Evaluation of strain and structural style variations along the strike of the Fuegian thrust-fold belt front, Argentina

*Pablo J. Torres Carbonell[1], Luis V. Dimieri[2], Eduardo B. Olivero[1]

[1] *Centro Austral de Investigaciones Científicas (CADIC-CONICET). Bernardo A. Houssay 200, 9410 Ushuaia, Tierra del Fuego, Argentina.*
torrescarbonell@cadic-conicet.gob.ar; emolivero@gmail.com

[2] *Instituto Geológico del Sur (INGEOSUR-CONICET), Departamento de Geología, Universidad Nacional del Sur. San Juan 670, 8000 Bahía Blanca, Buenos Aires, Argentina.*
ldimieri@uns.edu.ar

*Corresponding author. torrescarbonell@cadic-conicet.gob.ar

ABSTRACT. The Fuegian thrust-fold belt (TFB) forms the thin-skinned outer wedge of the Andes in Tierra del Fuego. Using subsurface and outcrop data from two areas (Western and Eastern) of the TFB front in Argentina we aimed to verify and characterize the apparent structural variations along the strike. Both areas reveal pro- and retro-vergent fault-related folds detached at similar horizons, with a youngest early to middle (?) Miocene deformation age. However, the Western Area has gentle, large-wavelength folds whereas the Eastern Area is characterized by a very tight structural geometry, with closer fold geometries. This difference manifests itself in the shortening of analogous structures: below 5.5% in the west as against ~22% in the Eastern Area. Our findings verify structural style variations along the strike and suggest that the Eastern Area endured higher strain. We evaluate two possible causes of this strain gradient, assuming homogeneous regional shortening: (**i**) lateral rheological variations at the base of the thrust wedge, namely the occurrence of more competent beds which would have restrained the propagation of the detachment toward the east; and (**ii**) the effect of strong buttressing in the eastern TFB exerted by the Río Chico arch basement promontory during deformation. Published results, together with our current subsurface and outcrop data, rule out significant rheological gradients in a preferred direction along the TFB. On the other hand, we present evidence of the nucleation of frontal thrusts above basement steps at the Río Chico arch western margin, which comprise local buttresses. We speculate that this buttressing was mantained along the TFB front and is enhanced toward the east, where forward TFB propagation was hindered due to the southern projection of the Río Chico promontory. This would explain the higher strain and more complex structural style in the Eastern Area.

Keywords: Thrust-fold belt front, Structural style, Shortening, Buttressing, Río Chico arch, Fuegian Andes.

RESUMEN. Evaluación de variaciones en el grado de deformación y el estilo estructural a lo largo del frente de la faja corrida y plegada Fueguina, Argentina. La faja corrida y plegada Fueguina (FCP) comprende el cinturón de piel fina en el antepaís de los Andes en Tierra del Fuego. Con la finalidad de verificar y caracterizar posibles variaciones estructurales a lo largo del frente de la FCP en Argentina, hemos analizado datos de subsuelo y superficie en dos áreas (occidental y oriental). Ambas revelan pliegues relacionados con fallas, tanto provergentes como retrovergentes, que despegan en niveles similares, y tienen una edad mínima miocena temprana a media (?). Sin embargo, en el área occidental el plegamiento es suave y de alta longitud de onda mientras que en el área oriental la estructura es muy apretada, con pliegues más cerrados. Esta diferencia se manifiesta al comparar el acortamiento en estructuras análogas: menor a 5,5% en el oeste contra ~22% en el área oriental. Por lo tanto, queda verificada la existencia de variaciones en el estilo estructural a lo largo del rumbo, y se pone en evidencia que el área oriental fue sometida a mayor deformación. Evaluamos dos causas posibles para este gradiente de deformación, asumiendo una magnitud de acortamiento regional homogénea: (**i**) variaciones laterales en la reología de la base de la FCP, por ejemplo capas más competentes hacia el este que podrían haber dificultado la propagación del despegue en ese sector, y (**ii**) una fuerte obstaculización al avance de la FCP en el este, ejercida por el promontorio de basamento del Arco Río Chico. La información publicada previamente, así como los datos de este trabajo, descartan un gradiente reológico significativos en una dirección preferencial a lo largo de la FCP. Al contrario, nuestros datos evidencian localización de corrimientos frontales sobre escalones en el basamento del Arco Río Chico en el área occidental, que localmente obstaculizan el avance de la deformación. Especulamos con que este efecto obstaculizador se mantuvo a lo largo del frente de la FCP, con mayor intensidad hacia el este, donde el avance de la FCP fue restringido por la proyección austral del arco Río Chico. De esta manera se puede explicar la mayor deformación y el estilo estructural más complejo en el área oriental.

Palabras clave: *Frente de la faja corrida y plegada, Estilo estructural, Acortamiento, Promontorio, Arco Río Chico, Andes Fueguinos.*

1. Introduction

The Fuegian thrust-fold belt (TFB) constitutes the thin-skinned outer wedge of the Fuegian Andes orogenic belt in Tierra del Fuego, Argentina (Fig. 1). The structures at the leading edge of this belt involve strata from the Upper Cretaceous to Neogene infill of the Austral (Magallanes) foreland basin (Olivero and Malumián, 2008; Torres Carbonell *et al.*, 2011), an important hydrocarbon source in southernmost South America (Rossello *et al.*, 2008). Many previous structural studies assessed the TFB on a regional scale (*e.g.*, 1:500,000), providing cross sections focusing on the general structural style (*e.g.*, Álvarez-Marrón *et al.*, 1993; Kraemer, 2003; Rojas and Mpodozis, 2006; Ghiglione *et al.*, 2010). Although the TFB front overlaps with the zone of hydrocarbon exploration in the Austral basin (Robbiano *et al.*, 1996; Rossello *et al.*, 2008), published studies on its detailed geometry are sparse. The few papers presenting detailed data on the TFB front are mostly constrained to good outcrops from the Atlantic coast of Tierra del Fuego (Ghiglione *et al.*, 2002; Torres Carbonell *et al.*, 2008a).

Despite the lack of detail, a significant variation in structural style along the strike of the foreland TFB is apparent from the regional studies, although this may be partly due to differences of interpretation (Alvarez-Marrón *et al.*, 1993; Torres Carbonell *et al.*, 2008a; Ghiglione *et al.*, 2010). The purpose of this work is to verify and characterize these apparent variations in structural style through the detailed analysis of two selected areas of the TFB front in Argentina, combining outcrop and subsurface information. In this manner we provide additional information concerning the geometric constraints on the deformation front, establishing a basis for evaluating the possible causes of differential evolution along the TFB front and providing important insight into the boundary conditions that may have influenced such evolution.

2. Methodology

Two areas of the TFB were selected for this study, based on data availability. The two areas (Western and Eastern, see below) are separated by ~140 km along the strike (Figs. 1 and 2); data from the Western Area include abundant subsurface information, whereas the Eastern Area bears the best exposures of the TFB in Argentine Tierra del Fuego.

Outcrop data used in this paper were obtained using traditional mapping techniques integrated into detailed maps (Fig. 2), from which balanced cross sections were produced (*e.g.*, Torres Carbonell *et al.*, 2008a; Torres Carbonell *et al.*, 2011). These cross
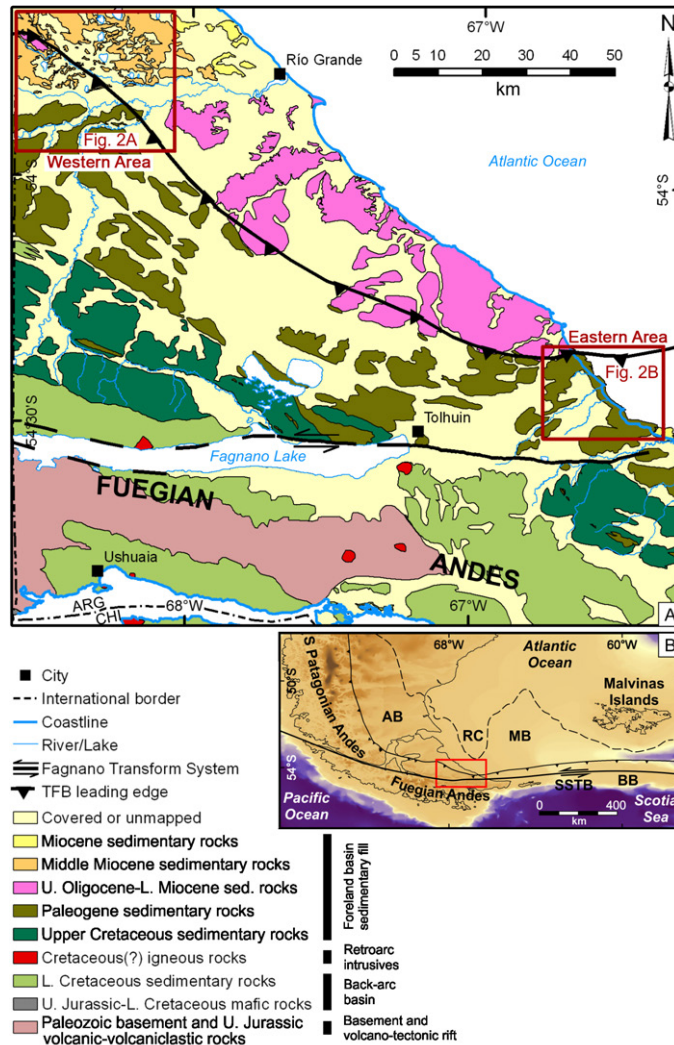
FIG. 1. **A.** Main geologic features of Tierra del Fuego, with location of the areas of the Fuegian thrust-fold belt front (TFB) selected for this study. **CHI**: Chile; **ARG**: Argentina. Based on Olivero and Malumián (2008) and authors' data; **B.** Regional situation of Tierra del Fuego. Red rectangle marks area of figure 1A. **AB**: Austral basin; **MB**: Malvinas basin; **RC**: Río Chico arch; **SSTB**: Scotia-South America plates transform boundary; **BB**: Burdwood bank. Digital Elevation Model from the GEBCO One Minute Grid, version 2.0 (http://www.gebco.net).

sections provide a geometrically reasonable solution that, despite not being unique, is very useful for constraining structural geometries.

Subsurface data consist of seismic reflection lines, mostly 2D, with complementary well logs that help to identify key horizons tracked across the Austral Basin (*e.g.*, Masiuk *et al.*, 1990; Robbiano *et al.*, 1996) (Fig. 3). This data set was provided by Pan American Energy between 2002 and 2006, and was combined with limited published information (Cagnolatti *et al.*, 1987) to construct structural maps

of the TFB leading edge in an area of approximately 120 km² (Fig. 2A). In addition, seismic line interpretations allowed us to construct cross sections from which a shortening estimate was possible.

3. Stratigraphy

The stratigraphic framework of the frontal TFB (Fig. 3) comprises several lithostratigraphic units originated during the Mesozoic-Cenozoic evolution of southern South America. The oldest rocks in the
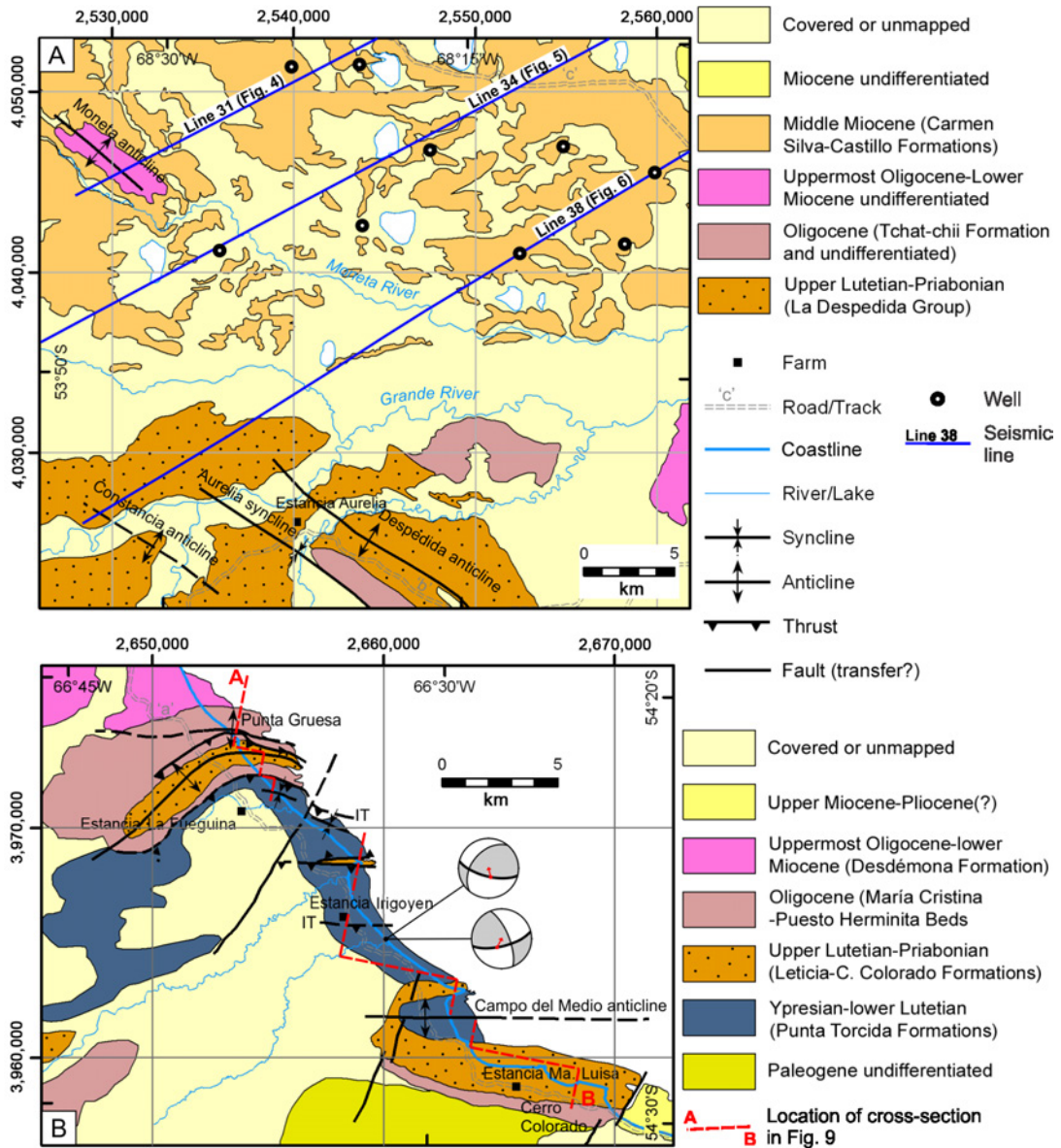
FIG. 2. **A.** Geologic map of the Western Area of this study, with location of figures 4, 5, and 6; **B.** Geologic map of the Eastern Area, with location of figure 9. **IT**: Irigoyen thrust. Fault solution diagrams (equal area, lower hemisphere) are for fault sets in the hangingwall of the IT (described in text): bold lines represent the fault plane and red dots slickenlines with sense of hangingwall movement; white and gray correspond to P and T quadrants, respectively. Planar coordinates in both maps are Gauss Krüger (Argentina zone 2). See figure 3 for the stratigraphic nomenclature.

area include Paleozoic igneous and metamorphic rocks (Söllner *et al.*, 2000; Hervé *et al.*, 2010). These rocks are unconformably covered by volcanic and volcaniclastic rocks of the Tobífera Formation (Thomas, 1949; Flores *et al.*, 1973), which filled grabens and hemigrabens in a volcano-tectonic rift

formed in the region (SW Gondwana) during the Late Jurassic (Wilson, 1991; Calderón *et al.*, 2007).

The Tobífera Formation is unconformably covered by Lower Cretaceous sedimentary rocks deposited during continued extension, which led to the evolution of the prior volcano-tectonic rift into

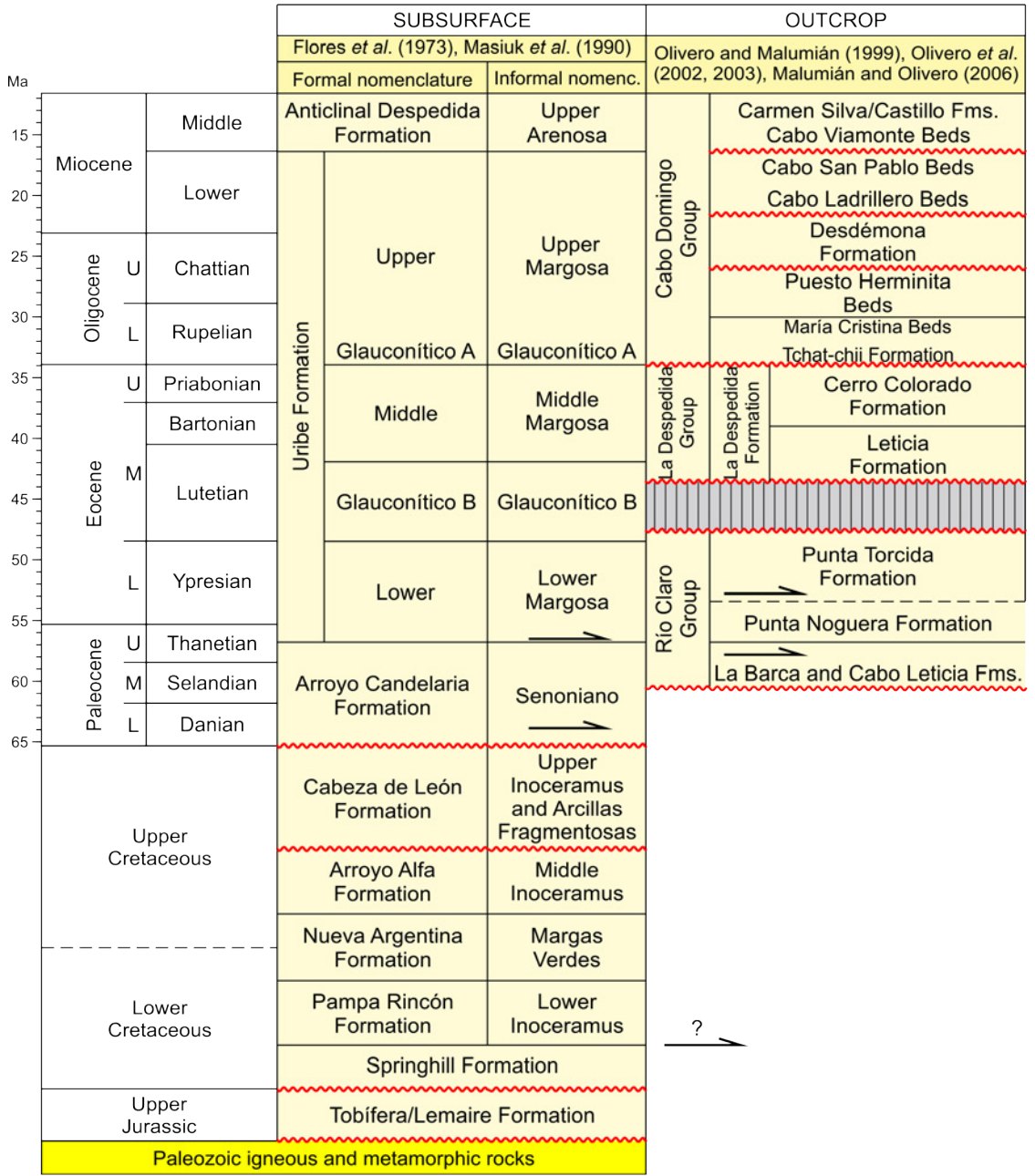| Ma	Age			SUBSURFACE — Flores *et al.* (1973), Masiuk *et al.* (1990)		OUTCROP — Olivero and Malumián (1999), Olivero *et al.* (2002, 2003), Malumián and Olivero (2006)
				Formal nomenclature	Informal nomenc.	
15	Miocene		Middle	Anticlinal Despedida Formation	Upper Arenosa	Carmen Silva/Castillo Fms. Cabo Viamonte Beds (Cabo Domingo Group)
20	Miocene		Lower	Uribe Formation — Upper	Upper Margosa	Cabo San Pablo Beds; Cabo Ladrillero Beds (Cabo Domingo Group)
25	Oligocene	U	Chattian	Uribe Formation — Upper	Upper Margosa	Desdémona Formation; Puesto Herminita Beds (Cabo Domingo Group)
30	Oligocene	L	Rupelian	Glauconítico A	Glauconítico A	María Cristina Beds; Tchat-chii Formation (Cabo Domingo Group)
35	Eocene	U	Priabonian	Middle	Middle Margosa	Cerro Colorado Formation (La Despedida Group / La Despedida Formation)
40	Eocene		Bartonian	Middle	Middle Margosa	Leticia Formation
45	Eocene	M	Lutetian	Glauconítico B	Glauconítico B	
50	Eocene	L	Ypresian	Lower	Lower Margosa	Punta Torcida Formation (Rio Claro Group)
55	Paleocene	U	Thanetian	Lower	Lower Margosa	Punta Noguera Formation (Rio Claro Group)
60	Paleocene	M	Selandian	Arroyo Candelaria Formation	Senoniano	La Barca and Cabo Leticia Fms. (Rio Claro Group)
65	Paleocene	L	Danian	Arroyo Candelaria Formation	Senoniano	
	Upper Cretaceous			Cabeza de León Formation	Upper Inoceramus and Arcillas Fragmentosas	
	Upper Cretaceous			Arroyo Alfa Formation	Middle Inoceramus	
	Lower Cretaceous			Nueva Argentina Formation	Margas Verdes	
	Lower Cretaceous			Pampa Rincón Formation	Lower Inoceramus	?
	Lower Cretaceous			Springhill Formation		
	Upper Jurassic			Tobífera/Lemaire Formation		
				Paleozoic igneous and metamorphic rocks		

FIG. 3. Stratigraphic framework of the TFB and Austral foreland basin in Argentine Tierra del Fuego, based on subsurface and outcrop studies (cited in the figure). The main detachment horizons of the studied areas are shown. The chronostratigraphic boundaries are set according to the most recent calibrations (most accurate for the Cenozoic units), obtained from outcrop studies (summarized in Malumián and Olivero, 2006; Olivero and Malumián, 2008). **U**: Upper; **M**: Middle; **L**: Lower.

a back-arc basin (Biddle *et al.*, 1986; Wilson, 1991; Calderón *et al.*, 2007). In the study area subsurface, this succession is a very homogeneous shaly package (Flores *et al.*, 1973; Biddle *et al.*, 1986; Olivero and Martinioni, 2001) subdivided into several units known by both informal and formal nomenclature, as depicted in figure 3. None of these Cretaceous units crop out at the TFB front.

The Lower Cretaceous rocks are covered by Upper Cretaceous-Cenozoic sedimentary rocks accummulated in the Austral (Magallanes) foreland basin (Olivero and Malumián, 2008). This basin formed due to foreland flexure during closure of the Late Cretaceous back-arc basin and subsequent growth of the Fuegian Andes (Biddle *et al.*, 1986; Wilson, 1991; Olivero and Martinioni, 2001). While the Upper Cretaceous rocks are lithologicaly not very different from the Lower Cretaceous rocks (Flores *et al.*, 1973; Olivero and Martinioni, 2001), the Cenozoic package, with a minimum thickness of 3,000 m at its thickest portions, is composed of interbedded conglomerates, sandstones and mudstones. These deposits form marine clastic wedges that evolved in synchrony with the advance of the TFB (Olivero and Malumián, 2008; Ponce *et al.*, 2008; Torres Carbonell *et al.*, 2009; Martinioni, 2010; Torres Carbonell, 2010). The nomenclature of the Cenozoic units in the TFB front is shown in figure 3. Further information on the sedimentologic, stratigraphic, and tectonostratigraphic features of these units, not pertinent to the current work, can be found in the cited references (Fig. 3).

The lithostratigraphic units of the frontal TFB are differently involved in the orogenic wedge of the Fuegian Andes. In the leading edge of the TFB, the structural basement (*i.e.*, the rocks below the basal detachment) is composed of Paleozoic rocks, the Tobífera Formation and the lowermost Cretaceous horizons (Springhill Formation?) (Fig. 3). Younger Lower Cretaceous rocks act as a favorable detachment, as seen in seismic imagery, and comprise the base of the thrust wedge. It should be pointed out, however, that in the inner portions of the TFB, the complete lower Cretaceous sedimentary package is involved in the thrust wedge above the basal detachment (Klepeis, 1994; Torres Carbonell *et al.*, 2011).

4. Structure

4.1. Western Area (subsurface data)

The Western Area of our study occupies part of the Austral Basin's 'Fracción E', 'Fracción Chorri-llos', and CA12 block, and is located adjacent to the Argentina-Chile borderline near the Río Grande middle course (Fig. 2A). The area occupies the northwestern portion of the structures mapped by Cagnolatti *et al.* (1987) near Estancia Aurelia (Despedida Anticline, Aurelia Syncline and Constancia Anticline) (Fig. 2A). Outcrops in the area consist of folded Eocene and Oligocene rocks in the southwestern part (La Despedida and Tchat-chii Formations, respectively) and subhorizontal or gently folded Miocene strata in the central and northern parts (Fig. 2A) (Malumián and Olivero, 2006; Olivero and Malumián, 2008).

Interpretation of seismic lines reveals many fault-related folds, with fault surfaces manifested in the truncation of the reflectors by discrete linear discontinuities, or zones where resolution is abruptly interrupted (Figs. 4-6). One possible detachment fold is also identified (Despedida anticline in line 38) (Fig. 6). Two basal detachment levels are recognized: the shallower structures are detached at or just above a Paleocene stratigraphic interval known as Arroyo Candelaria Formation or Senoniano. The deeper detachment is located within the Cretaceous stratigraphic interval, although its specific strati-graphic location is not revealed by the available data (Figs. 3-6). The folds in the Western Area are mostly gentle, with amplitudes between 400 and 1,100 m and wavelengths between 5 and 7.6 km.

The older age-constraint on deformation in the area is formation of the Despedida Anticline, as suggested by an interpreted angular unconformity in its southern limb, between the Eocene La Des-pedida Group and Oligocene Tchat-chii Formation (Malumián and Olivero, 2006). Although the un-conformable surface is subexposed, it is covered by coarse conglomerates and sandstones with clasts of deformed rhyolite and tuff, fragments of slate, sandstone and calcareous concretions, as well as vertebrate and invertebrate resedimented fossils. This detrital composition indicates uplift and ero-sion of Upper Jurassic to Paleogene rocks from the Fuegian Andes core and thrust-fold belt (Malumián and Olivero, 2006). The same unconformity is recognized along the TFB front, in the Eastern Area, where it also indicates a contractional stage (Torres Carbonell *et al.*, 2009, 2011). The youngest age of deformation can be accurately constrained by a notable progressive unconformity on top of the Upper Margosa unit, covered by chaotic reflectors (mass transport deposits?) in middle(?) Miocene beds above the deformation front (Figs. 5 and 6).

A particular feature of the deep detachment is that it interacts with the basement, whose topography
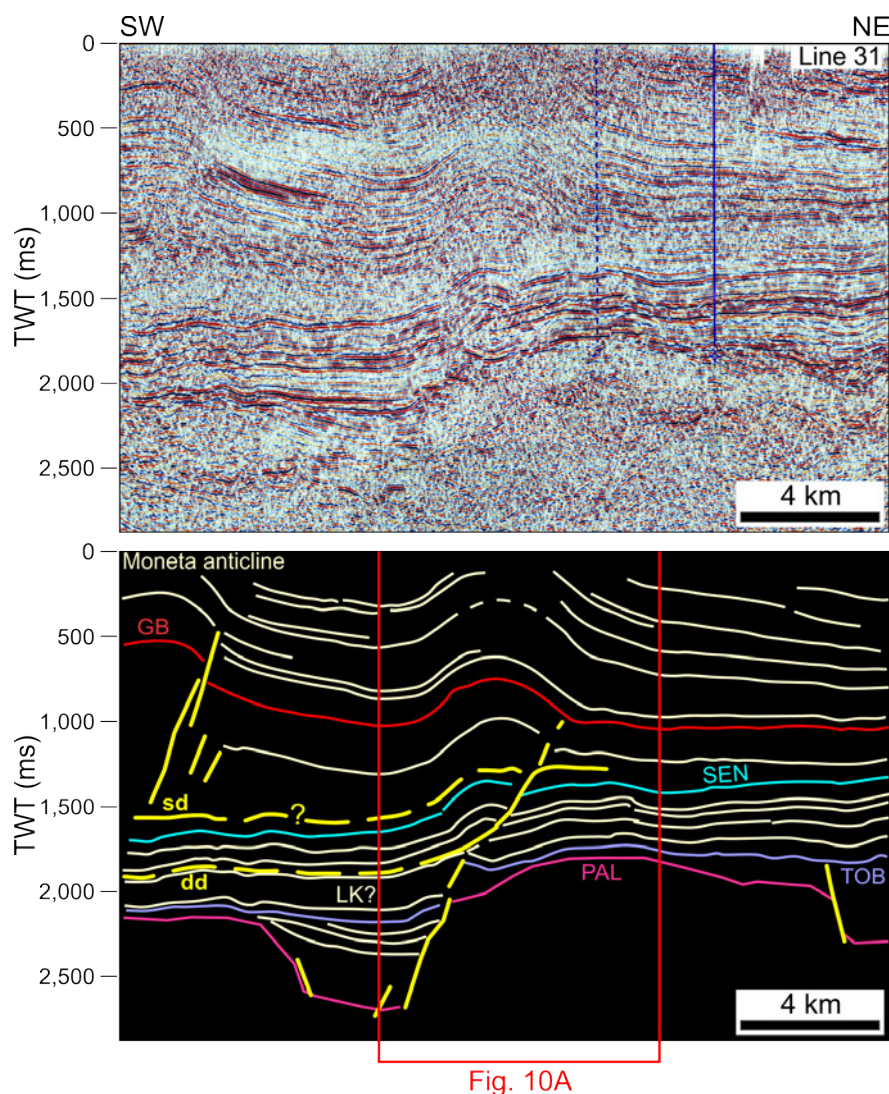
FIG. 4. Seismic line 31 (located in figure 2A) and its interpretation. The stratigraphic markers (top of beds) are identified with the aid of well logs (located in figure 2A). **GB**: Glauconítico 'B'; **SEN**: Senoniano; **LK**: Lower Cretaceous; **TOB**: Tobífera Formation; **PAL**: Paleozoic basement (compare with figure 3). Bold yellow lines are interpreted faults, dashed when less certain; **dd**: deep detachment; **sd**: shallow detachment.

influences the location of thrust ramps branching from the detachment. This is well exemplified in line 31 (Fig. 4), which shows a basement high bounded by a south-dipping normal fault formed during the Late Jurassic-Early Cretaceous rift to back-arc extension. The graben formed against the fault is filled with a synrift succession composed of the Tobífera Formation and Lower Cretaceous strata. There are no evident signs to indicate a late inversion of the normal fault. On the other hand, a thrust ramp branches from the deep detachment and

joins the shallow detachment just above the border of the basement high, with an associated anticline in its hangingwall (Fig. 4). We interpret that the basement step, inherited from the Mesozoic extension, acted as a stress riser localizing the formation of the thrust ramp (cf. Coward *et al.*, 1991). This interpretation has been proposed for similar structures in the foreland of the Alps and Apennines, in thrust-fold belts formed above previously extended continental crust (Butler, 1989; Coward *et al.*, 1991; Tavarnelli, 1996).
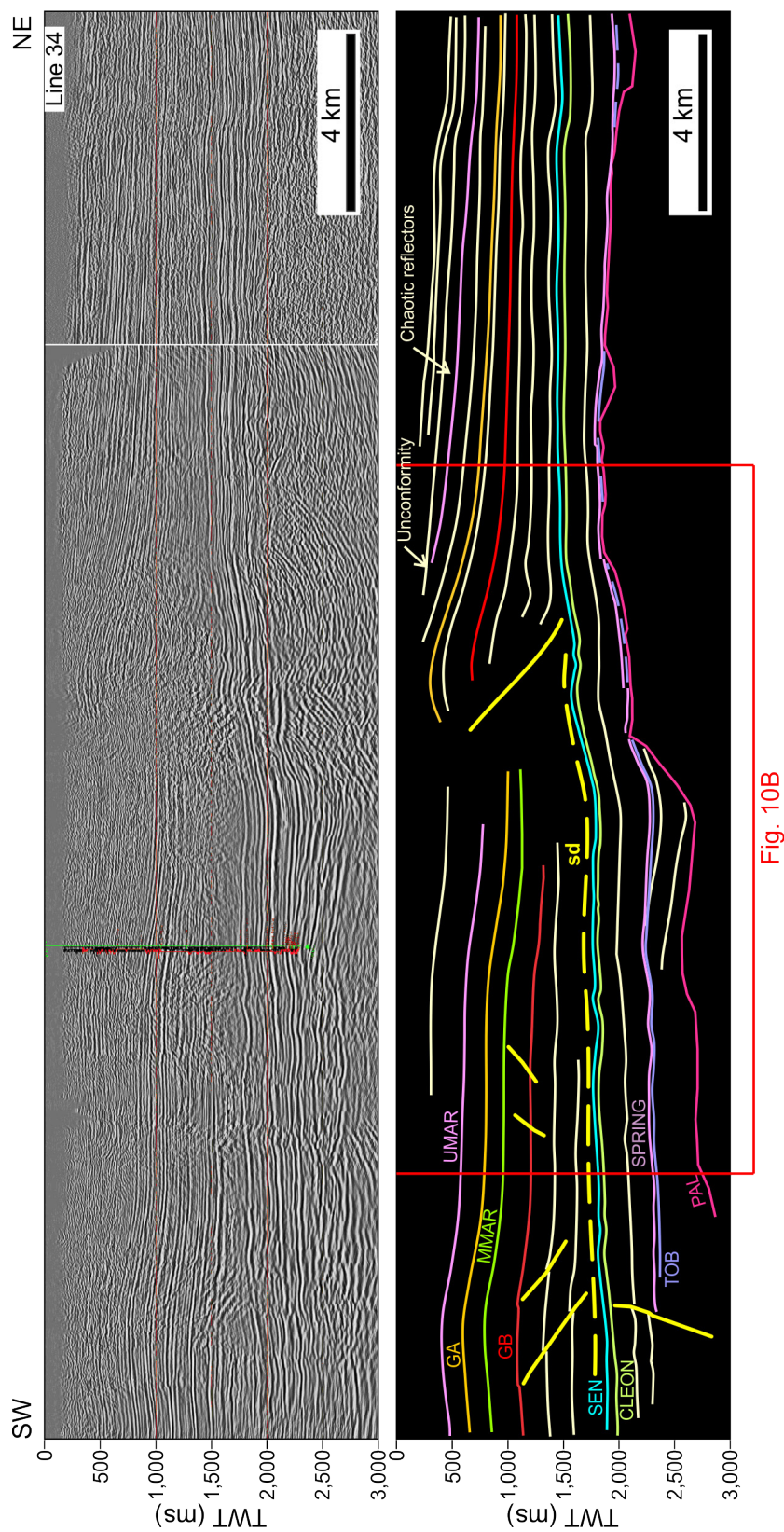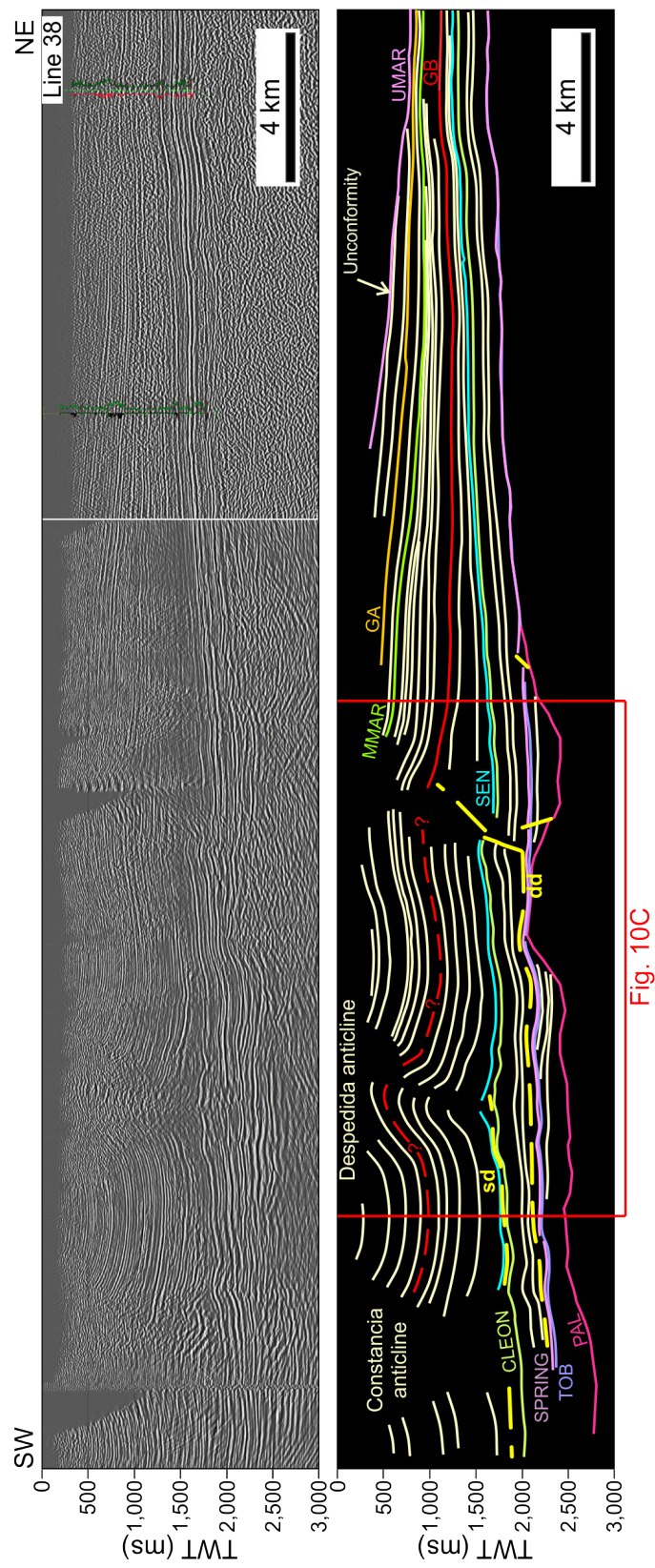
FIG. 5. Seismic line 34 (located in figure 2A) with its interpretation. Stratigraphic markers (top of beds) are identified with the aid of well logs (located in figure 2A). **UMAR**: Upper Margosa; **GA**: Glauconítico 'A'; **MMAR**: Middle Margosa; **GB**: Glauconítico 'B'; **SEN**: Senoniano; **CLEON**: Cabeza de León Formation; **SPRING**: Springhill Formation; **TOB**: Tobífera Formation; **PAL**: Paleozoic basement (compare with figure 3). Bold yellow lines indicate interpreted faults, dashed when less certain. **sd**: shallow detachment.

FIG. 6. Seismic line 38 (located in figure 2A) with its interpretation. Stratigraphic markers (top of beds) are as in figure 5. Bold yellow lines indicate interpreted faults, dashed when less certain. **dd**: deep detachment; **sd**: shallow detachment.

An additional notable feature of the TFB geometry in the Western Area is that bivergent structures occur. This is exemplified in line 34, where the anticline that marks the leading edge of deformation verges to the hinterland, with a causative backthrust rooted at the shallow detachment, above the Senoniano horizon (Fig. 5). Laterally, a few kilometers northward, this structure disappears and shortening is accommodated by the anticline of line 31 (Fig. 4). The latter is interpreted as a fault-bend fold formed above the ramp that connects the deep and shallow detachments. Both structures form the leading edge of the TFB, which changes vergence laterally (Fig. 7).

It is interesting to note that the backfold of line 34 is located just above the same basement step seen in line 31. Thus, it is very probable that the nucleation of the backthrust was in some way also associated with the stress riser basement high (Figs. 7 and 8). Accordingly, in the structural map of the Tobífera Formation, which approximately describes the basement's topography, the NW-SE abrupt step is roughly copied by the tip lines of both the deep and shallow detachments (Fig. 8C).

Doubly-vergent structures as recorded in the seismic lines, not previously mentioned for the area, have also been described in the coastal sector of the TFB, as addressed below (Torres Carbonell *et al.*, 2008a; Torres Carbonell *et al.*, 2011), as well as in cross-sections from the Chilean sector of the TFB (Álvarez-Marrón *et al.*, 1993).

4.2. Eastern Area (outcrop data)

The surface area selected for this comparison is located between Punta Gruesa and Cerro Colorado, on the eastern coast of Tierra del Fuego, where the frontal structures of the TFB are exposed (Ghiglione, 2002; Torres Carbonell *et al.*, 2008a) (Fig. 2B). Previous interpretations of the structure of this area were provided by Ghiglione (2002) and Ghiglione *et al.* (2002), and discussed extensively by Torres Carbonell *et al.* (2008a), who put forward a geometrically constrained (balanced) structural model. The general basis of this latter interpretation is maintained here, with some modifications and improvements in the model as explained below. The exposed stratigraphy in the area includes the Ypresian-lower Lutetian Punta Torcida Formation, the upper Lutetian-Priabonian Leticia and Cerro Colorado Formations (La Despedida Group), the Oligocene María Cristina and Puesto Herminita Beds, and the uppermost Oligocene-lower Miocene Desdémona Formation (Figs. 2B and 3). All these units are involved in a series of thrust sheets and unconformably covered by subhorizontal Miocene beds (Cabo Ladrillero and Cabo San Pablo Beds) (Malumián and Olivero, 2006; Ponce *et al.*, 2008; Torres Carbonell *et al.*, 2008a) (Fig. 3). The age of deformation spans from the Oligocene to the early Miocene (Torres Carbonell *et al.*, 2008a). The youngest age is constrained by growth strata above the frontal exposed structures, in the Desdémona Formation. These growth strata form a progressive unconformity changing in dip from 20°N to 5°N away from the anticline (northward) (Ponce *et al.*, 2008; Torres Carbonell *et al.*, 2008a) and are also intruded by syntectonic clastic dikes (Ghiglione, 2002).

The structural model proposed by Torres Carbonell *et al.* (2008a) included a system of bivergent fault-bend and fault-propagation folds detached in a common horizon at Paleocene(?)-Ypresian rocks, with an upper detachment (for the fault-bend folds) in upper Eocene beds (Cerro Colorado Formation) (Fig. 9). These structures nucleated in the pre-existing leading edge of the TFB, which was formed during the Ypresian-early Lutetian and manifested as a structural high with unknown geometry in the Punta Torcida Formation and older units, as schematically depicted in figure 9 (Torres Carbonell *et al.*, 2008a; Torres Carbonell *et al.*, 2011).

Evidence in support of this interpretation includes the following: **a.** the notable angular unconformity between the Leticia and Punta Torcida Formation (Torres Carbonell *et al.*, 2008a; Torres Carbonell and Olivero, 2012), which involves a hiatus of ~4 Ma (Olivero and Malumian, 1999; Olivero and Malumián, 2008; Barbeau *et al.*, 2009; Torres Carbonell *et al.*, 2009); **b.** the wedging of the Leticia Formation against an uplifted paleotopography coinciding with the structural high (Olivero *et al.*, 2008; Torres Carbonell *et al.*, 2008a; Torres Carbonell, 2010); and **c.** the exposure of part of that high, comprising a narrow belt parallel to the TFB (E-W) where the Punta Torcida Formation crops out extensively, with deformation suggesting localized shortening and uplift of the unit (Figs. 2B and 9) (Torres Carbonell *et al.*, 2008a). This structural high separated two contemporaneous depocenters of the Austral foreland basin system: the wedge-top (southward) and the foredeep (northward) (Torres
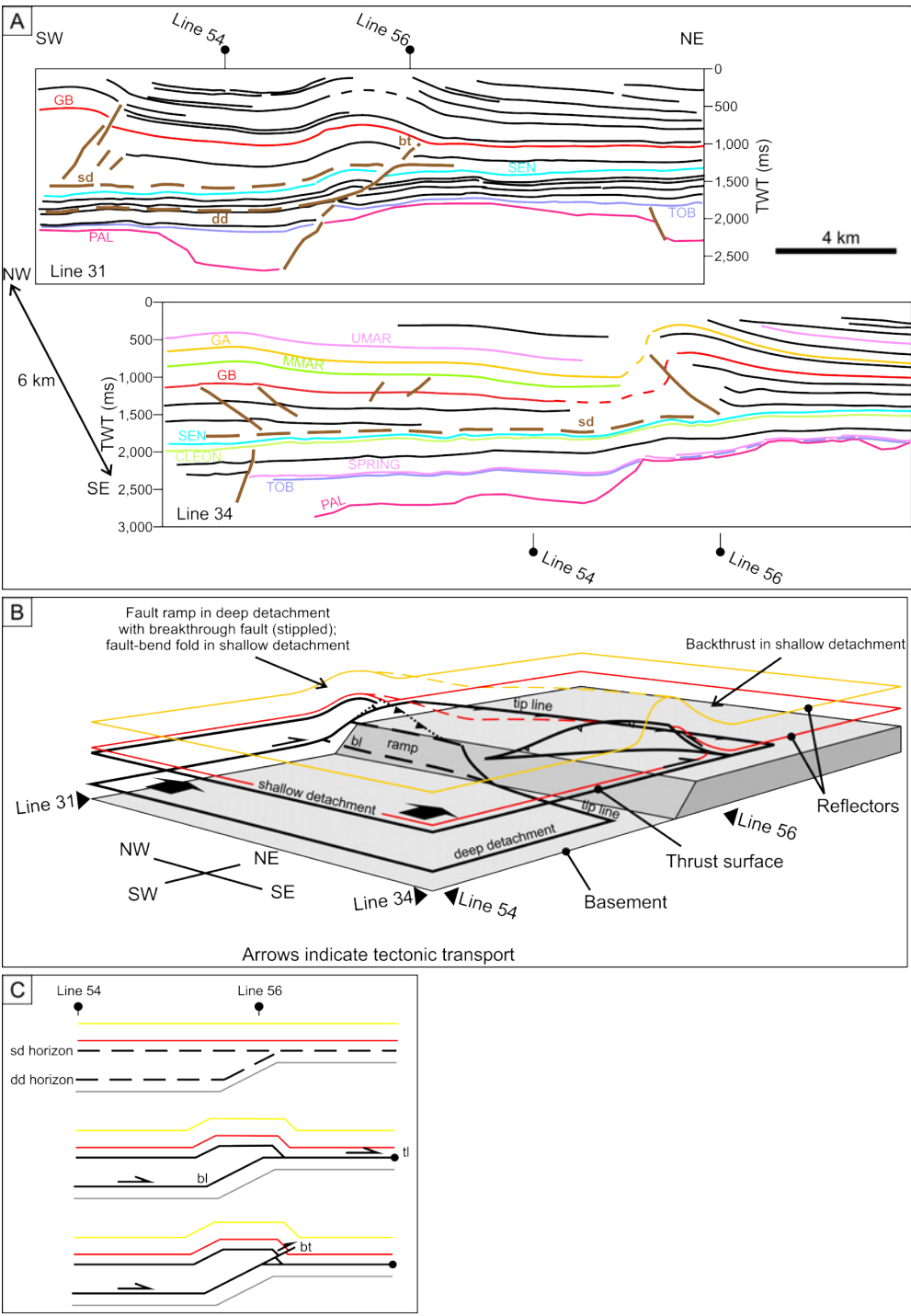
FIG. 7. **A.** Lateral correlation and comparison of the structure between lines 31 (Fig. 4) and 34 (Fig. 5), both located in figure 2A. The stratigraphic references are indicated in Figs. 4 and 5. **bt**: breakthrough fault; **dd**: deep detachment; **sd**: shallow detachment; **B.** Schematic (not scaled) 3D diagram illustrating the interpreted lateral structural link between lines 31 and 34 and the relationship of the deep and shallow detachments with the basement geometry. **bl**: branch line; **C.** Explanation of the interpreted kinematic evolution of the anticline of line 31. **tl**: tip line.

TOP GLAUCONÍTICO 'B'

TOP TOBÍFERA
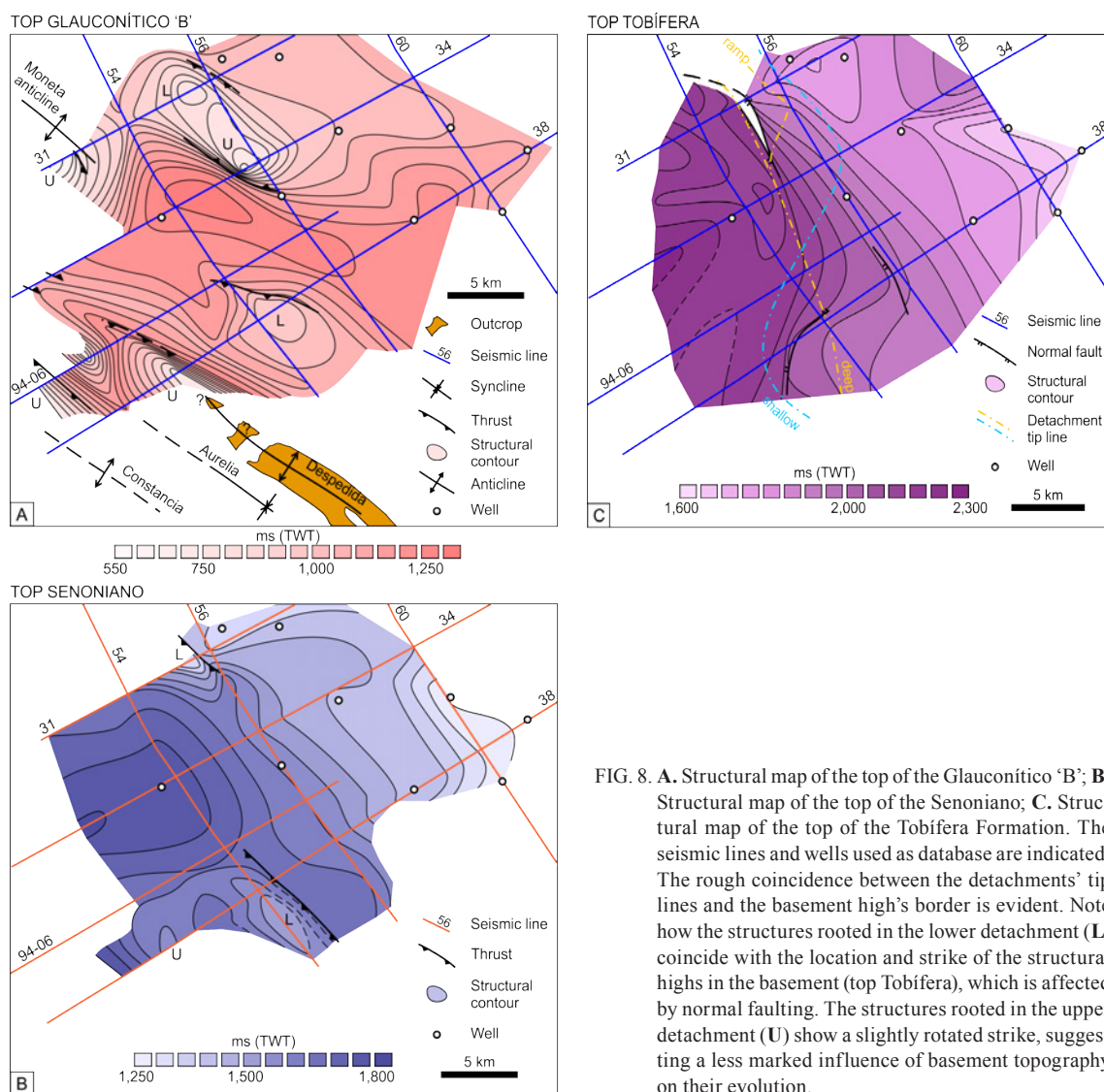
TOP SENONIANO

FIG. 8. **A.** Structural map of the top of the Glauconítico 'B'; **B.** Structural map of the top of the Senoniano; **C.** Structural map of the top of the Tobífera Formation. The seismic lines and wells used as database are indicated. The rough coincidence between the detachments' tip lines and the basement high's border is evident. Note how the structures rooted in the lower detachment (**L**) coincide with the location and strike of the structural highs in the basement (top Tobífera), which is affected by normal faulting. The structures rooted in the upper detachment (**U**) show a slightly rotated strike, suggesting a less marked influence of basement topography on their evolution.

Carbonell *et al.*, 2008a; Torres Carbonell *et al.*, 2009; Torres Carbonell, 2010).

Deformation in the Punta Torcida Formation in the area interpreted as a structural high (nearby Estancia Irigoyen) (Fig. 2B) involves structures formed just above the basal detachment of the cross section, exhumed by a folded thrust called Irigoyen thrust (Fig. 9). The fault is subexposed, but the Punta Torcida Formation, comprising mudstones of undetermined thickness, reveals systematic variations in bed attitude suggestive of folding, and several discrete fault zones 5-10 m thick, more abundant near the interpreted trace of the Irigoyen

thrust (Fig. 2). The fault zones are characterized by some mesoscopic faults and several microfaults with s/c-type structures, with polished and striated slickensides containing abundant gouge or rock powder.

The hangingwall of the northernmost fault-bend fold depicted in figure 9 is deformed by an imbricate system of fault-propagation folds rooted in the upper detachment, called Punta Gruesa imbricate system. The detailed description of these structures and their kinematics are addressed in a previous paper, which modeled the Punta Gruesa imbricate system using line length conservation and simplified kink hinges
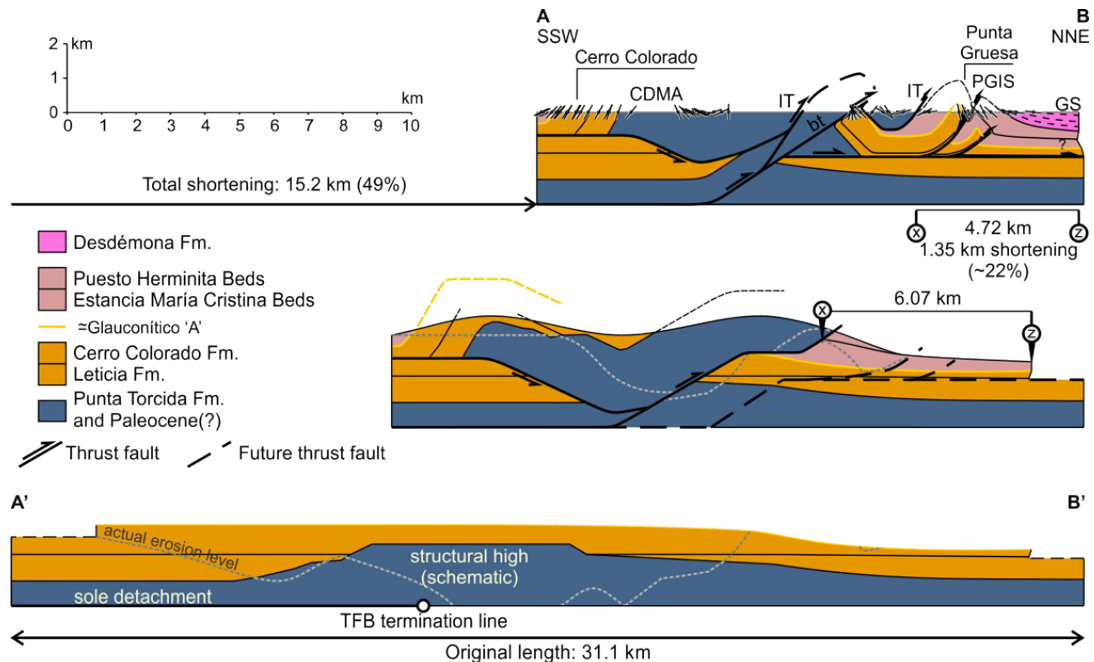
FIG. 9. Balanced cross section depicting the interpreted geometry of the TFB at the Eastern Area, modified after Torres Carbonell *et al.* (2008a) (combined between endpoints A-B in figure 2B). The topographic heights in the intermediate section are schematized in order to visualize the fold geometry only. **CDMA**: Campo del Medio anticline; **IT**: Irigoyen thrust; **bt**: breakthrough fault; **PGIS**: Punta Gruesa imbricate system; **GS**: growth strata. The Glauconítico 'A' equivalent horizon is shown for comparison with figures. 5, 6 and 10 (correlations established by Malumián and Olivero, 2006). X and Z are pinpoints used to calculate shortening of the PGIS.

according to standard balancing techniques (Torres Carbonell *et al.*, 2008a). In this new contribution, we incorporated area balancing to our model, which allowed us to reproduce more realistic fold geometries (Fig. 9). It is assumed that some shortening may be transferred to the foreland northwards of the Punta Gruesa imbricate system, manifested as probable buried structures, as suggested by very gentle warps exposed along the coast (Ghiglione, 2002; Ponce *et al.*, 2008). This shortening may be very low, though, as exemplified in figure 9.

In summary, the style of deformation of the Cerro Colorado-Punta Gruesa cross section includes a system of imbricated, bivergent thrust sheets with related folding, a basal detachment with staircase geometry, and complex accommodation structures such as breakthrough faults. Folds range from open to closed, with approximate wavelengths ranging from 4 to 0.5 km and amplitudes larger than 500 m, forming a generally tight structure that records a significant local shortening.

4.3. Shortening magnitudes

Line-length restoration of the interpreted seismic lines 31, 34 and 38 indicates low shortening magnitudes for the frontal TFB structures (13 to 16 km frontal section of the western TFB) in the order of a few hundred meters, representing very low local shortening percentages (1 to 3% of the restored cross sections' lengths) (Fig. 10). It is remarkable that in an almost equal length across the TFB leading edge, the cross section from the Eastern Area reveals a total shortening of 15.2 km, 49% of the restored length (Fig. 9). The possible existence of buried structures ahead of the Punta Gruesa imbricate system (see previous section) analogous to those observed in the seismic lines of the Western Area with no outcrop expression would only increase the restored length by a few kilometers, with the shortening percentage remaining above 40%.

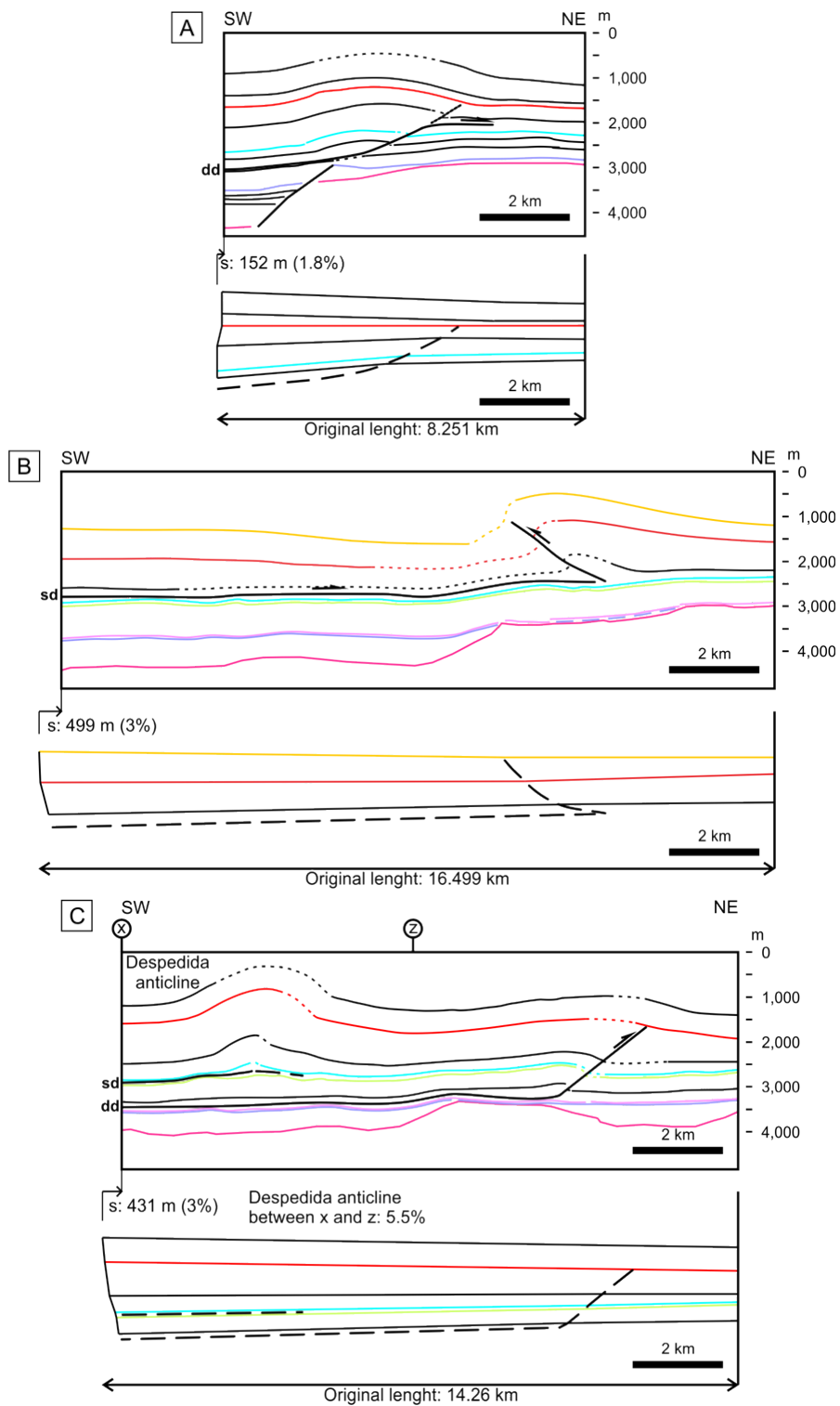We can further detail our comparision considering the exposed frontal structures in the two areas: the

FIG. 10. **A.** Balanced restoration of a depth-converted portion of seismic line 31, located in figure 4; **B.** Balanced restoration of a depth-converted portion of seismic line 34, located in figure 5; **C.** Balanced restoration of a depth-converted portion of seismic line 38, located in figure 6; **dd**: deep detachment; **sd**: shallow detachment; **s**: shortening.

Punta Gruesa imbricate system in the east and the Despedida and Moneta anticlines in the west. The latter is not completely registered in line 31, but the Despedida Anticline is fully imaged by line 38 (Figs. 6 and 10C). The Despedida anticline and Punta Gruesa imbricate system have comparable amplitudes (~500 m), and their wavelengths are ~6 km and more than 3 km, respectively. In addition, both structures expose Eocene rocks at the core. However, the Despedida anticline together with the deeper anticline in front of it accommodates only 431 m of shortening, with the Despedida anticline alone accommodating about 5.5% of local shortening (Fig. 10C), whereas the Punta Gruesa imbricate system alone (without taking into account possible buried frontal structures) accommodates 1.35 km of shortening (~22%) (between points x and z in figure 9). This marked difference is evident when comparing the complexity of the Punta Gruesa imbricate system, which comprises two or more stacked thrust sheets, with the simple buckle in the sedimentary succession that forms the Despedida anticline (Figs. 6, 9 and 10C).

5. Discussion

The similarities observed between the studied areas of the TFB leading edge include comparable detachment levels (Senoniano and Paleocene-Ypresian beds), bivergent structures, similar ages of deformation starting in the Oligocene and ending coevally as constrained by early to middle (?) Miocene unconformities and growth strata (Figs 4, 5, 6 and 9). Although there is no evidence of a detachment horizon in Cretaceous strata in the Eastern Area, a similar detachment is involved further southward in the TFB with an unknown northward termination (Torres Carbonell *et al.*, 2011). The structural difference between these areas seems to be more important: a very tight structural geometry in the coastal sector as against large-wavelength and gentle structures in the Western Area, manifested by significantly lower shortening percentages in the latter (Figs. 9 and 10). We therefore corroborate the existence of structural style variations along the strike of the TFB front, suggesting higher local strain at the eastern TFB.

At first glance an increase in the regional shortening toward the east would be a logical and simple explanation for the increased structural complexity in that direction. However, this argument does not

appear to be supported by comparative regional shortening estimates: the estimated TFB shortening range is between 30 km (Álvarez-Marrón *et al.*, 1993) and 50 km (Rojas and Mpodozis, 2006) (see also Kley *et al.*, 1999; Kraemer, 2003) in Chile and ~45 km in eastern Argentine Tierra del Fuego (Torres Carbonell, 2010). Taking into account differences in balancing techniques and inherent assumptions for each case, this difference along the TFB (5 to 15 km) is not significant on a regional scale of analysis.

We can therefore assume that the regional shortening was roughly homogeneous along the strike and that there must be some other explanation for the higher strain observed at the Eastern Area, causing its tighter structural style. Two possible reasons to explain this strain gradient along the strike are analyzed in the following sections.

5.1. Potential rheological control over the structural development of the foreland TFB

Previous papers proposed that the foreland successions involved in folding are dominated by thick piles of ductile fine-grained sediment, which exerted a rheological control over the development of the TFB (Ghiglione *et al.*, 2002; Ghiglione *et al.*, 2010). According to these authors, along-strike variations in structural style were due to the more ductile behavior of the strata at the base of the western TFB, which favored detachment folding, whereas in the eastern TFB a more competent rheology led to faulted-detachment folds (cf. Mitra, 2002) being more common (Ghiglione *et al.*, 2010).

This interpretation, if valid, would explain the along-strike structural variations documented here: stiffer beds at the base of the thrust wedge could effectively restrain its advance in the east, hindering forward propagation of the detachment and thus enhancing internal deformation in order to accommodate shortening (*i.e.*, producing tighter structures). However, we consider that the available geological evidence does not support such rheological behavior for the base of the TFB: several outcrops and wells involving the foreland successions associated with detachments reveal a highly heterogeneous lithology, with no linear rheological gradients in any direction. For example, in wells drilled near the Western Area, the Senoniano is characterized by 'sandstones, claystones and siltstones in variable

proportions, although generally the first [sandstones] are dominant' (Masiuk *et al.*, 1990, p. 79). At outcrop, the formations that involve the detachment level in the Eastern Area (Punta Torcida Formation, La Barca Formation -Río Claro Group-, Fig. 3) (Torres Carbonell *et al.*, 2008a, 2011) are composed of intercalated mudstone and sandstone (even conglomerate) packages (Olivero and Malumian, 1999; Olivero *et al.*, 2002; Torres Carbonell and Olivero, 2012). This means that even if the detachment fault surface propagated through mudstone horizons, the whole sedimentary pile involved in deformation in the basal part of the thrust wedge is not necessarily ductile.

In part, the interpretation of a ductile rheology at the base of the thrust wedge was established in relation to the inference of widespread detachment folding in the foreland TFB (Ghiglione *et al.*, 2002; Ghiglione *et al.*, 2010). However, our data show only one example of a possible detachment fold, interpreted on the basis of fold geometry itself (Despedida anticline in line 38) (Fig. 6), the rest being either fault-bend or fault-propagation folds (Figs. 4-6).

In summary, the available data only indicate that the mechanical stratigraphy may have controlled the local geometry and kinematics of individual structures, as is common in heterogeneous multilayers (Chester *et al.*, 1991; Butler and McCaffrey, 2004) and is observed in some outcrop examples of the TFB (Torres Carbonell *et al.*, 2011). It is also to be expected that the detachment horizons will preferably locate in mudstone horizons. However, since there is no record or feasible sign of significant lithologic variation along the TFB, it cannot be unequivocally claimed that the rheology of rocks is the main control on the observed regional differences in structural style.

5.2. Evaluation of a buttressing effect in the Eastern Area

Another type of restraint on thrust advance causing higher strains in the Eastern Area could be that posed by boundary conditions during deformation of the TFB, namely the buttressing effect possibly exerted by the Fuegian Andes foreland basement (Torres Carbonell, 2011; Torres Carbonell *et al.*, 2013). The latter is formed by the cratonic border of the Early Cretaceous back-arc basin (see Stratigraphy) (Biddle *et al.*, 1986), which has an irregular map-view configuration inherited from the prior Late

Jurassic rifting stage (Wilson, 1991; Calderón *et al.*, 2007) that conditioned the pre-basin topography.

A notable and long-recognized feature of the cratonic border is a N-S promontory, called Río Chico (Dungeness) arch, which projects toward the south into the foreland basin system dividing the Austral and Malvinas depocenters (Biddle *et al.*, 1986; Yrigoyen, 1989; Galeazzi, 1998) (Fig. 11A). The structural geometry of the southernmost tip of the Río Chico arch is not well defined owing to the lack of subsurface data in eastern Tierra del Fuego. However, it is clear from data relating to areas surveyed in greater detail (Biddle *et al.*, 1986; Yrigoyen, 1989; Galeazzi, 1998) that the promontory further projects southwards in the region where the TFB forms a recess (Península Mitre recess), marked precisely by the Eastern Area structures (Fig. 11B) (Torres Carbonell, 2011; Torres Carbonell *et al.*, 2013).

The top basement structural maps show a sharp break in the Río Chico arch topography both on its western (Austral basin) and eastern (Malvinas basin) flanks (Biddle *et al.*, 1986; Yrigoyen, 1989). This break in the margin's topography can be seen in the interpreted N-S seismic lines offshore (eastward) of Tierra del Fuego, in the western Malvinas Basin (Galeazzi, 1998) and in the seismic lines inland (Fig. 4). At least in the latter, it is clear that this basement slope coincides with the TFB leading edge (Figs. 8 and 11B).

The available data, therefore, highlights three principal features of the TFB front: **a**. the Río Chico arch margin exerts control over the location of the leading structures of the TFB at the Western Area; **b**. there is a significant increase in strain towards the Eastern Area; and **c**. this area is located where the Río Chico arch margin extends further south-ward. As already established, the true geometry and extent of the Río Chico arch structural contours is unknown (Fig. 11B), as is the extent of a potential deep detachment analogous to the one at the Western Area, which would be more likely to interact with eventual basement highs or steps.

However, considering that the western TFB leading edge approximately copies the trace of the Río Chico arch western margin and the fact that the Península Mitre recess occurs just south of the axis of the promontory (Fig. 11B), we speculate that the control exerted by basement steps on the location of thrust-related folds (*e.g.*, Fig. 4) was maintained
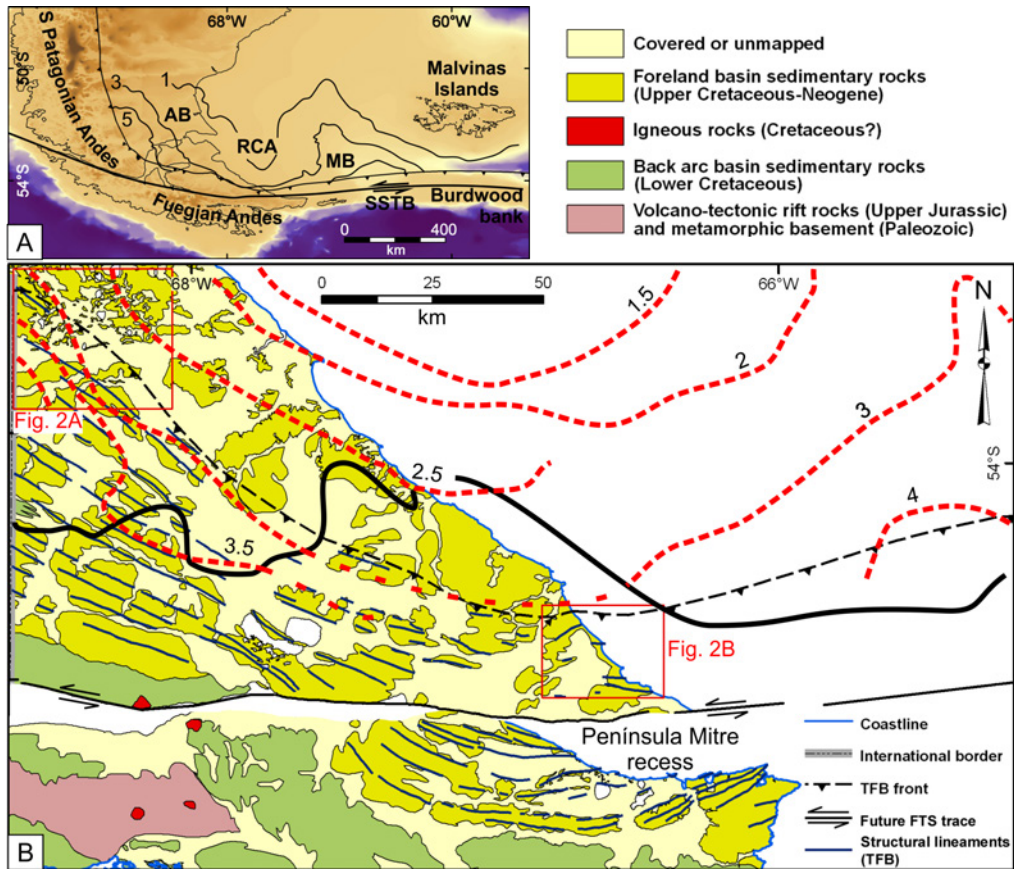
FIG. 11. **A.** Regional situation of tectonic and morphologic features discussed in the text. **RCA**: Río Chico arch; **AB**: Austral basin; **MB**: Malvinas basin; **SSTB**: Scotia-South American plates transform boundary. Numbers (1-5) indicate structural contours (in kilometers) at the top of the Tobífera Formation in the Austral and Malvinas basins, according to Biddle *et al.* (1986) and Yrigoyen (1989); **B.** Map of the structural lineaments of the TFB and the structural contours of the Río Chico arch (dashed red lines, in kilometers) according to Biddle *et al.* (1986) and Yrigoyen (1989). The bold lines show the southern limit of onshore and offshore seismic line coverage. Structural contours beyond that limit are only an interpreted approximation. The portion of the Fuegian Andes south of the Fagnano transform system (FTS) is located in its Paleogene-early Neogene position, prior to left-lateral strike-slip along the FTS (cf. Torres Carbonell *et al.*, 2008b; Torres Carbonell *et al.*, 2011).

along the TFB front towards the east. This would therefore imply a stronger buttressing effect for thrust advance in the Eastern Area (Torres Carbonell, 2011), causing a stress rise towards the east along the TFB front. This effect is a viable explanation for the higher strain resulting in tighter structures and high local shortening percentages in the Eastern Area (cf. Marshak, 2004).

6. Conclusions

The detailed geometric analysis of the structures in two areas of the TFB front (western and eastern)

in Argentina using a combination of subsurface and outcrop data allowed us to verify and characterize the structural variations along the strike suggested by previous regional studies. The major differences lie in the general style of deformation: the Western Area shows gentle, large-wavelength folds whereas the general structural geometry in the Eastern Area is tighter, with closer fold geometries. A comparison of shortening in structures from both areas, with analogous dimensions and positions in the TFB front, indicates very low shortenings in the Western Area, below 5.5%, against ~22% in the Eastern Area. Thus, both the structural style and

shortening differences suggest that the Eastern Area endured higher strain.

Assuming a roughly homogeneous regional shortening along the strike, we evaluated two possible explanations for this strain gradient along the foreland TFB. The first one considers a rheological control of the successions involved in deformation at the base of the thrust wedge. We concluded that there is no geological evidence indicating significant rheological gradients in a preferred direction along the TFB, and that rheology may only influence the local geometry and kinematics of individual structures.

The second possible explanation for the higher strain towards the eastern TFB is the strong buttressing exerted during deformation in the area by the Río Chico arch. This interpretation is based on evidence from the western flank of the Río Chico arch, where seismic lines show the nucleation of the frontal thrust faults on basement steps that act as local buttresses. We speculate that the buttressing was exerted along the TFB front and that the southward projection of the Río Chico arch in the region of the Eastern Area hindered forward TFB propagation, providing a logical explanation for the higher strain and more complex structural style recorded in the eastern TFB.

Acknowledgements

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