

Both monoclines appear to be the result of westward-verging steep faults rooted in basement levels (Fig. 6B). These structures can be broadly interpreted as inversion structures although synrift deposits associated with them are not clearly identified. Our correlation yields a broad Campanian-early Maastrichtian age for the unconformity, i.e. postdating deposition of Cerro Toro Formation.

A equivalent unconformity with a similar geometry is partially envisaged on outcrops at the Cerro Teta on the southern shore of Lago Viedma (Fig. 3). Here pelitic Campanian units of the upper Alta Vista Formation dip ~10º to the SW, while overlaying sandstones of the Campanian Asunción Member of the lower Anita Formation are clearly steeper, with an average dip of ~30º SW (Fig. 8). According to diagnostic fossil content, the upper levels of the Alta Vista Formation are lower Campanian while lower levels of the Anita Formation are also lower Campanian (Arbe & Hechem,1984; Kraemer & Riccardi, 1997), yielding an early Campanian age for the unconformity at Cerro Teta (Fig. 2).

DISCUSSION

Onset of deformation and inception of Cerro Toro Conglomerates

Early contractile phases have been described by Fildani & Hessler (2005) and by Calderon *et al.,* (2007) among others. Fildani & Hessler (2005) propose a partitioned basin with arc sediment sequestered up dip before the Punta Barrosa sediment reached the basin. The main difference with our interpretation is that our data support active faulting on the Patagonian fold-thrust belt at the time of obduction, while previous works restricted Late Cretaceous deformation to the hinterland (Fildani & Hessler 2005; Fosdick et al., 2011; Calderon *et al.,* 2012). On these previous interpretations the orogenic front is located along the eastern boundary of the basement domain during the Campanian-early Conicacian, while our data shows that the leading edge of deformation was located along the eastern boundary of the internal domain of the fold thrust belt (Fig. 9).

Based on a stratigraphic correlation, the synkinematic sequences at Lago Argentino belong to the upper member of Cerro Toro Formation (CT2), a stratigraphic position similar to conglomeratic channels from Última Esperanza region (Fig. 2). New U/Pb dating of zircons from volcanic ashes and sandstones, coupled with strontium isotope stratigraphy, bracket the age of Silla syncline conglomerates between ca. 87–82 Ma, and that of the Sierra del Toro channel between ca. 84-82 Ma (Bernhardt *et al.,* 2011). The basal ages for the conglomerates broadly coincide in time with the observed synsedimentary graben inversion and related deformation in Lago Argentino (Figs 2 and 6A). The age of the unconformity separating pre-kinematic strata Coniacian or older and lower middle Coniacian to upper Santonian synkinematic sequences (Kraemer & Riccardi, 1997; Kraemer, 1998), can be constrained as early-middle Coniacian. A conservative estimated age span for the unconformity and onlapping synkinematic sediments at Lago Argentino would be Coniacian-Santonian, matching in time with the ~87 to 82 Ma deposition of Silla syncline conglomerates (Bernhardt *et al.,* 2011). The Campanian-lower Maastrichtian (ca. 84-70 Ma) unconformity and onlapping sequences at the Santa Cruz river overlap in time with the onset and deposition of the Sierra del Toro channels.

Arbe & Hechem (1984) proposed that a relative sea-level lowering, tectonically or eustatically induced, caused introduction of conglomeratic channels to the abyssal platform. A recent analysis of the architectural elements of the axial channel belt from Hubbard et al (2008) did not yield conclusive evidence to support such a theory, although the study showed that the eastern channels (Fig. 3) are bound by constructional levees, and this is not inconsistent with the lowstand interpretation. This transition from erosion and bypass north of Lago Argentino to deposition southward is associated at least with a major discontinuity to the north, manifested as a large-scale erosion surface and hiatus separating members CT1 and CT2 from Cerro Toro Formation (CoP/CoU in Figs 2 and 9; unconformity d4 from Kraemer & Riccardi, 1997).

We propose a causative relation between uplift in the internal domain, and the onset of conglomeratic channels that strengthens the proposal from Arbe & Hechem (1984). The proposed tecto-sedimentary context of a synorogenic origin for the conglomerates is also in concordance with a local context of deformation in Cordillera Sarmiento, where ophiolite tectonic emplacement deformation took place from 85 to 78 Ma (Calderón *et al.,* 2012) and detrital content (Fildani & Hessler, 2005) showing the exposure of the Tobífera duplex to the west by the Zapata-Upsala thrusts (Fig. 3).

A Coniacian-Campanian advance of the orogenic front and its effects on sedimentation

The upper Albian-Turonian Punta Barrosa Formation (Fildani *et al.,* 2003; Fosdick *et al.,* 2011) represents the first coarse grained sediments entering the basin south of 50°30´SL, containing zircon grains derived from Proterozoic, Paleozoic, and Triassic metamorphic complexes (Fildani *et al.,* 2008). Previous studies interpreted that the scarcity of zircon grains in the known age range of the Tobífera Formation implied that Jurassic grabens were not inverted during the Punta Barrosa deposition (Fildani *et al.,* 2008), altought geochemical and petrographic data confirm that the Andean fold-thrust belt influenced the composition of the Punta Barrosa Formation (Fildani & Hessler, 2005). We argue, however, that initial partial positive inversion of Jurassic grabens could have taken place during the Turonian, e.g. along the basement thrust front, exposing only the upper-sag levels of graben infill. The predominance of thick (>1 m) turbidite sand beds reflects the presence of a proto Andean cordillera with deformation restricted to the basement domain and involved conspicuous crustal shortening (Fildani & Hessler, 2005). In light of new U/Pb geochronology of volcanic ash (Fig. 7) interbedded with thin-bedded turbiditic sandstone and shale within the upper parts of the Zapata– Punta Barrosa transition, incipient thrust belt formation was under way as early as 101 Ma (Fosdick et al., 2011).

The shale-rich Cerro Toro Formation represents the climax of deep-water sedimentation (Fildani *et al.,* 2008), where the appearance of grains ca. 160-145 Ma old indicates that the Tobífera Formation really started to provide detritus to the basin during the Santonian and was an important source of detrital sediments by Maastrichtian time (Romans *et al.,* 2009). The Santonian input of Tobífera detritus into the basin seems to represent a reactivation of the basement thrust front since it is the only structure exposing significant outcrops of the Tobífera Formation across the study zone (Fig. 3).

While previous works restricted Late Cretaceous deformation mainly to the hinterland, our data points out that basement uplift and faulting by means of rift inversion during the Coniacian-Santonian produced the partial inversion of a rift depocenter between Lago Argentino and Lago Viedma, extending from río Guanaco on the west up to the eastern coast of the lakes (Figs 3, 5 and 6A). Compressional deformation continued its advance during the Campanian, reaching the Santa Cruz river with inversion of eastward dipping normal faults (Fig. 6B). This means that the non-emergent orogenic front advanced some 50 km, from the basement front up to the eastern boundary of the internal domain (Figs 3 and 6A), and afterward it moved another 30 km reaching east of the Paso Charles Fuhr well (Figs 3 and 6B).

The forward advance of the orogenic thrust front registered in Coniacian-Campanian synkinematic sequences, matches the position of the present leading edge of deformation (Figs 3, 4 and 6). The modern orogenic front is supposed to have reached its position during an important Miocene deformational event (Kraemer, 1998; Fosdick *et al.,* 2013), that was also accompanied by exhumation of the basement domain, as shown by data from apatite fission tracks indicating a 4 to 9 km total amount of exhumation since 30 Ma (Thomson *et al.,* 2001). Miocene uplift and deformation produced the change from the shallow marine condition of a major Cenozoic transgression affecting Patagonia, known as *Patagoniano*

(Centinela Formation) towards nonmarine conditions (Cuitiño & Scasso, 2010; Cuitiño et al., 2012).

Syntectonic unconformities are found along the eastern flank of the monocline at Rio Turbio Locality (Fig. 3) recording a middle Eocene–lower Oligocene deformational event (Malumián et al., 1999; Fosdick et al., 2013) that also forced shallow conditions of sedimentation (see Lagabrielle et al., 2009): The Eocene deformational event involved the passage from marine to shallow marine conditions of the Dorotea and Man Aike Formations towards marine and terrestrial sandstones and conglomerates including syntectonic sequences of the Rio Turbio Formation of middle Eocene age, with coal beds, indicating shallow environments (Griffin, 1991), and followed by the Rio Leona and Rio Guillermo fluvial deposits (upper Eocene–lower Oligocene; Malumián et al., 1999).

Tectono-sedimentary setting

Following the trace of the eastern boundary of the internal domain south of Lago Argentino, it is clearly noticeable that the deposition of conglomeratic channels was confined between main anticlines within the internal domain (Fig. 3). Sedimentological constraint and structural data and interpretation from Crane & Lowe (2008), Gonzales & Aydin (2008) and Bernhardt *et al.,* (2011) indicate that faults located east of the Silla syncline, i.e. a structural position within the internal domain, were also active in the Última Esperanza region during the Coniacian deposition of the western channel system. Crane & Lowe (2008) interpreted that the channel complex in the Silla syncline may mark either an early axial zone of the Magallanes Basin or a local slope mini-basin developed behind a zone of slope faulting and folding now present immediately east of the syncline. In our view, the fact that deposition of conglomerate channels was confined to the present internal domain of the fold-thrust belt, following its actual shape and boundaries (Fig. 3), gives strength to the idea of a causative relationship between deformation and conglomerate deposition. The concept that the main axial channels were deposited in a confined trough, although not necessarily tectonically active, has been proposed before. Conglomerate outcrops south of Sierra del Toro show that sediment distribution is contained within a belt that narrowed southward (Hubbard *et al.,* 2008). Regional relationships suggest that mid to Late Cretaceous sedimentation was confined to an elongate trough that was topographically isolated from the foreland ramp to the east (Wilson, 1991).

From a structural point of view, and taking into account a similar shortening rate from Lago Viedma (26%; Kraemer, 1998) to Lago Toro (20%–23%; Fosdick *et al.,* 2011; this work), it is logical to assume that the eastern boundary of the internal domain, represented by the Simon and Toro thrusts (Figs 4, 5 and 6) was active along its entire trace (Fig. 3) during deposition of the synkinematic sequences at Lago Argentino (Fig. 6A). We see a causality in the fact that deposition of conglomerate channels was confined to the present internal domain of the fold-thrust belt, following its actual shape and boundaries (Fig. 3).
While previous works restricted Late Cretaceous deformation to the basement domain, given the presented data, it is possible to state that during the Coniacian-Campanian, the orogenic front between Argentino and Viedma lakes advanced around 80 km forward from the basement thrust front to the eastern boundary of the internal domain and further east (Figs 3 and 4), affecting the previous foreland depocenter. In this context, orogenic uplift somehow triggered the inception of large axial submarine channels. We assume that deformation probably also affected the internal domain south of Argentino lake, maybe with a lesser magnitude, conditioning the paleogeographic setting where the conglomerates developed.

We argue that the described structural style of positive inversion of N-S oriented Jurassic grabens led to a particular Late Cretaceous paleogeography that controlled the sediment dispersal pattern and distribution of axial channels. This configuration formed longitudinal structural broad submarine valleys divided by ridges, as shown by a recent study (Likerman *et al.,* 2013). Figure 9 is an oblique view of a sandbox analogue model involving the positive inversion of an extensional depocenter with a structural configuration following parameters similar to those of the studied region (see Likerman *et al.,* 2013 for a detailed explanation) that was customized to illustrate the proposed Coniacian-Campanian geodynamic context.

The proposed step by step evolution can be summarized in the following schematic stages (stages A to D from Fig. 9):

A- Turonian foredeep: An initial partial positive inversion of Jurassic grabens could have taken place during the Turonian, e.g. along the basement thrust front, exposing only the upper-sag levels of graben infill. Eastward from the orogen a foredeep depozone developed, where deposition of the Punta Barrosa Formation took place (Fig. 9A).

B- Early Coniacian foredeep: thrust faulting and topographic uplift continued advancing north of Lago Argentino, producing the earlier sea shallowing in that northern region (Fig. 9B).

C- Basement uplift and faulting by means of rift inversion during the Coniacian-Santonian affected the internal domain between Viedma and Argentino lakes, producing the partial inversion of a rift depocenter. Uplift of the Simon thrust, the eastward boundary of the internal domain, probably continued farther south (Toro thrust), encompassing the deposition of the Cerro Toro Conglomerates in a wedge-top depozone (Fig. 9C).

D- Deformation and inversion of rift depocenters continued during the Campanian as shown by the Campanian syntectonic unconformity (Fig. 9D).

Geodynamic Implications

The proposed Coniacian-Santonian advance of the thrust front, that lasted up to the Campanian, is in coincidence with ophiolite obduction at 86 Ma in the Cordillera Sarmiento constituting the basement domain of the study zone (Fig. 4C) that occurred between ca. 85 and 80 Ma (Santonian-early Campanian) with fast uplift rates of ca. 1–2 mm/yr (Calderón *et* *al.,* 2012) producing an increase in the critical taper wedge. It have been proposed before that closure of Rocas Verdes Basin marked by ophiolitic obduction and uplift of the basement domain produced-induced the initiation of the foreland stage in the Magallanes Basin (Fildani & Hessler, 2005; McAtamney *et al.,* 2011). We argue that this fast uplift of the basement domain produced an increase in the critical taper wedge, inducing the cratonward propagation of the orogenic front.

More regionally, a first episode of rapid exhumation and cooling of the Cordillera Darwin representing the continuation of the metamorphic basement domain at Tierra del Fuego (Fig. 1), from 500–600°C to 350°C, took place between 90 and 70 Ma (Kohn *et al.,* 1995). Structural data and U-Pb isotopic ages on zircon from granite plutons near the Beagle Channel (Fig. 1) show that basin inversion and thrusting of the Rocas Verdes Basin on top of adjacent continental crust occurred just prior to ~86 Ma (Klepeis *et al.,* 2010).

The described ~80 km advance of the orogenic front throughout the internal domain, together with a ca. 8 km exhumation of the Sarmiento Complex (Calderón *et al.,* 2012), implies that the Late Cretaceous deformational event was more significant in terms of uplift and widening of the orogenic wedge than subsequent Andean deformation.

This deformational event coincides in time with the final closure of the Rocas Verdes basin ocean, and geodynamic reconstructions predicting the collision of its western margin and the Antarctic Peninsula against the Patagonian-Fuegian Andes(Suarez et al., 2010) between 95 and 84 Ma (Fig. 10; Vérard *et al.,* 2012). It also clearly coincides with the westward acceleration of South America in the Late Cretaceous between 90 and 80 Ma, suggesting that the continent episodically overrode the Andean trench by that time (Somoza and Saffarana, 2008). The 103 to 84 Ma period coincides also with an acceleration of the opening of the Atlantic Ocean (measured in Fig. 5 from Vérard et al., 2012), in accordance with intracontinental compressional stresses due to ridge push forces. An earlier deformational event affecting northern Patagonia occurred between ~122 and 118 Ma, associated to ridge push forces against the patagonian passive margin during the Aptian high-speed opening of the south Atlantic Ocean (Ghiglione et al., 2014).

Our data supports the idea that the collision of the western rim of Rocas Verdes Basin was an orogenic building process itself (e.g. Cunningham, 1995; Suarez et al., 2010; Calderón et al., 2012; McAtamney et al., 2011) together with Atlantic ridge push forces due to its accelerated opening. This tectonic configuration (Fig. 10) explain the absence of a subduction-related volcanic arc from 126 to 75 Ma west of the study zone as shown by U–Pb SHRIMP zircon age from the Patagonian Batholith (see yellow hexagons in Fig.1, Hervé *et al.*, 2007). A major global plate reorganization that occurred between 105 and 100 Ma, could have driven the Rocas Verdes Basin closure (Matthews *et al.,* 2012) and provide the force needed to produce a significant collision-related orogeny.

Previous tectonic studies further north interpreted the Late Cretaceous Patagonian deformational event as the consequence of the Pacific ocean plate's fast orthogonal subduction, flat-slab subduction or ridge collision against South America (Suarez *et al.,* 2000; Ramos, 2005; Somoza & Ghidella 2005, 2012; Ghiglione & Cristallini, 2007; Ramos & Ghiglione, 2008) that could have also acted as geodynamic factors producing Rocas Verdes closure and Andean mountain building.

CONCLUSIONS

1. While previous works restricted Late Cretaceous deformation to the present basement domain, synkinematic sequences show that initial deformation of the Patagonian Andes fold-thrust belt began during the Coniacian-Santonian. Basement uplift and faulting by means of rift inversion during the Coniacian-Campanian produced the partial inversion of rift depocenters forming the internal domain. The non-emergent orogenic front advanced

some 50 km, from the basement front up to the eastern boundary of the internal domain, and afterward it advanced another 30 km to the east.

2. A causative relationship between deformation in the fold-thrust belt and deposition of contemporaneous Cerro Toro Formation axial conglomeratic channels systems, is proposed. In this context, deposition of Cerro Toro Formation conglomerates took place in a wedge top-depozone. The positive inversion of N-S oriented Jurassic grabens led to a particular Late Cretaceous paleogeography that controlled the sediment dispersal pattern and distribution of axial channels. This configuration formed longitudinal structural broad submarine valleys divided by ridges.

3. The described ~50-80 km advance of the orogenic front throughout the internal domain, together with the exhumation of the basement domain, implies that the Late Cretaceous deformational event was more significant in terms of orogenic wedge widening than all subsequent Andean deformational stages.

4. This south Patagonian orogenic event can be related to compressional stresses generated by the combination of both the collision of the western margin of Rocas Verdes Basin during its closure, and Atlantic ridge push forces due to its accelerated opening, during a global-scale plate reorganization event.

5. Later Eocene and Miocene deformation followed the position of the Late Cretaceous orogenic front, and also produced previously studied changes in sedimentary conditions.

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FIGURES

Fig. 1: Location of the study zone from high-resolution digital elevation model (DEM; Mercator projection) from processed National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission data (SRTM; Farr *et al.,* 2007) showing sediment distribution from Austral basin. Contours indicate foreland sediment thickness within the undeformed depocenters from seismic information in kilometers are from Heine (2007) at ***www.basinatlas.com***; outcrop information is not represented. Yellow hexagons show distribution of 126 to 75 Ma U–Pb SHRIMP zircon age for the Patagonian Batholith from Hervé

et al. (2007). FTB – fold-thrust belt; RVB – Rocas Verdes Marginal Basin; TJ: Triple Junction.

Fig. 2: Top: Simplified stratigraphic columns from north and south of Lago Argentino and their correlation. Left column is representative of Última Esperanza and Río Turbio sectors from Fosdick et al. (2011) and references therein. Right column correspond to sector between Argentino and Viedma lakes modified after Kraemer & Riccardi (1997). Lateral correlation between both profiles is after Macellari et al. (1989) and Bernhardt *et al.,* (2012). CaU: Campanian syntectonic angular unconformity; CoU: Coniacian syntectonic angular unconformity; CoP: Coniacian Paraconformity; **Bottom:** *Inoceramus steinmanni* Wilckens. Left, specimen with partially preserved shell in lateral view from Cerro Solitario, original collection of Hauthal (1905), Cerro Toro Formation (CPBA 8061), Right, external mould in lateral view from Laguna 3 de Abril (CPBA 20990.1). Specimens whitened with ammonium chloride. Scale bar 1 cm. Repository: CPBA, Paleontology Collection, University of Buenos Aires. Time scale is from the International Commission on Stratigraphy - ICS (2013), www.stratigraphy.org.

Fig. 3: Integrated geological map of the study zone, based on collected field data, and on SERNAGEOMIN (2003); Wilson (1991); Kraemer (1998); Malumián *et al.,* (2000); Gonzalez & Aydin (2008); Fosdick *et al.,* (2011). Deep Water channels modified from Hubbard et al. (2007). See Fig. 1 for location.

Fig. 4: Structural cross sections. See Fig. 3 for locations.Cordillera Sarmiento sector from Section 4C is modified after Calderón et al. (2012).

Fig. 5: Seismic time sections. **A-B:** Profiles across the fold-thrust belt showing conspicuous influence of tectonic inversion. Seismic horizons are: An: Anita Formation; AV: Alta Vista Formation; CT: Cerro Toro Formacion; EQ: El Quemado Formation; RM: Río Mayer Formation. See Fig. 3 for location.

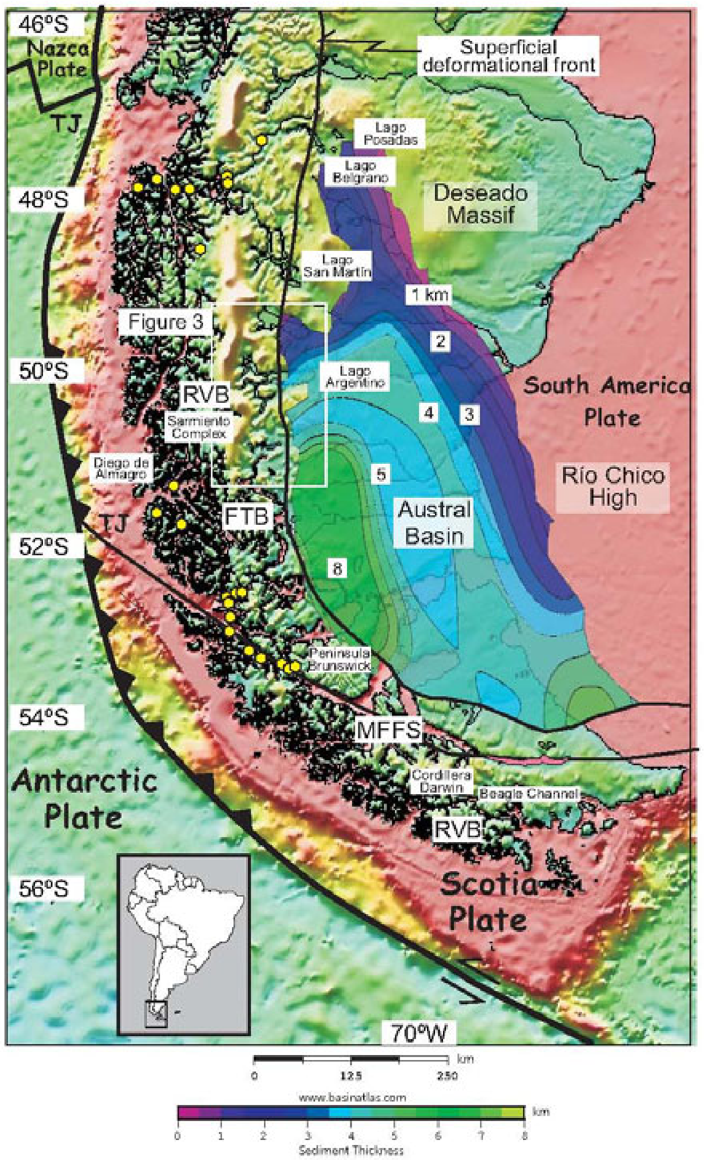
Fig. 6: Seismic time sections showing syntectonic angular unconformities. **A:** Seismic line from the northern shore of Lago Argentino, showing a Coniacian-Santonian syntectonic angular unconformity within the Cerro Toro Formation along the northern boundary of the internal domain. **B:** Seismic line along the Santa Cruz river showing early Campanian unconformities between the Alta Vista Formation and the Anita Formation. Age of seismic horizons was correlated from available exploratory wells (see text). Seismic horizons are: An: Anita Formation; AV: Alta Vista Formation; CT: Cerro Toro Formacion; CaU: Campanian syntectonic angular unconformity; CoU: Coniacian syntectonic angular unconformity; CoP: Coniacian Paraconformity; ELQ: El Quemado Formation; JKB: Jurassic-Cretaceous boundary; KTB: Cretaceous-Tertiary boundary; PPC: probable paleochannel; RMY: Río Mayer Formation. Stratigraphic intervals after Kraemer & Riccardi (1997) and Kraemer (1998). See Fig. 3 for location**.**

Fig. 7: Forward kinematic modeling for section 4C constructed with the *2D Move* software (© copyright Midland Valley Exploration Ltd).

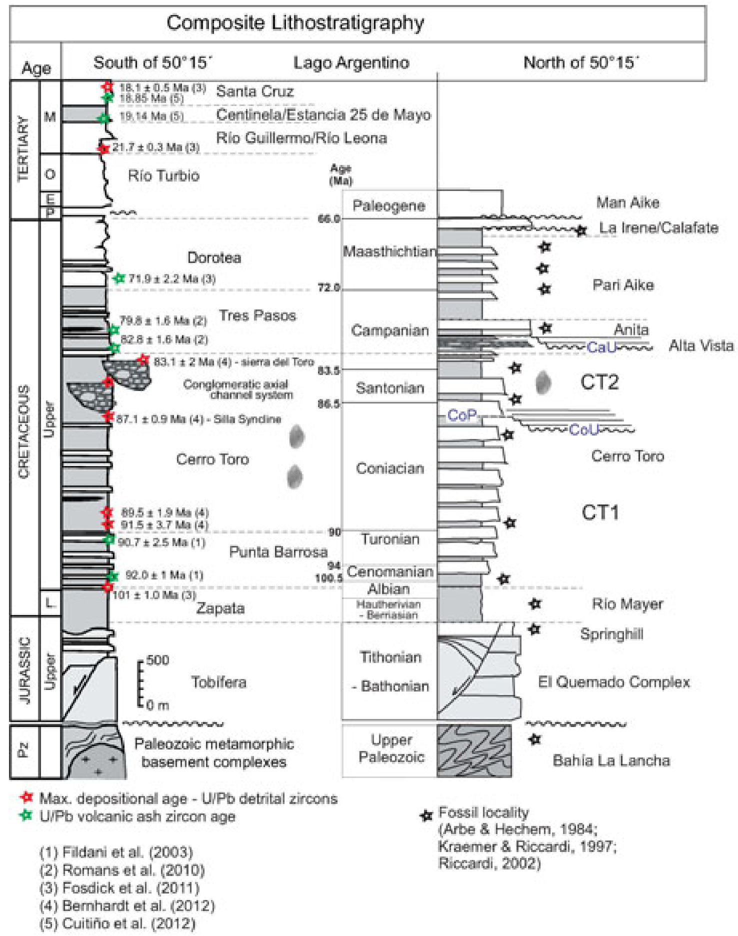
Fig. 8: Angular unconformity at Cerro Teta, on the southern shore of Lago Viedma, photograph is looking to the SE. Sandstone crest at the bottom of the hill belogs to lower Campanian upper Alta Vista Formation and dips ~5-10º to the SW, while overlaying sandtones on top of the hill constitute the Asunción Member of the lower Anita Formation with an average dip of ~30º SW, also lower Campanian. CaU: Campanian syntectonic angular unconformity.

Fig. 9: **Top:** Proposed Coniacian-Campanian geodynamic context. **A** to **D** Turonian to Campanian paleogeographic reconstructions showing proposed geodynamic context for the deposition of Cero Toro conglomerates. See text for discussion.

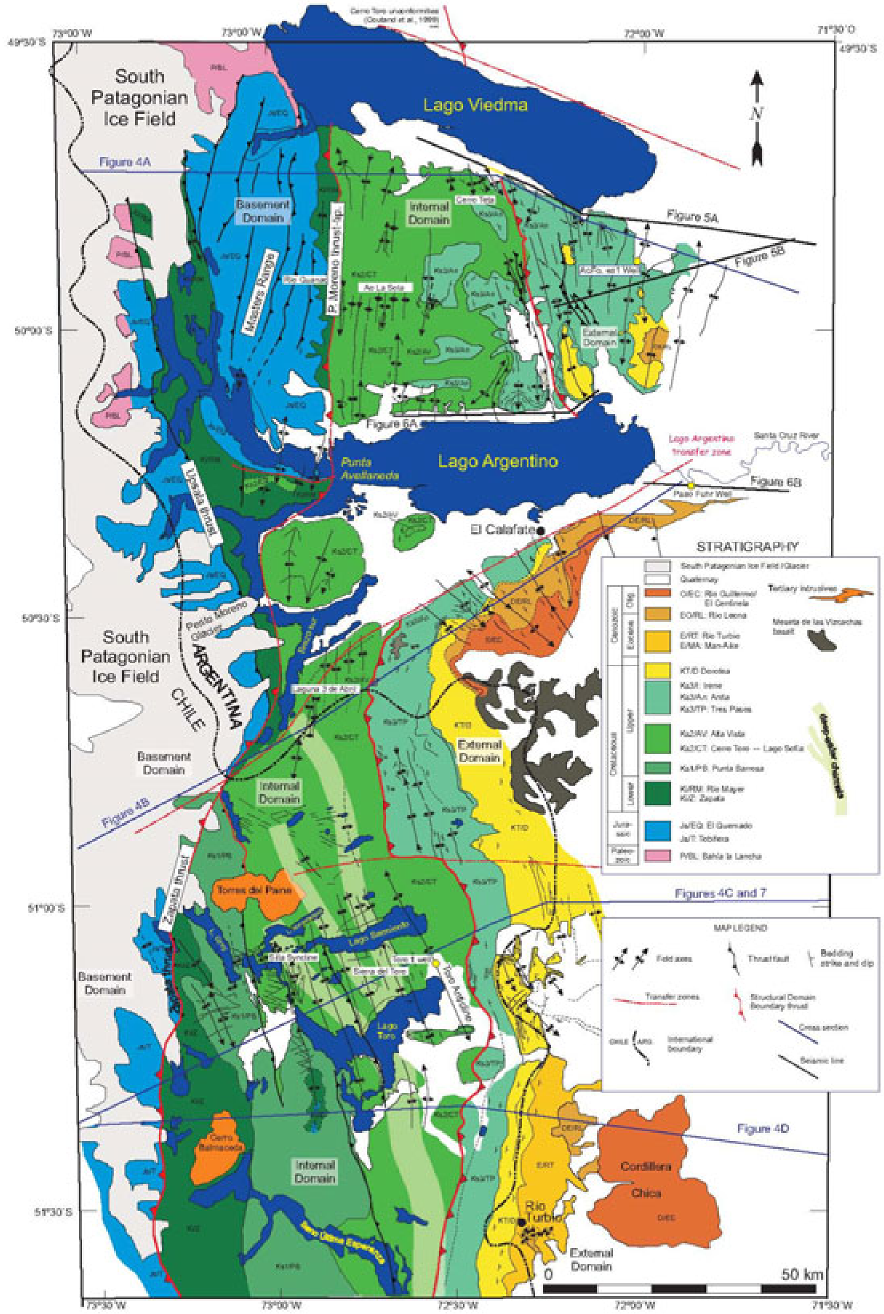
Fig. 10: Paleotectonic reconstruction showing the changing regional geodynamic context of the study zone. **A:** Final stages of Rocas Verdes basin closure, coincident with initial basement uplift. **B:** Basin closure trough collision of its western margin produced strong basement uplift and forward migration of the orogenic front throughout cratonward transfer of shortening. RV: Rocas Verdes Basin; CDF: Canal Darwin fault mapped from Glasser & Ghiglione, 2009. Modifed from Vérard *et al.* (2012) and Suarez et al. (2010). Distribution and convergence of Pacific ocenic plates is from Somoza & Ghidella (2012).



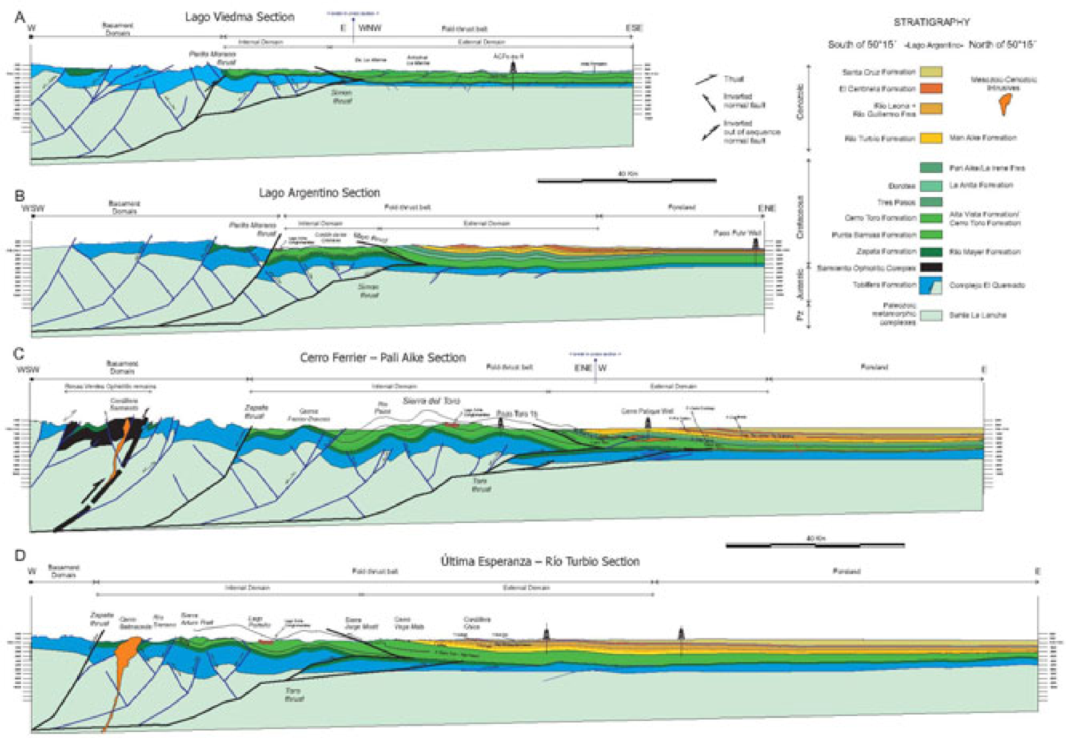
Ghiglione et al. ms - Figure 1


Composite Lithostratigraphy
Age
South of 50°15´
Lago Argentino
North of 50°15´
TERTIARY
CRETACEOUS
JURASSIC
Pz
Upper
Santa Cruz
Centinela/Estancia 25 de Mayo
Río Guillermo/Río Leona
Río Turbio
Dorotea
Tres Pasos
Conglomeratic axial channel system
Cerro Toro
Punta Barrosa
Zapata
Tobífera
Paleozoic metamorphic basement complexes
Paleogene
Maasthichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Hauterivian - Berriasian
Tithonian - Bathonian
Upper Paleozoic
Man Aike
La Irene/Calafate
Pari Aike
Anita
Alta Vista
CT2
Cerro Toro
CT1
Río Mayer
Springhill
El Quemado Complex
Bahía La Lancha
Max. depositional age - U/Pb detrital zircons
U/Pb volcanic ash zircon age
(1) Fildani et al. (2003)
(2) Romans et al. (2010)
(3) Fosdick et al. (2011)
(4) Bernhardt et al. (2012)
(5) Cuitiño et al. (2012)
Fossil locality (Arbe & Hechem, 1984; Kraemer & Riccardi, 1997; Riccardi, 2002)

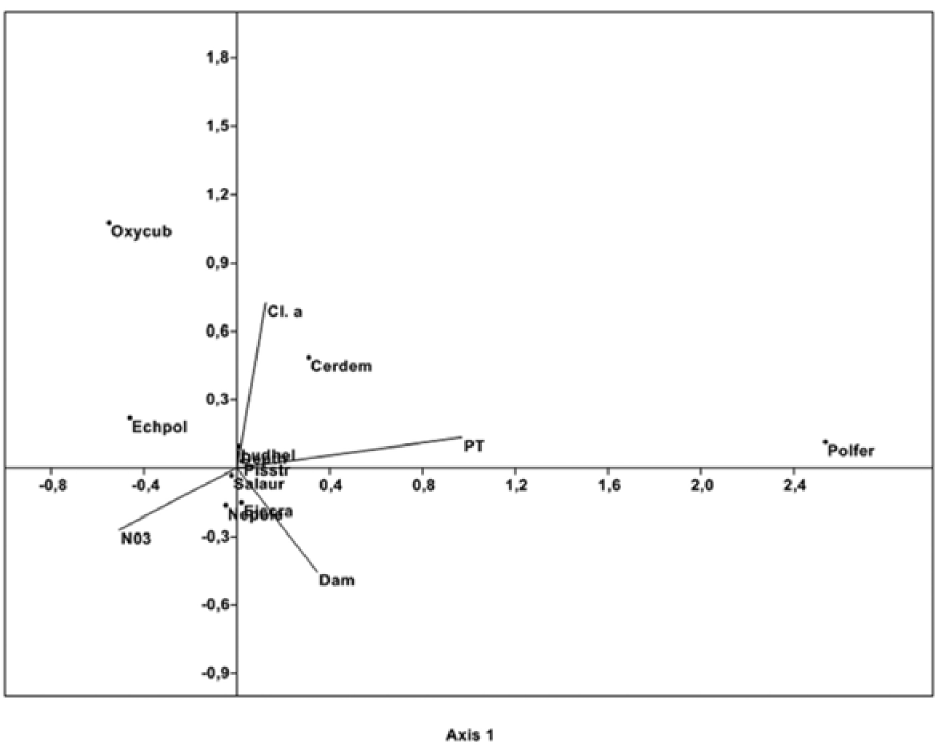

1 cm
Inoceramus steinmanni Wilckens



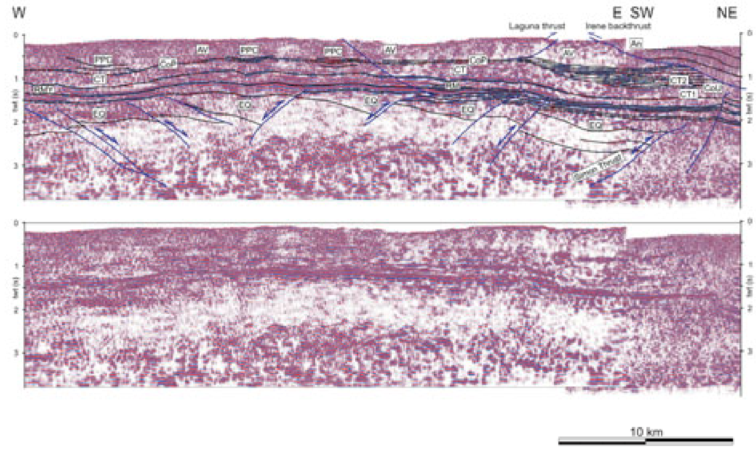
Ghiglione et al. ms - Figure 3



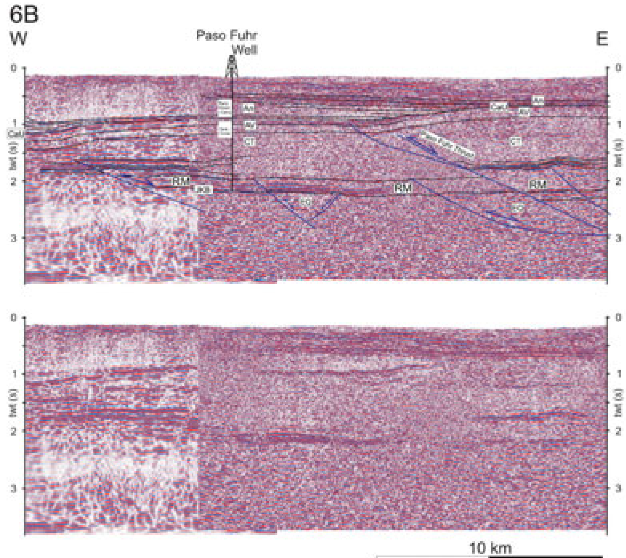
Ghiglione et al. ms - Figure 4

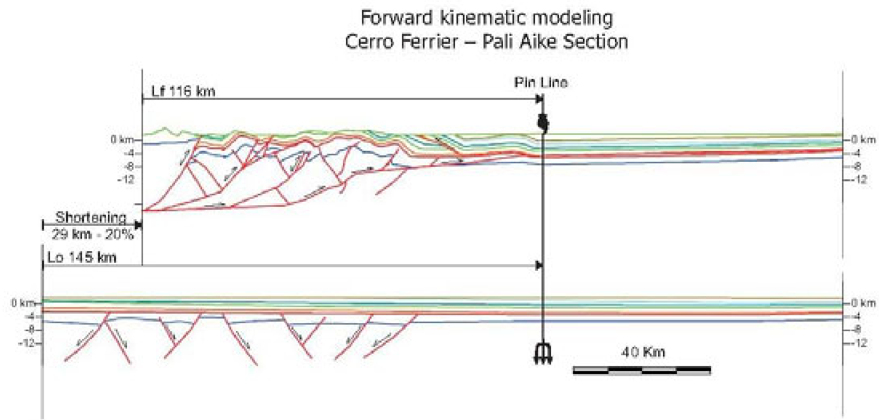


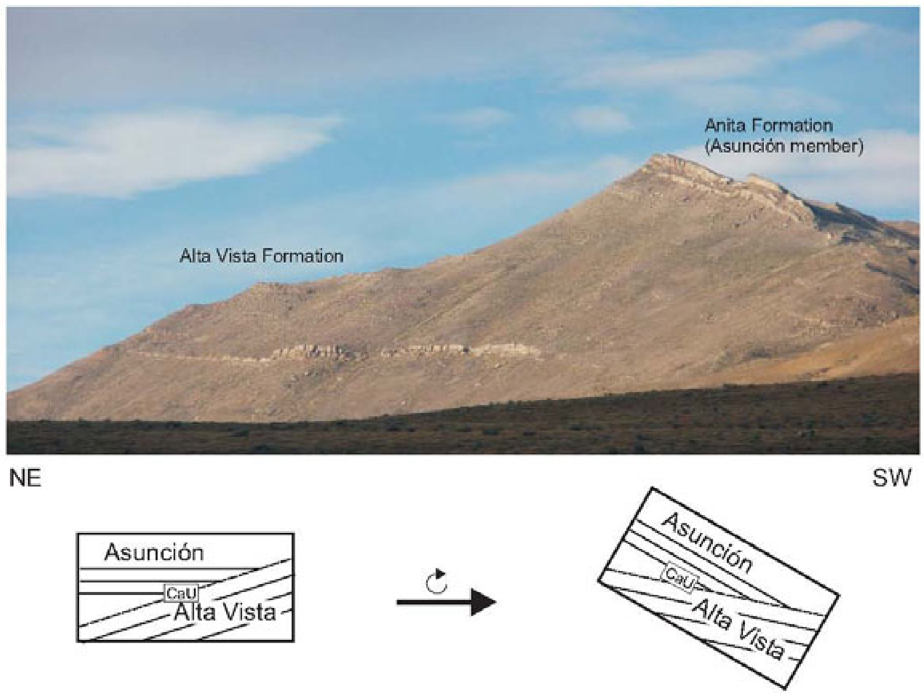
6A

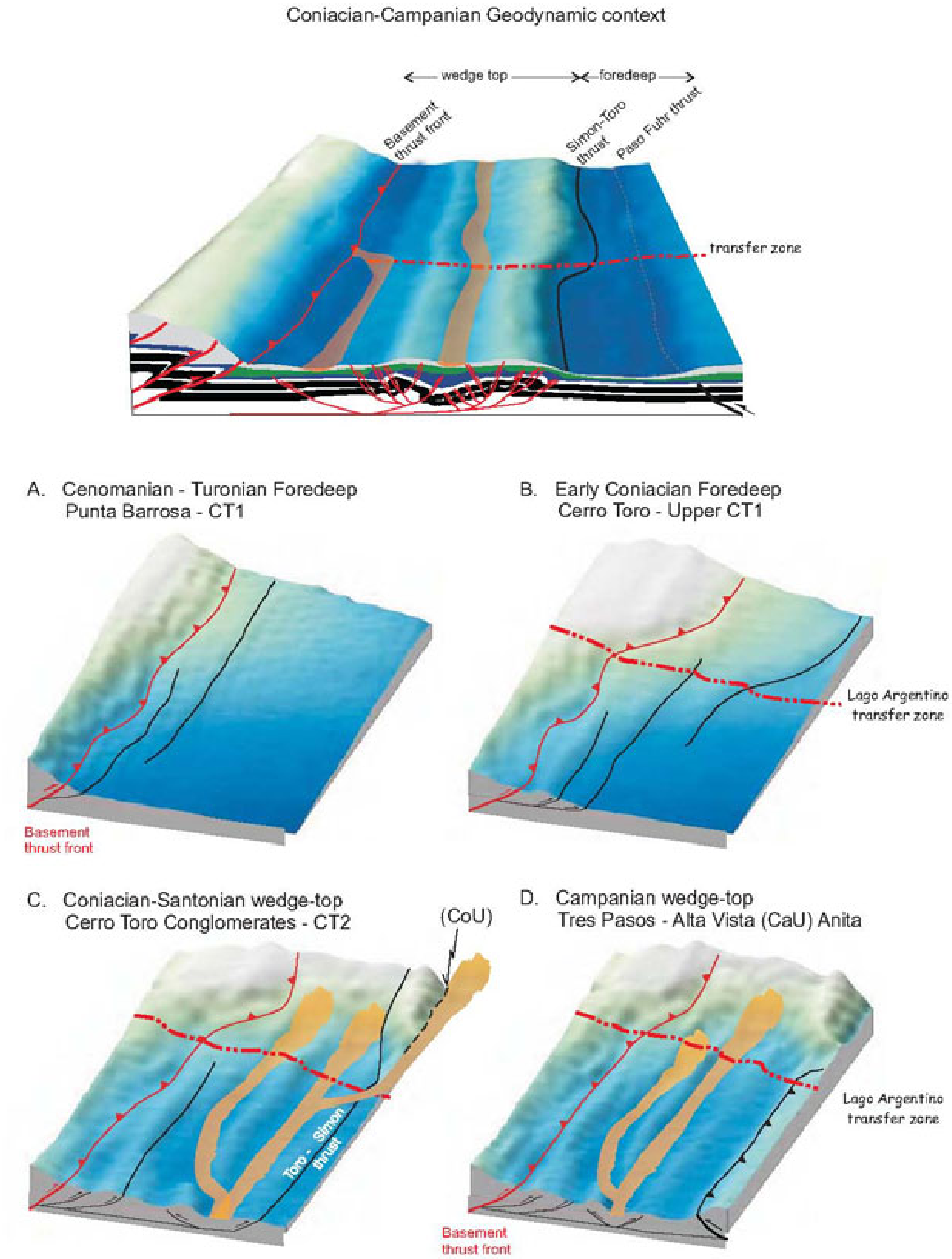

W
E SW
NE
Laguna thrust
Irene backthrust
twt (s)
10 km

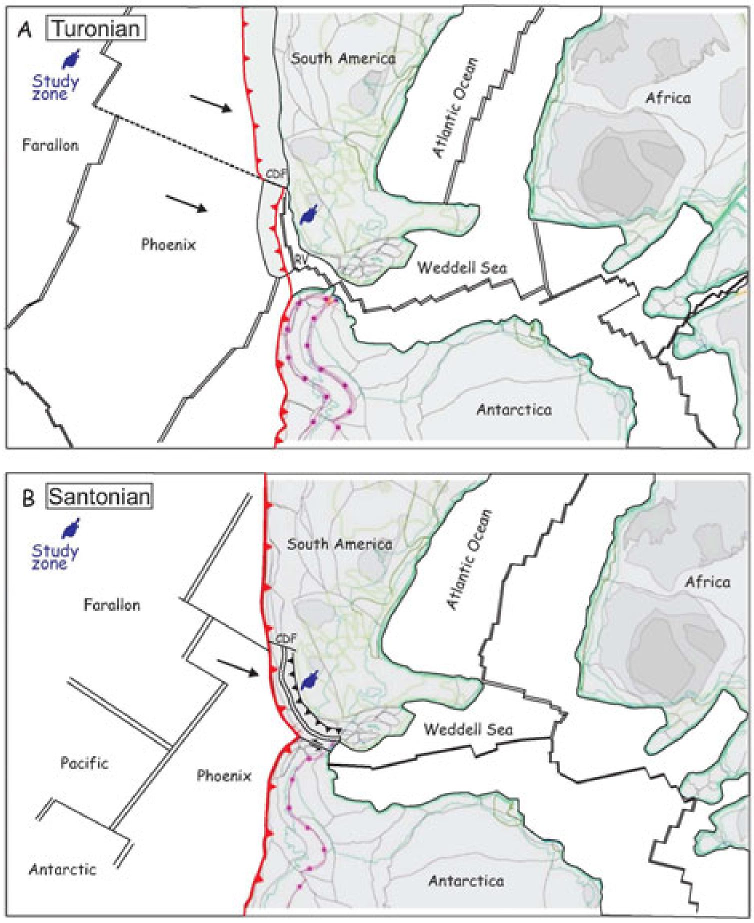
6B


W
Paso Fuhr
Well
E
RM
CT
twt (s)
10 km


Forward kinematic modeling
Cerro Ferrier – Pali Aike Section
Lf 116 km
Pin Line
0 km
-4
-8
-12
Shortening
29 km - 20%
Lo 145 km
40 Km


Anita Formation
(Asunción member)
Alta Vista Formation
NE
SW
Asunción
CaU
Alta Vista
Asunción
CaU
Alta Vista


Coniacian-Campanian Geodynamic context
wedge top
foredeep
Basement thrust front
Simon-Toro thrust
Paso Fuhr thrust
transfer zone
A. Cenomanian - Turonian Foredeep
Punta Barrosa - CT1
Basement thrust front
B. Early Coniacian Foredeep
Cerro Toro - Upper CT1
Lago Argentino transfer zone
C. Coniacian-Santonian wedge-top
Cerro Toro Conglomerates - CT2
(CoU)
Toro - Simon thrust
D. Campanian wedge-top
Tres Pasos - Alta Vista (CaU) Anita
Lago Argentino transfer zone
Basement thrust front


A Turonian
Study zone
Farallon
Phoenix
CDF
RV
South America
Atlantic Ocean
Africa
Weddell Sea
Antarctica
B Santonian
Study zone
Farallon
Pacific
Phoenix
Antarctic
CDF
South America
Atlantic Ocean
Africa
Weddell Sea
Antarctica