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Structure and evolution of the Fuegian Andes foreland thrust-fold belt, Tierra del Fuego, Argentina: Paleogeographic implications

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Abstract

Field work in the frontal part of the foreland thrust-fold belt of the Fuegian Andes reveals complex relationships between stratigraphy and structure. Construction of balanced cross-sections allows us to infer the geometry and kinematics of structures controlling the thrust-fold belt evolution. The sequential restoration of these cross-sections to their undeformed state reveals the architecture of the Austral foreland basin in relation to the evolving deformation front. This front was developed after incorporation of the Paleocene–earliest Eocene foredeep of the basin to the thrust-fold belt. A wedge-top depozone formed over this former foredeep, bounded by the late-middle to late Eocene thrust front. The wedge-top basin was filled by a quartz-rich sandstone-dominated succession of Andean provenance. The same succession filled the foredeep formed northwards of the deformation front, active from late-middle Eocene. Further reactivation of compression led to backthrusting of the wedge-top clastic succession in the late Eocene, and to subsequent foreland propagation of the deformation, manifested by a sequence of low angle thrusts that affected the foredeep. The foredeep migrated forelandwards as the tectonic load advanced, to finally act as a passive depozone after the earliest Miocene, when the propagation of the deformation front stopped. The paleogeographic reconstruction from late Paleocene to earliest Miocene shows a strong linkage between tectonics and sedimentation in the Atlantic coast of the frontal Fuegian Andes.

Keywords: Balanced cross-sections; Kinematic evolution; Basin's paleogeography; Fuegian Andes; Austral basin; Tierra del Fuego; Argentina

1. Introduction

The east coast of Tierra del Fuego reveals good outcrops of Tertiary sedimentary rocks related to the evolution of the Austral basin, an important hydrocarbon producer in the Argentine Shelf (Ramos and Turic, 1996; Rosello et al., in press). These rocks comprise marine sandstones and mudstones of Andean provenance that were deposited in successive foredeeps and satellite basins developed in relation to the forward propagation of the Fuegian thrust-fold belt (Olivero and Malumián, 1999, 2002; Ghiglione and Ramos, 2005).

Previous work in the east coast of Tierra del Fuego pointed out the structural complexity of the Tertiary rocks (Ghiglione et al., 2002) and the syntectonic deposition of some sedimentary successions (Ghiglione, 2002). Diraison et al. (2000) introduced a kinematic analysis that depicts a wrenching model for the tectonic evolution of the frontal Fuegian and Patagonian Andes, and Schmitt (1991) analyzed sandstone clastic dikes probably related to sinistral

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transcurrence north and northwest from the study area. A general palinspastic cross-section of the Fuegian Andes was presented by Kraemer (2003); however, semi-detailed balanced cross-sections of the thrust-fold belt were only constructed for the central-western part of the Fuegian Andes in the Chilean sector (Álvarez-Marrón et al., 1993; Klepeis, 1994a). The detailed structure and possible kinematics of the study area (Atlantic coast thrust-fold belt front), was only studied by Ghiglione et al. (2002) and Ghiglione (2002, 2003), who introduced a geometric and kinematic model that includes faulted detachment folds and transpression at the final stages of thrust-fold belt formation. We discuss these previous models in this paper, and propose a new geometric and kinematic model for the evolution of the frontal thrust-fold belt.

The present work, based exclusively in field observations and intensive mapping, proposes new interpretations for the structural and stratigraphic evolution of the frontal foreland thrust-fold belt and related foreland basin system. The new balanced cross-sections presented intend to approximate, from a geometrically reasonable focus, the possible configuration of the deformed foreland basin. Also, the previous sedimentological and paleontological data added to our field observations on the stratigraphy within these sections, allow the kinematic history of the thrust-fold belt and its relation to the evolution of the Austral foreland basin to be inferred. From this study, the amount of shortening at this portion of the basin is obtained and a model for the paleogeographic evolution of the foreland basin system proposed.

The study area is located in the frontal part of the eastern Fuegian thrust-fold belt, along the Atlantic coast of Tierra del Fuego between 54°20′S and 54°30′S (Fig. 1). Although this area is included in the transition zone between the Austral and Malvinas basins (see Galeazzi, 1998), we opt to reefer to the foreland basin system as Austral basin, following the name used in Tierra del Fuego Island. A detailed geologic map of the study area was constructed, from which two balanced cross-sections were obtained.

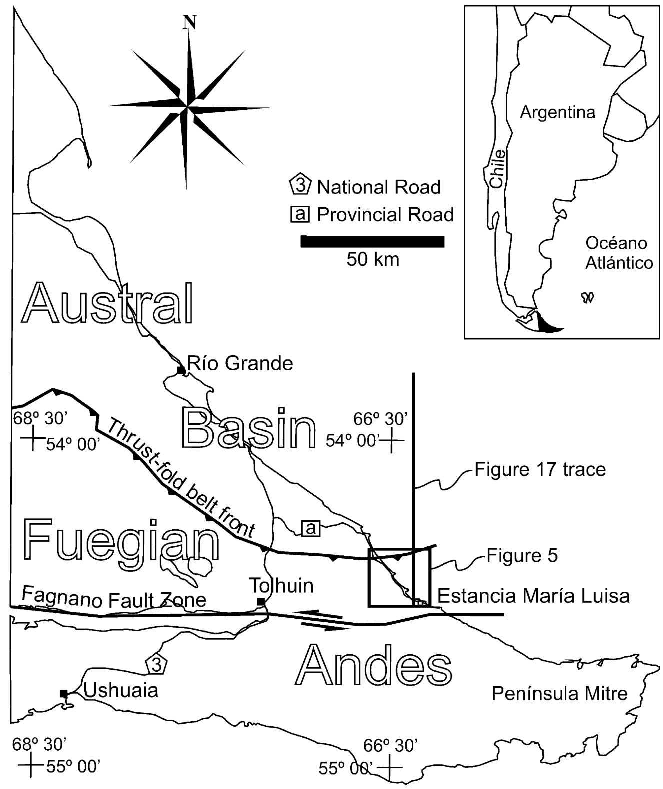

Fig. 1. Location map of the studied area in South America (inset). Area of Fig. 5 and trace of Fig. 17 are shown for reference.

2. Regional geology

The known geologic history of southern South America reveals a complex succession of contrasting tectonic regimes, including late Jurassic–early Cretaceous extension, late Cretaceous–Paleogene compression, and Cenozoic strike-slip faulting (Katz, 1972; Dalziel et al., 1974; Dalziel and Palmer, 1979; Kohn et al., 1995; Klepeis, 1994a, b; Kraemer et al., 1996; Kraemer, 2003; Lodolo et al., 2003). Also, several models for orocline or orogenic curve formation at the southernmost Andes have been proposed (Cunningham et al., 1991; Cunningham, 1993; Kraemer, 2003; Diraison et al., 2000; Ghiglione and Cristallini, 2007).

The early extensional regime involved a rifting phase, related to the development of silicic volcanism in a wide region of southern South America (Bruhn, 1979; Hanson and Wilson, 1991) and to the opening of Rocas Verdes Marginal Basin, partially floored by oceanic crust (Katz, 1972; Dalziel et al., 1974). In the northern cratonic side of the marginal basin an Aptian-Maastrichtian succession of marine sedimentary rocks was deposited during tectonic quiescence (Biddle et al., 1986; Galeazzi, 1998); while in the southern edge of the basin a compressive regime prevailed since at least late Cretaceous (Olivero et al., 2003). The compressive regime caused ductile deformation, isoclinal folding and low grade metamorphism in the marginal basin's sedimentary fill (Bruhn, 1979; Caminos, 1980), whereas high grade metamorphism was attained between 100 and 90 Ma because of basin closure and crustal overthickening (Dalziel and Brown, 1989; Kohn et al., 1995).

The closure of the Rocas Verdes Marginal Basin was followed by the development of a thrust-fold belt in front of the growing collisional orogen, along with the propagation of compressive deformation to the north. The development of the Fuegian Andes thrust-fold belt implied the formation of a foreland basin system (Austral–Malvinas basins; Wilson, 1991; Biddle et al., 1986) that includes four main depocenters. The first three depocenters range from late Campanian to the Eocene–Oligocene. These comprise thick marine successions of upper Campanian to Maastrichtian-Danian, upper Paleocene to lowest Eocene and upper mid Eocene to upper Eocene, all recognized in the Fuegian Andes Atlantic coast. A fourth depocenter is recognized in front of the compressive structures of the thrust-fold belt, including deformed to subhorizontal sedimentary rocks from uppermost Eocene to middle Miocene, considered to be the fill of the last foredeep formed within the Austral and Malvinas basins prior to the deactivation of the compressive regime (Fig. 2; Olivero and Malumián, 1999; Olivero et al., 2002, 2003; Malumián and Olivero, 2006; Olivero and Malumián, in press).

After the compression stopped, the tectonic regime changed in southern South America in relation to the formation of the Scotia Plate and a transform boundary between this and the South American Plate was formed affecting part of the Fuegian Andes. The left-lateral strike-slip Fagnano–Magallanes fault system represents the portion of this plate boundary in Tierra del Fuego (Fig. 2; Klepeis, 1994b; Barker, 2001; Olivero and Martini-

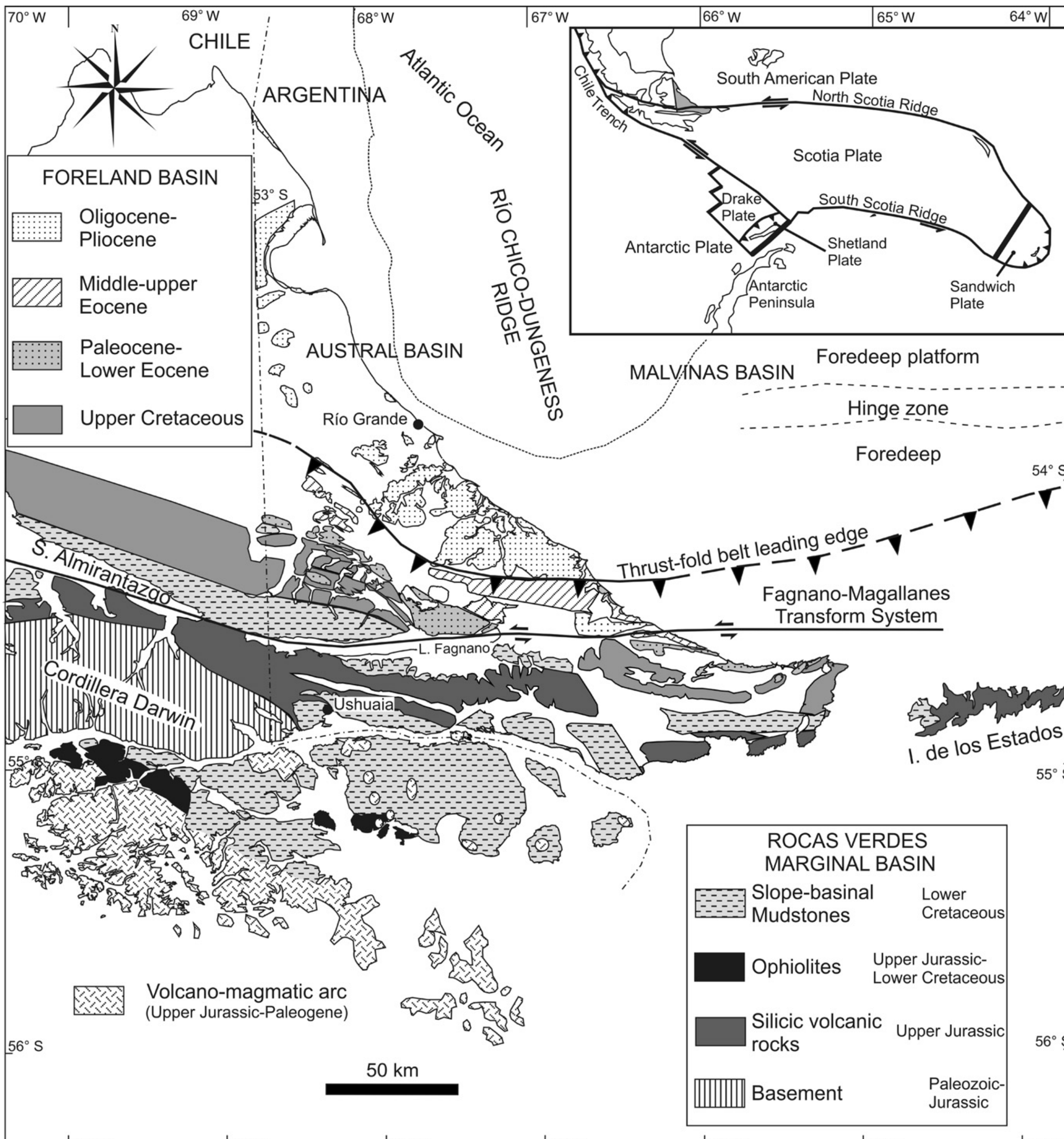

Fig. 2. Geological sketch of Tierra del Fuego and its tectonic context (inset). Geology after: Nelson et al. (1980), Suárez et al. (1985) in Chile; Olivero et al. (in press) in Argentina; Harrington (1943), Dalziel and Palmer (1979) in Isla de los Estados; Biddle et al. (1986), Galeazzi (1998) in the Argentine Shelf.

oni, 2001; Lodolo et al., 2003; Smalley et al., 2003; Torres Carbonell et al., 2008).

3. Stratigraphy

The stratigraphy of the studied area comprises Paleocene to Miocene sedimentary rocks grouped in several units (Figs. 3A and 4). The oldest rocks are represented by the Punta Torcida Formation (upper Paleocene–lower Eocene; Olivero and Malumián, 1999) cropping out discontinuously between Punta Torcida and the cliffs north of Río Azara mouth (Fig. 5). The Punta Torcida Formation includes mudstones and tuffaceous sandstones deposited in shelfal to deeper settings, with marked anoxic conditions (Olivero and Malumián, 1999). Olivero and Malumián (in press) added to the unit a thick sandstone package (previously assigned to the base of the Leticia Formation) and included the Formation in the Río Claro Group, which comprises a regressive megasequence formed by packages of deep-water turbidite systems with abundance of carbonaceous plant fragments.

The Punta Torcida Formation is unconformably covered by the Leticia Formation (Olivero and Malumián, 1999), which is composed of thick packages of late-middle Eocene quartz-rich sandstones. These sandstones crop out from Cabo Tiburones to Cabo Campo del Medio, where the unconformity at the base of the Leticia Formation is well exposed.

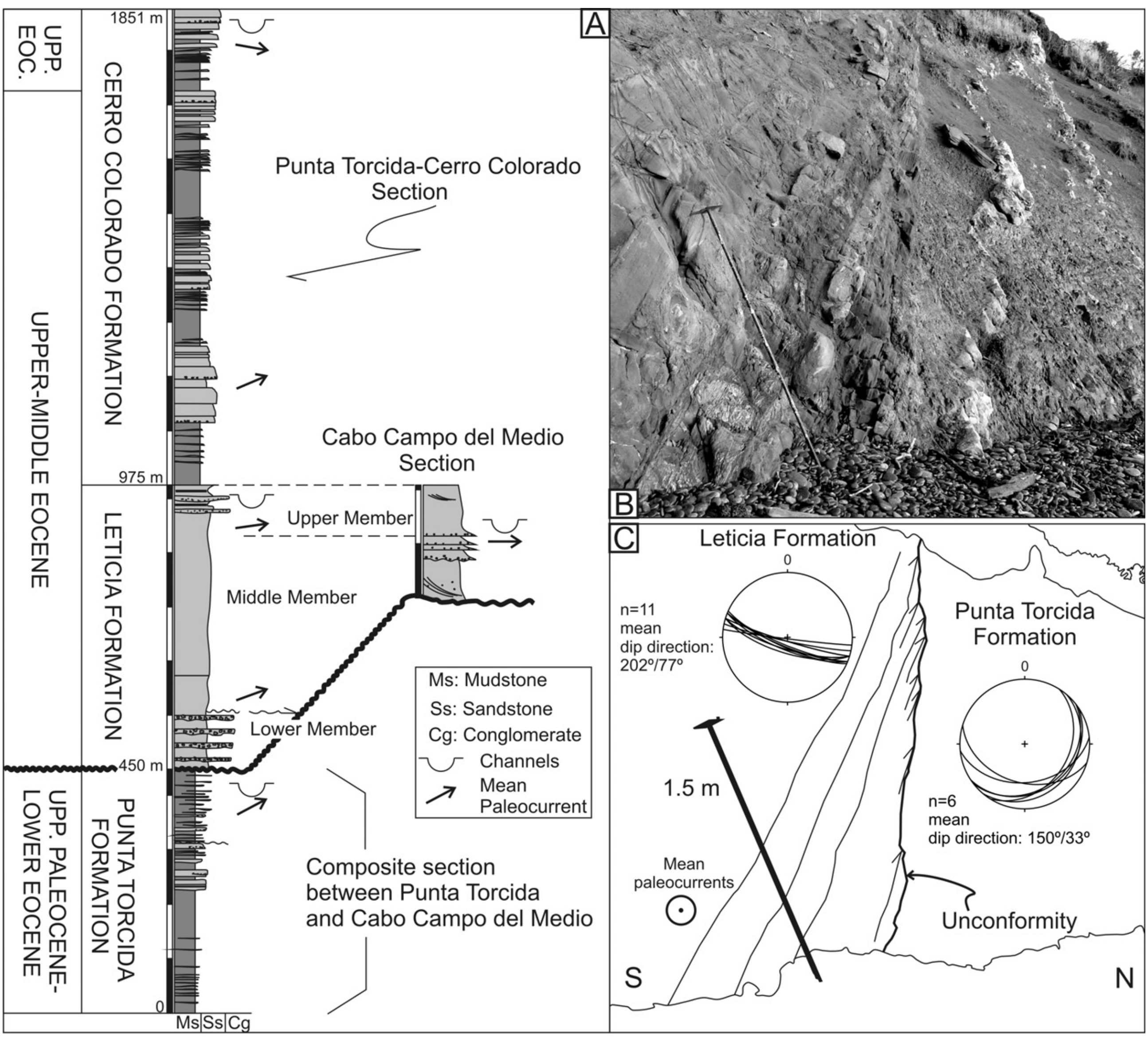

Fig. 3. (A) Stratigraphic column including units between Paleocene and Upper Eocene. Partly modified from Olivero and Malumián (1999). (B) Detail of the angular unconformity at the base of the Leticia Formation. Punta Torcida Formation attitude (light bed in picture) clearly differs from Leticia sandstones, which are onlapping the erosive unconformity (towards N). (C) Diagram highlighting the onlap geometry seen in (B); mean paleocurrent directions in Leticia Formation are indicated, and attitude data from both formations is shown in equal area, lower hemisphere stereographic projection, highlighting the angular relationship between them.

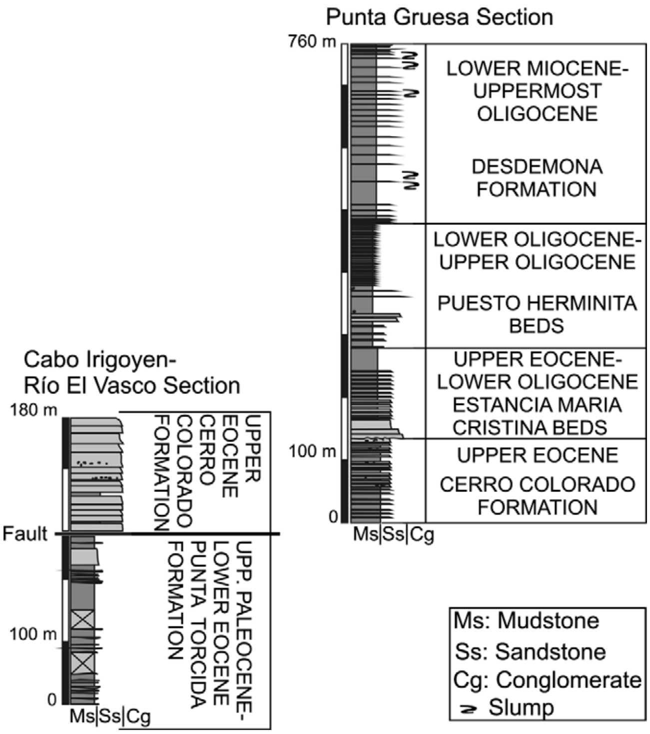

Fig. 4. Stratigraphic column including units between Upper Eocene and Lower Miocene. Partly modified from Jannou and Olivero (2001) and Malumián and Olivero (2006).

The unconformity that separates the Punta Torcida from the Leticia Formation is recognized regionally in the foreland basin system (Galeazzi, 1998; Olivero and Martinioni, 2001; Olivero and Malumián, 2002). The sandstones of the Leticia Formation have been in part deposited by gravity-flow currents with high rates of sedimentation in shallow marine settings. They are commonly channelized, and provenance studies reveal an important sediment influx from the uplifting Andes located southwards (Olivero, 2002).

The Leticia Formation includes three members that show marked variations in thickness between the northern Cabo Campo del Medio and southern Punta Torcida-Cabo Tiburones areas (Olivero and Malumián, 1999). These members are useful as markers in order to construct with accuracy the structure of the Campo del Medio Anticline (next section) and to define an important thickness increase towards the south, mainly in the middle member (see Fig. 4). Paleocurrent directions are towards the east (Fig. 3A), and the sandstone beds onlap the basal unconformity with a northward direction, as seen at Punta Torcida (Fig. 3B and C).

The late-middle Eocene to late Eocene Cerro Colorado Formation unconformably covers the Leticia sandstones (Olivero and Malumián, 1999). The unit is exposed continuously along the Cerro Colorado cliffs at Cabo Irigoyen and at Punta Gruesa. The formation comprises four coarsening–thickening upward sandstone-dominated members, each one starting with dark-gray mudstones at the base and grading to quartz-rich sandstones at the top. The sandstones represent deposition from sedimentary gravity flows and preserve a suite of trace fossils, including graphoglyptids, indicative of deep-marine settings (Olivero et al., 2005). At Punta Gruesa the uppermost member consists of classical turbidites (PG1 of Ponce et al., in press).

Paleocurrent vectors from our field observations indicate an eastern directed sediment transport (Fig. 3A). These paleocurrent vectors are similar to those measured in the Leticia Formation, supporting the inference that the Cerro Colorado and Leticia Formations where both deposited into an E–W oriented depocenter (see Section 5); although the Cerro Colorado Formation represents deeper depositional settings.

The following unit, the Estancia María Cristina Beds (uppermost Eocene–Lower Oligocene; Malumián and Olivero, 2006) lies over an erosive unconformity developed on top of the Cerro Colorado Formation. These beds crop out at Punta Gruesa and south of Cerro Colorado. In the Punta Gruesa area they comprise a fining and thinning upward sandstone-dominated succession, interpreted as the deposits of sustained hyperpycnal flows (Ponce et al., in press). Its depositional setting corresponds to deep-water environments (Malumián and Olivero, 2006).

At Punta Gruesa, the Estancia María Cristina Beds are thrusted over the mudstones of the Puesto Herminita Beds (upper–lower Oligocene to upper Oligocene; Malumián and Olivero, 2006), which correspond to turbidite deposits of deep sea settings. These beds form a nearly symmetric anticline in the frontal thrust-fold belt. The Puesto Herminita Beds also crop out south of Cerro Colorado, where they conformably cover the Estancia María Cristina Beds and comprise channelized mudstone–sandstone intercalations. North of Punta Gruesa, these Beds are followed northwards through a buried contact by the slope mudstones of the Desdémona Formation, of latest Oligocene–earliest Miocene age (Malumián and Olivero, 2006).

4. Structure

Two balanced cross-sections are introduced in this paper, the first one includes the southern part of the NW–SE trending coast (cross-section A), and the second one the frontal part of the thrust-fold belt to the north (cross-section B). Both cross-sections have lateral continuity, but are cross-cut by a NE–SW strike-slip dextral fault (Fueguina fault, Fig. 5) that, in addition to the NW trend of the outcrops, makes it necessary to analyze the cross-sections separately. Based on the rheology of the rocks involved in deformation, composed mainly by sandstones or sandstone–mudstone intercalations, we opted to construct these sections using the kink-band method for the conservation of thicknesses (Suppe, 1983; Woodward et al., 1985; Suppe and Medwedeff, 1990). The Punta Torcida Formation comprises at least 250 m of mudstones with ductile deformation (Olivero and Malumián, 1999; Ghiglione et al., 2002; Fig. 3A), but we consider as a first

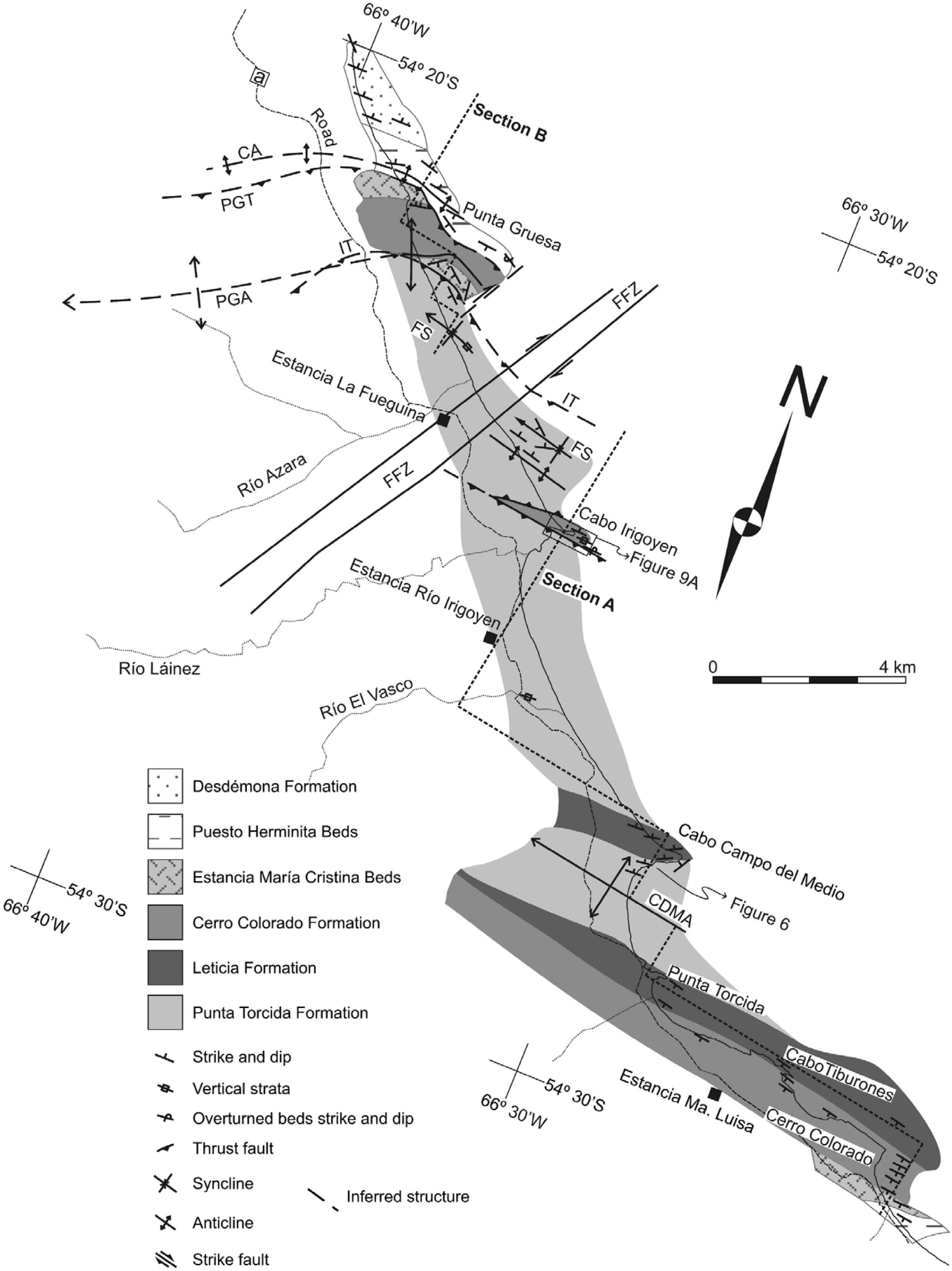

Fig. 5. Geologic map of the studied area (location shown in Fig. 1). Traces of cross-sections A and B (Figs. 11 and 14) and location of Figs. 6 and 9A are indicated. IT, Irigoyen thrust; CDMA, Campo del Medio anticline; CA, Castor anticline; PGT, Punta Gruesa thrust; PGA, Punta Gruesa anticline; FFZ, Fueguina fault zone; FS, La Fueguina syncline.

approximation that the higher competence of the late-middle Eocene–Oligocene sandstone-dominated succession (more than 1400 m, Fig. 3A) controls the development of the shallow structures (cf. Twiss and Moores, 2007, p. 378). There is not certainty on the composition of the Paleocene rocks that constitute the detachment level used for the structural model, because this layer does not crop out in the studied area. The exposures of the Punta Torcida Formation between Cabo Campo del Medio and Cabo Irigoyen have an important percentage of mud, but no accurate stratigraphic sections exist and the thickness involved in that pelitic succession in unknown. Nearby Cabo Irigoyen a succession of 250 m of Punta Torcida Formation was measured, composed of at least 70 m of sandstone interlayered within the mudstone section (Fig. 2 of Jannou and Olivero, 2001; Fig. 4). Finally, the sandstones at the top of the Punta Torcida Formation cropping out at Cabo Campo del Medio, and the ones exposed near the Azara River mouth, do not reveal ductile deformation but fragile structures such as fractures, minor faults and gentle accommodation folds (Fig. 6A and B).

4.1. Cross-section A

4.1.1. Description

The trace of this section trends N9° and it is segmented because of the irregular shape of the coast. The section cuts almost perpendicular to the axis of the Campo del Medio anticline, an asymmetric fold with a minimum half-wavelength of 3 km and an axis oriented roughly E–W, inclined westwards (Fig. 7). The southern limb of the anticline comprises the Leticia Formation, the Cerro Colorado Formation and the Estancia María Cristina and Puesto Herminita Beds, which unconformably lay over the Cerro Colorado Formation showing a slight decrease in bed dip more evident at the Puesto Herminita Beds (Fig. 7). This situation probably represents the syntectonic fill of the southern syncline by the Estancia María Cristina and Puesto Herminita Beds.

For the construction of the cross-section, two dip domains where defined in the southern limb, one of 60°S and the other of 51°S, both presenting ESE strike. There is no evidence of diachronism between folding of the Leticia and Cerro Colorado Formations. Even though a slight non-depositional unconformity separates both units, these represent a nearly homogeneous dipping section. If the folding had been coeval with deposition of any of these formations, it should have generated a growth structure unlikely to be recognizable from beds attitude, except from a continuous exposure of anticlinal limbs or their axial plane zones (cf. Suppe et al., 1992). As this kind of exposure is not present at the southern limb, we assume that the folding post-dated both formations.

The southern part of the core of the anticline is represented by the mud-rich basal section of the Punta Torcida Formation, which is highly deformed and presents abundant minor thrusts and folds well exposed between Cabo Campo del Medio and Punta Torcida that lay under the resolution of our mapping. Moreover, at least part of the deformation presented by the Punta Torcida Formation corresponds to the tectonic event that induced the major unconformity between Paleocene–earliest Eocene and late-middle Eocene units; therefore the deformation recorded should be only in part a consequence of the formation of the Campo del Medio anticline.

In the northern limb of the anticline, the upper section of the Punta Torcida Formation is composed of a thick succession of tuffaceous sandstones displaying several cycles of channelized packages. The upper part of this succession was originally assigned to the Leticia Formation (Olivero and Malumián, 1999), but later reassigned to the upper Punta Torcida Formation on the basis of its petrography (Olivero, 2002; Olivero and Malumián, in press). The sandstone succession shows a slight decrease in bedding dip towards the north that was previously interpreted as growth strata (Ghiglione et al., 2002). However, detailed field measures of beds attitude (Fig. 6C) suggest that the decreasing dip of bedding is a sedimentological feature related to the incision of at least three channels onto a previous package of lobe compensation cycles (Figs. 6A, B and 8). Thus, the slight changes in attitude are natural towards the axis of each channel while the beds accrete and aggrade, and the consecutive channel cut-and-fills in the succession lead to the observed decrease in dip as the channel axes migrate towards the north (Fig. 8). This argument is supported by ~N60° oriented paleocurrents, coincident with the trend of the channels' axes (Fig. 6D).

The sandstone beds of the Leticia Formation that rest on the major unconformity at the top of the Punta Torcida Formation dip ~25°N in the northern limb of the anticline (Fig. 7). We assumed that the attitude of the Punta Torcida upper section has been, at least in part, attained by a tectonic event that predates the folding stage responsible for the formation of Campo del Medio anticline (see Section 4.3). The attitude of the northern limb of this fold corresponds, therefore, to that of the Leticia sandstones. Considering then a ~25°N dip for the northern limb, the interpretation that the Campo del Medio anticline is an asymmetric south-vergent fold is supported. No fault outcrops were found related to this anticline, thus we propose that a possible thrust responsible for the development of this fold must be buried by the fill of the southern syncline by post-Eocene units (Cabo Domingo Group; cf. Malumián and Olivero, 2005, 2006), or affected by the Fagnano transform fault system and its related structures (Ghiglione, 2003; Ghiglione and Ramos, 2005).

The Leticia Formation is poorly exposed north of Cabo Campo del Medio, and its contact with the Punta Torcida Formation is not revealed. We assumed, however, that no tectonic contact is present, and that the occurence of the Paleocene mudstones to the north of the Campo del Medio anticline responds to the presence of a new anticlinal structure evidenced towards that direction, which we describe below.

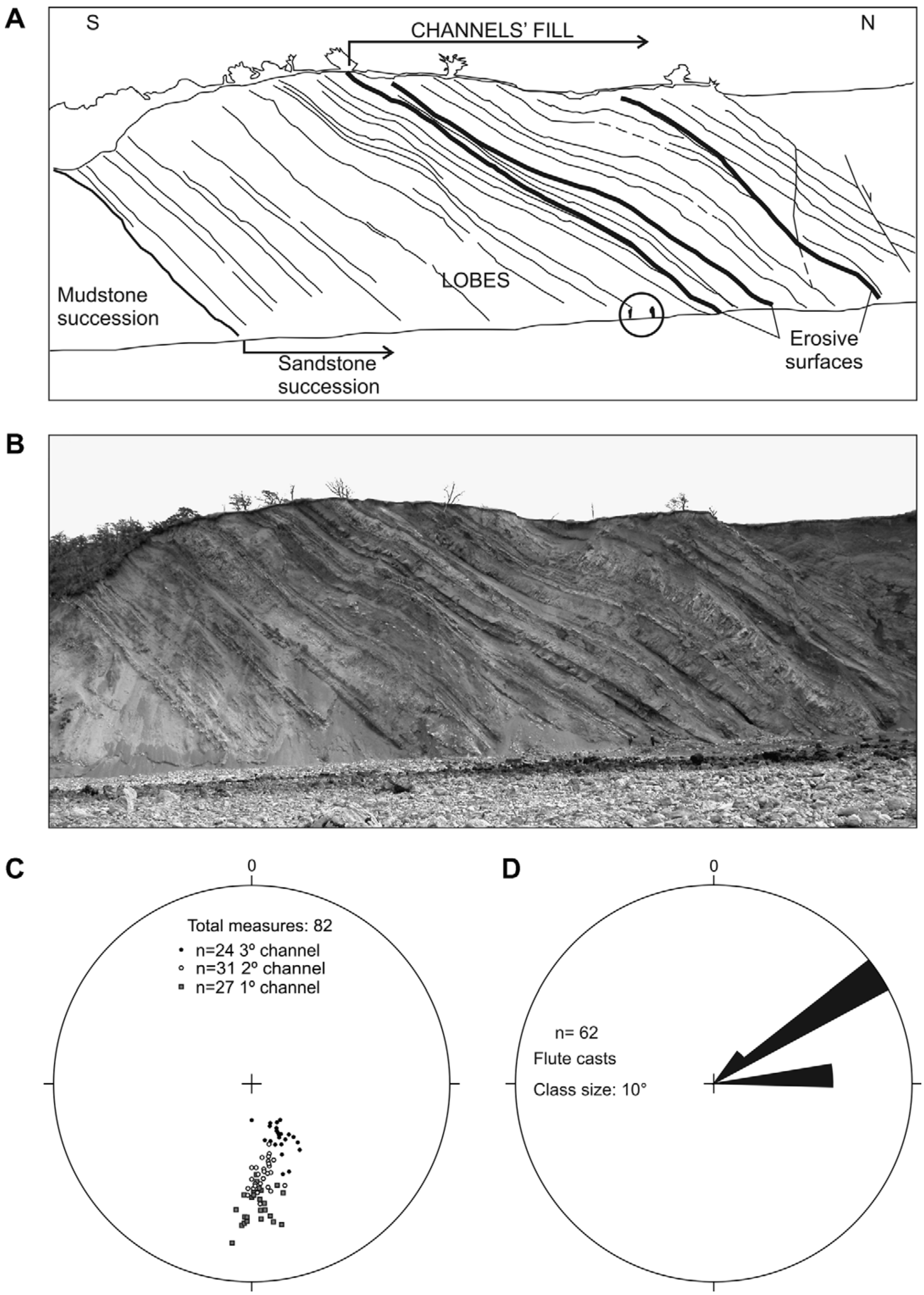

Fig. 6. Stratigraphic and structural features of Punta Torcida Formation upper succession at Cabo Campo del Medio (location in Fig. 5). (A) Line drawing of picture shown in (B), schematizing major channelized features in the sandstone succession. Encircled people for scale. (C) Poles to planes of stratification of three successive channels. Note attitude values of each channel overlapping with the subsequent one. Equal area projection, lower hemisphere. (D) Paleocurrent directions measured in strata plotted in (C).

From Cabo Campo del Medio up to the Cabo Irigoyen, the Punta Torcida Formation outcrops are discontinuous and limited to the cliffs, hiding attitude data. At the Río El Vasco, however, good exposures of turbidites reveal vertical stratification striking ~N80°. The contact between the Punta Torcida and Cerro Colorado Formations at the south cliffs of Cabo Irigoyen is a north-vergent reverse fault that places the Punta Torcida mudstones over the Cerro Colorado upper-Eocene sandstones. This thrust is also expressed as a well-defined lineament in aerial-photographs

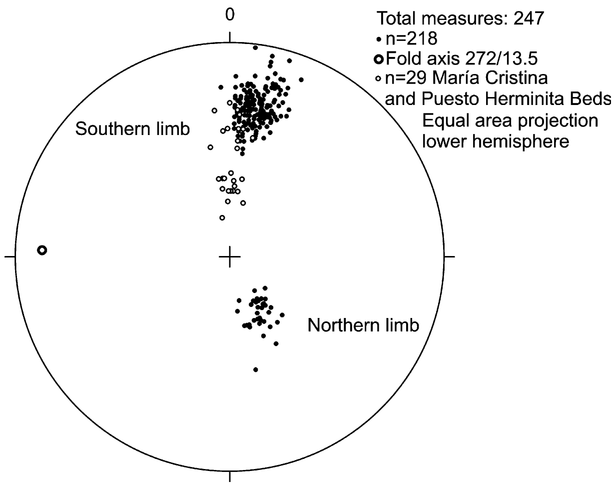

Fig. 7. Attitude data measured in both limbs of Campo del Medio Anticline (black dots are for Leticia and Cerro Colorado Formations). Poles to planes of stratification and the calculated axis for the fold are plotted. Note clear asymmetry of the fold, with vergence to the south. White dots represent poles to planes of stratification of Estancia María Cristina and Puesto Herminita Beds, showing a notable decrease in dip.

and satellite imagery. This feature was previously interpreted as the stratigraphic contact between the Punta Torcida and Leticia Formations by Ghiglione et al. (2002). We differ with that because not only the tectonic contact is clearly seen in the cliffs (Fig. 9B and C), but also the sandstones assigned by those authors to the Leticia Formation have facies and a petrography more suitable with the Cerro Colorado Formation.

Below the thrust, the succession of Cerro Colorado sandstones reveals a progressive change in dip from ~50°S overturned beds at the base to ~45°N dipping beds in normal position at its top. The strike of the strata is maintained near ~N93° (Fig. 9). The change from overturned to normal beds is progressive, including vertical strata in the middle of the succession, as it can be observed in the wave-cut platform of the intertidal zone (Fig. 9A). This feature was first interpreted as a growth structure by Ghiglione et al. (2002), who stated that four syntectonic sedimentary sequences, bounded each other by three syntectonic unconformities, could be seen. No evidence for this interpretation was found in the field, instead of minor channelized features, and therefore it is inferred here, on the basis of detailed mapping, that this structure represents deformed strata due to drag below the north-vergent thrust fault (Fig. 10).

To the north of Cabo Irigoyen, a south-vergent fault called Irigoyen thrust transports Punta Torcida mudstones over the top of the late-Eocene Cerro Colorado sandstones. Satellite imagery analysis reveals that this fault appears to terminate against the southern north-vergent thrust just about 2 km west from the coast (see Fig. 5). Thus, it is inferred that the north-vergent thrust cuts the south-vergent Irigoyen thrust surface. The Irigoyen thrust originally acted as the upper flat of a ramp. Movement over that ramp formed a fault-bend fold (anticline A, Fig. 10A) and placed the Punta Torcida Formation over the Cerro Colorado sandstones. Foreland propagation of the deformation led to folding of this anticline, of the ramp-flat thrust and of the sequence in the hanging wall (anticline B), forming an antiformal stack (Fig. 10B). This second anticline was developed over a thrust ramp called here North thrust. Further compression resulted in the formation of a breakthrough fault that branched from the North thrust, and has cut across the frontal limb of the anticline B with a high angle to the stratification (~100°, Fig. 11). It generated the drag structure in its footwall, favored by the high angle termination of the Cerro Colorado sandstones against the fault plane, and produced an offset that placed the Punta Torcida Formation over the Cerro Colorado Formation, as seen in the Cabo Irigoyen outcrops (Figs. 10C and 11).

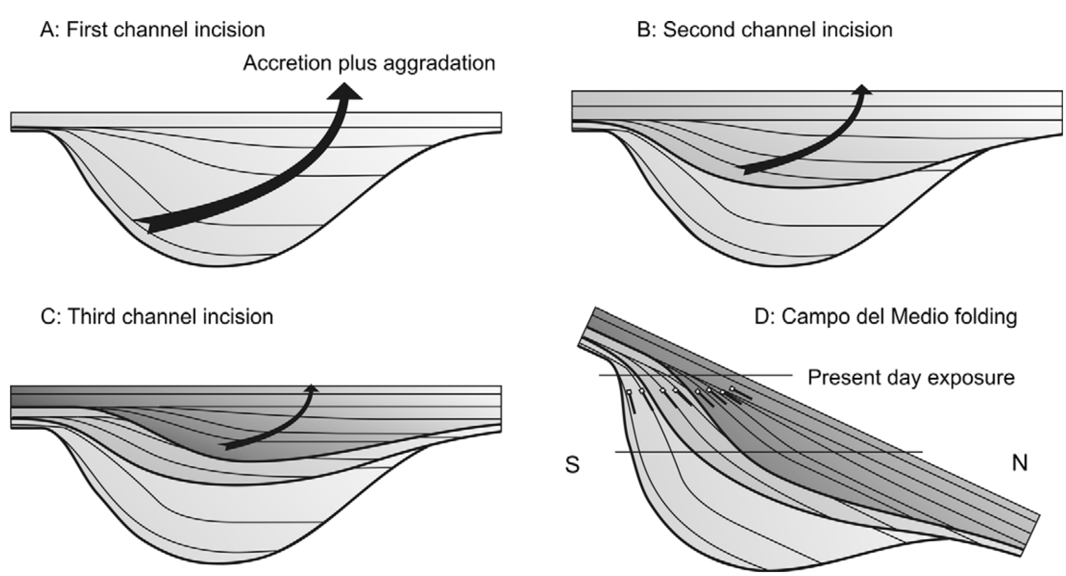

Fig. 8. Schematic model for the deposition and subsequent folding of the Punta Torcida sandstones cropping out at Cabo Campo del Medio.

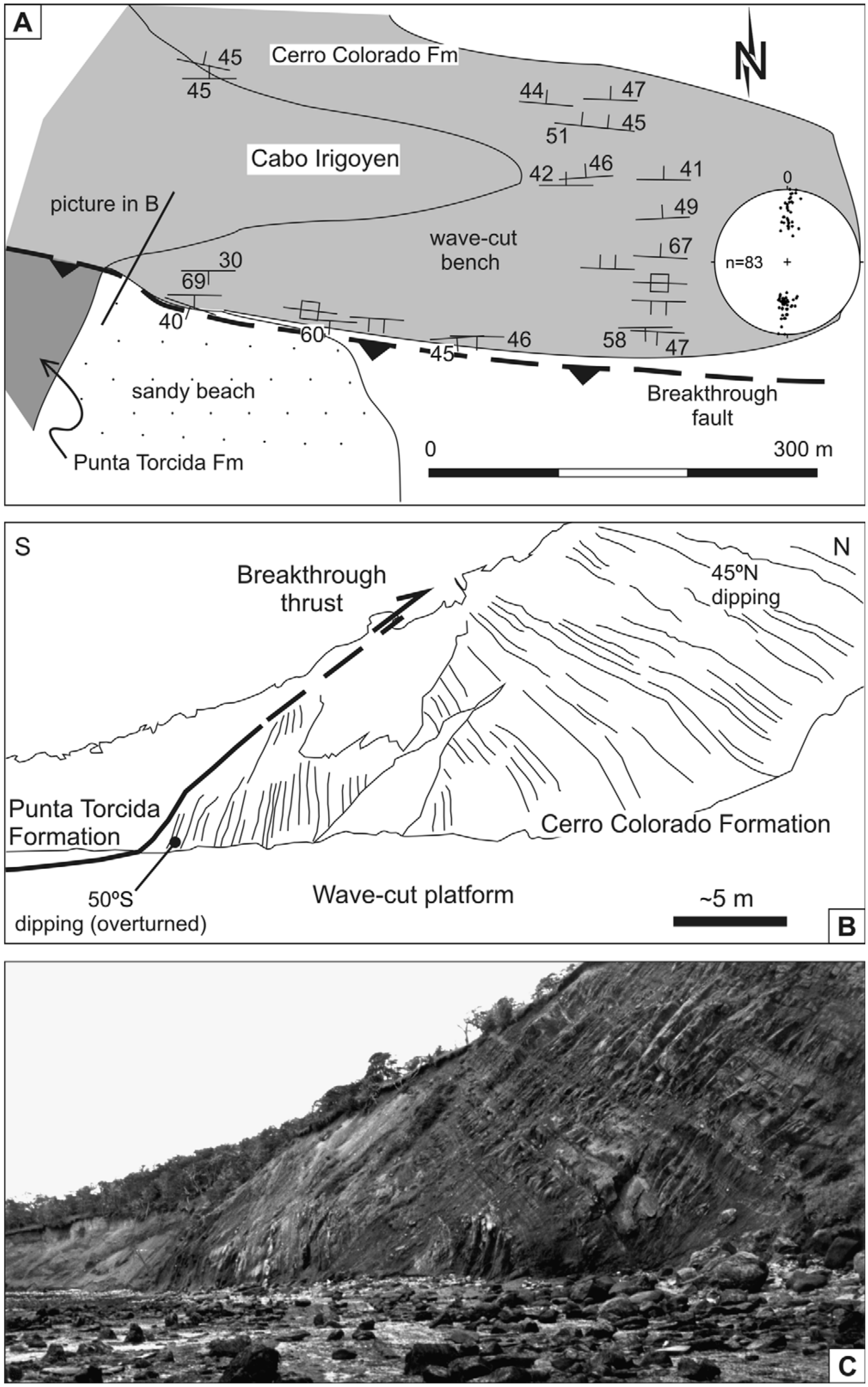

Fig. 9. Detail of structures at Cabo Irigoyen. (A) Detailed structural map of Cabo Irigoyen, with attitude data of Cerro Colorado sandstones. Note overturned to normal bedding change from south to north. No unconformity was seen in the wave-cut platform or in the cliff. Symbols are the same as in Fig. 5, numbers indicate bed dip in degrees (symbols with two lashes are for more than 75°). Stereographic net shows poles to planes of stratification of Cerro Colorado sandstones, equal area projection, lower hemisphere. (B) Line drawing of picture shown in (C), see location in (A). Main structural features seen in the cliff of Cabo Irigoyen are depicted. Note the lack of any unconformity, and the progressive change from overturned to normal beds. This feature is interpreted as a drag deformation zone formed bellow the propagated breakthrough fault, which is consistent with the high angle termination of the 45°N dipping beds against the fault plane (see Figs. 10 and 11).

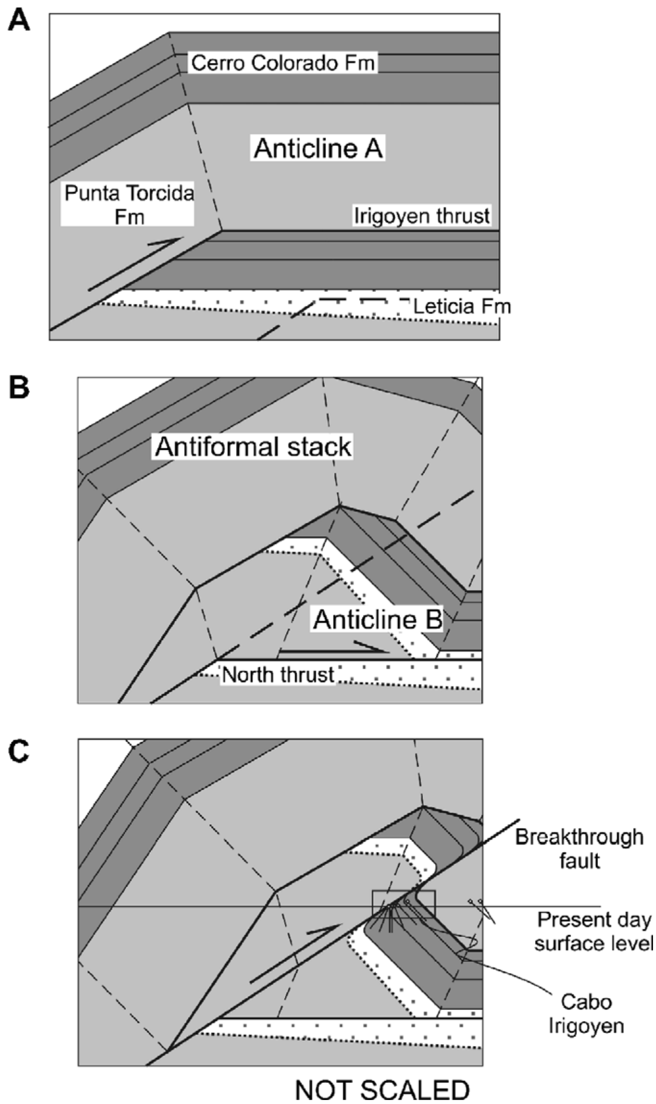

Fig. 10. Evolution of the Cabo Irigoyen drag structure related to a breakthrough of a deeper thrust. (A) Initial stage, the Irigoyen thrust puts the Punta Torcida Formation over the Cerro Colorado sandstones forming a fault-bend fold (anticline A). Future trace (stippled) of the deeper North thrust is shown. (B) Development of anticline B by displacement over the North thrust bend; note that the upper flat of the Irigoyen thrust has been also folded, forming part of the forelimb. Future trace of the breakthrough fault is shown. (C) Final geometry with a drag structure developed in the footwall of the breakthrough, which cuts across the forelimb of anticline B with a high angle, placing the Punta Torcida Formation over Cerro Colorado sandstones.

The section continues to the north with a minor syncline formed within sandstones of the Punta Torcida Formation. The sandstones were, in part, tentatively included in the Leticia Formation (Olivero and Malumián, 1999). Petrographic analysis, however, indicates a dominant composition of volcanic glass, volcaniclastic lithics and plagioclase, with subordinated quartz. This coincides with the composition of the Punta Torcida Formation tuffaceous sandstones at Cabo Campo del Medio (Olivero and Malumián, 1999; Olivero, 2002; Olivero et al., 2004). Also, foraminiferal assemblages are consistent with the late Paleocene–early Eocene of Tierra del Fuego (N. Malumián, personal communication). Therefore, these rocks are included in the Punta Torcida Formation.

Only the southern limb of the mentioned syncline is exposed in the wave-cut platform, dipping ~60°N, with a strike of about ~N105°. The syncline clearly closes towards the east, defining a west-plunging axis (Fig. 5). This fold probably reflects a new ramp of the Irigoyen thrust (Fig. 11). The evident drag effect of the Fueguina strike-slip fault in the western beds of the southern syncline limb supports the dextral kinematics established for this fault by Ghiglione et al. (2002).

4.1.2. Balanced construction

The section was resolved in depth with the construction of dip domains bounded by axial planes, according to the field data (Fig. 11). Due to the lack of additional information about the geometry of structures in depth, such as seismic lines or well-log data, we made several assumptions concerning location of faults and their geometry. These were made in order to obtain a geometrically reasonable balanced section that depicts a first approximation to the real geometry of structures in depth. The angles of faults were deduced from Suppe (1983) equations to maintain the least amount of shear, except from the Campo del Medio backthrust, which is assumed to dip the same as the anticline's back limb.

A fault-bend model was used for the Campo del Medio anticline, with a maximum possible depth to the upper flat obtained from the intersection of the axial planes of the anticline. The upper member of the Leticia Formation was used as a marker line for both limbs of the anticline. The fault involved is defined as a backthrust, because its vergence (consistent with the observed vergence of the anticline) is to the south, opposite to the regional transport direction. It branches from a detachment at about 2.67 km below sea level with an original angle of ~25°. The core of the anticline has been area-balanced in addition to the line-length balancing technique, assuming that an amount of shortening in that sector (less than 1.5 km) is due to inhomogeneous flattening (Ramsay and Huber, 1983).

The branching line of the backthrust has been folded by the younger Irigoyen thrust. This thrust branches from the same sole fault with an initial angle of 30° dipping to the south. It first generates the Irigoyen fault-bend anticline in the strata above (anticline A, Fig. 10), and later it is folded by the anticline formed above the North thrust (anticline B, Fig. 10) generating the Irigoyen antiformal stack. The breakthrough fault cropping out at Cabo Irigoyen later affects the frontal limb of this antiform, producing the drag structure observed at that site (Fig. 10, see above). The North thrust branches from the basal detachment with an angle of 33.4°. This fault has a narrow upper flat at a depth of about 1.3 km (Fig. 11), nearly coincident with the lower detachment level of the Punta Gruesa thrust (in cross-section B).

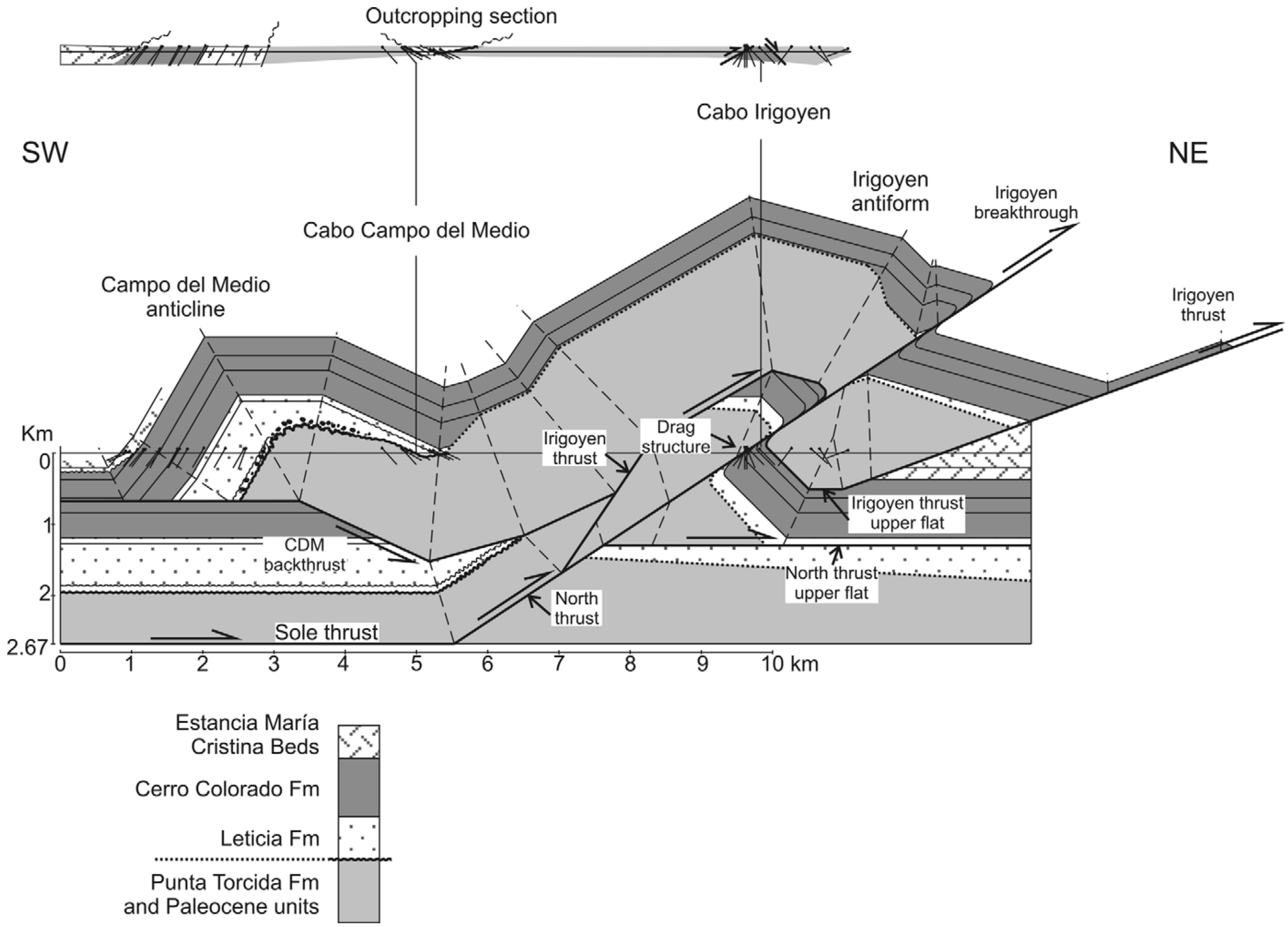

Fig. 11. Balanced cross-section A (see location in Fig. 5).

The restored section reveals an original length of 28.87 km, and a total shortening of 15.22 km (52.72%; Fig. 12). The residual anticline that results from the restoration of this section in the Punta Torcida Formation represents the early stages of deformation that affected these rocks before deposition of Leticia and Cerro Colorado Formations, as mentioned before. The configuration of this fold in Figs. 11 and 12 is only schematic, and the unconformity between the Punta Torcida Formation and the younger units might be of less angular relationships than those shown in our drawings. We have assumed the existence of this anticline structure previous to the deposition of late-middle Eocene units because of the following reasons: (a) there is marked erosion of the top of the Punta Torcida Formation towards the south, where at least 200 m of the upper section (Punta Torcida sandstones) are missing; (b) consistently, the Leticia Formation shows an increase in thickness of nearly 300 m from Cabo Campo del Medio towards the south (Fig. 3A); (c) there is an apparent pinch out of the Leticia Formation at Cabo Campo del Medio, as this unit does not crop out again in the whole Atlantic coast to the north of the orogenic front, being only recognized as a thin horizon in subsurface (Glauconítico A; cf. Masiuk et al., 1990a, b; Olivero and Malumián, 1999); (d) the Leticia Formation onlaps the unconformity with the Punta Torcida Formation with a northward direction (Fig. 3B and C) and (e) conversely, the Cerro Colorado Formation appears to have buried the Punta Torcida Formation high, as it crops out to the north of Campo del Medio anticline. These evidences, summed to the presence of the extensive exposure of Punta Torcida Formation between Cabo Campo del Medio and Cabo Irigoyen, allow us to define some kind of anticlinal structure involving Paleocene units located in that area. This structure somehow controlled the sedimentary evolution of the basin, as we propose in a following section. Also, we point out that the thickness and geometry of the Leticia Formation clastic wedge seen in the restored cross-section (Fig. 12) to the north of this structural high is schematic, as we do not have any subsurface information to precise its real architecture apart from well data located tens of kilometers away (Poseidón and Ciclón X-1 wells).

4.2. Cross-section B

4.2.1. Description

The trace of this cross-section is approximately parallel to cross-section A, and includes the northern part of the

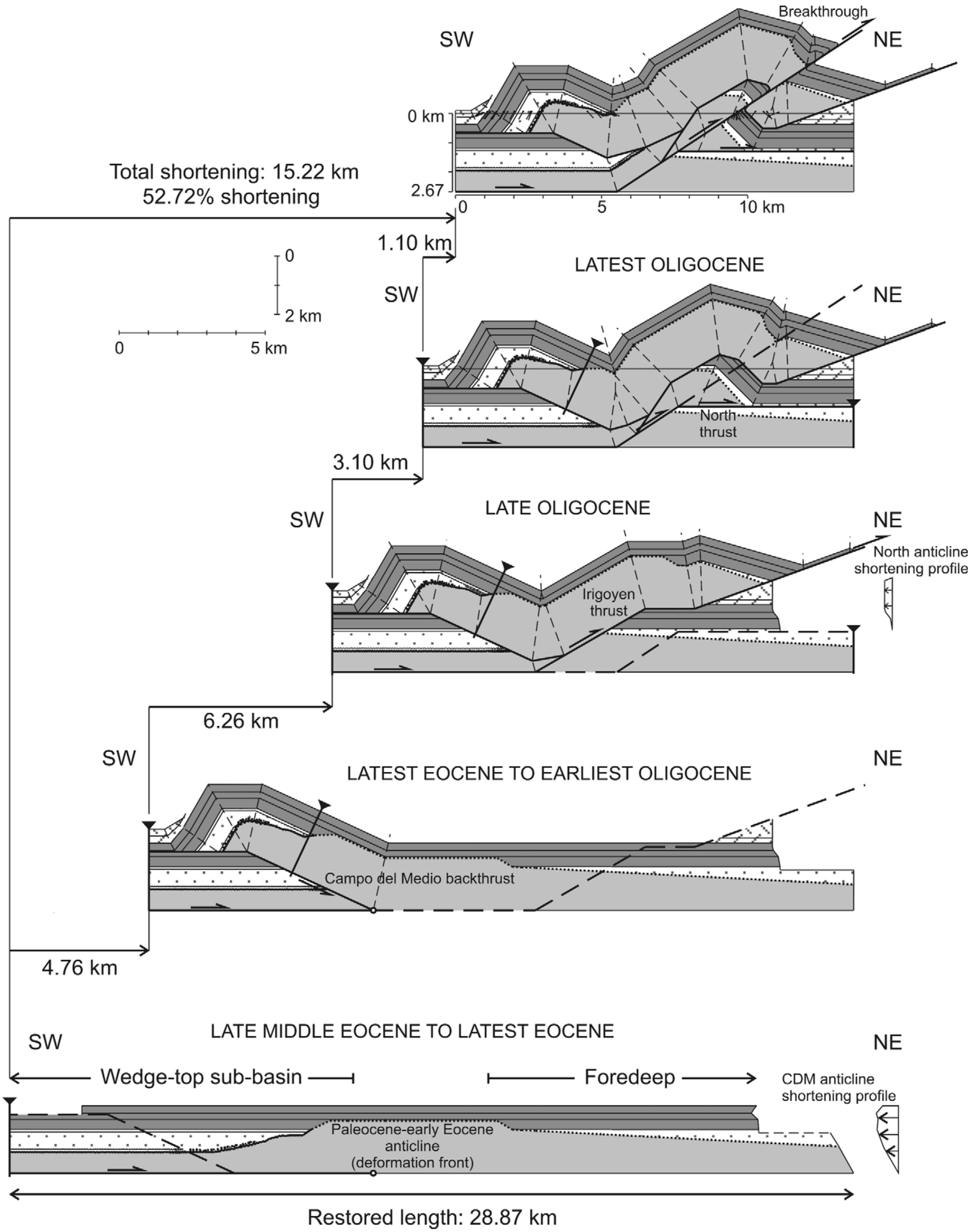

Fig. 12. Kinematics of balanced cross-section A (Fig. 11) and its relations to paleogeography of the Austral basin system. See Fig. 11 for labeled structures. The residual Paleocene–early Eocene anticline in the restored section is schematic, see text for further explanation.

studied area, which comprises the fossilized deformation front. The section starts from south to north with a syncline in the Punta Torcida Formation, poorly exposed in the cliffs south of Punta Gruesa, named here La Fueguina syncline (Fig. 5). The best defined northern limb is oriented about N118°, 33°SE. La Fueguina syncline is supposed to be the continuation to the west of the syncline developed in the Punta Torcida Formation, described in the previous cross-section north of the Cabo Irigoyen. The axes of both synclines are approximately parallel, and the one included in this cross-section is also plunging to the west, defining a combined fold axis which trends ~N290°, gently inclined westwards (Fig. 13A). This inference allows the kinematics of the Fueguina fault to be constrained, using as piercing points the intersection of the syncline axis with the fault zone. This approximation of the horizontal dextral offset is of about 500 m (see Fig. 5). The Fueguina fault zone affects at least the Puesto Herminita Beds, and so its age must post-date the late-early Oligocene to late Oligocene. This fault was proposed as an antithetic Riedel fault linked to the left-lateral Fagnano major fault (Ghiglione et al., 2002), which is in turn considered to be the transform boundary between the Scotia and South American Plates.

The Punta Torcida mudstones override the upper Eocene–lower Oligocene sandstones of the Estancia María Cristina Beds just south of Punta Gruesa. The involved thrust is identified only in the wave-cut platform between the Río Azara mouth and the Punta Gruesa, having apparently a curved trace of approximately NW–SE strike. This fault is inferred to be the outcrop of the Irigoyen thrust, which has been folded by the later Punta Gruesa anticline (see below).

To the north of this tectonic contact, the sandstones of the Estancia María Cristina Beds form the southern limb of the Punta Gruesa anticline. The attitude is obscured by their channelized features and by the deformation caused by subsidiary faults to the Fueguina strike-slip fault zone. It is possible, however, to estimate an attitude of about N65°, 25°SE for the southern limb (Fig. 13B). The core of the Punta Gruesa anticline comprises sandstone–mudstone intercalations of the Cerro Colorado Formation upper member. The contact between the Cerro Colorado Formation and the Estancia María Cristina Beds is obscured in the southern limb, but in the northern limb is a well exposed unconformity. The northern limb comprises nearly vertical beds (dipping ~84°N) in the south cliff of Punta Gruesa. To the north, approaching the Punta Gruesa thrust trace, the beds are intensely disrupted by fault splays that bound blocks of different attitudes. The Punta Gruesa anticline can be defined from the attitude data as a north verging fold affecting the Cerro Colorado Formation upper member and the Estancia María Cristina Beds. The axis of the fold is oriented N78°, with a gentle inclination (~8°) towards the ENE (Fig. 13B).

The morphology of the land west of Estancia La Fueguina indicates the continuation of the Punta Gruesa anticline towards the SW, with its axis rotated to nearly N240° and closing its nose in that direction (Fig. 5). The architecture of this fold suggests that the Punta Gruesa thrust (responsible for the development of the anticline) rejoins its basal detachment westwards, forming an oblique ramp. This rejoining probably reflects a transfer zone towards the west, but the lack of exposures does not allow its geometry to be interpreted accurately.

The Punta Gruesa thrust crops out in the northern cliff of Punta Gruesa, where it transports the Estancia María Cristina Beds onto the mudstones of the Puesto Herminita Beds. It is also exposed in the wave-cut platform adjacent to the Punta Gruesa, where several minor splays cut through the frontal limb of the Punta Gruesa anticline. The trace of this fault is sinuous to the east, and we infer that the reason for this is dragging against the Fueguina

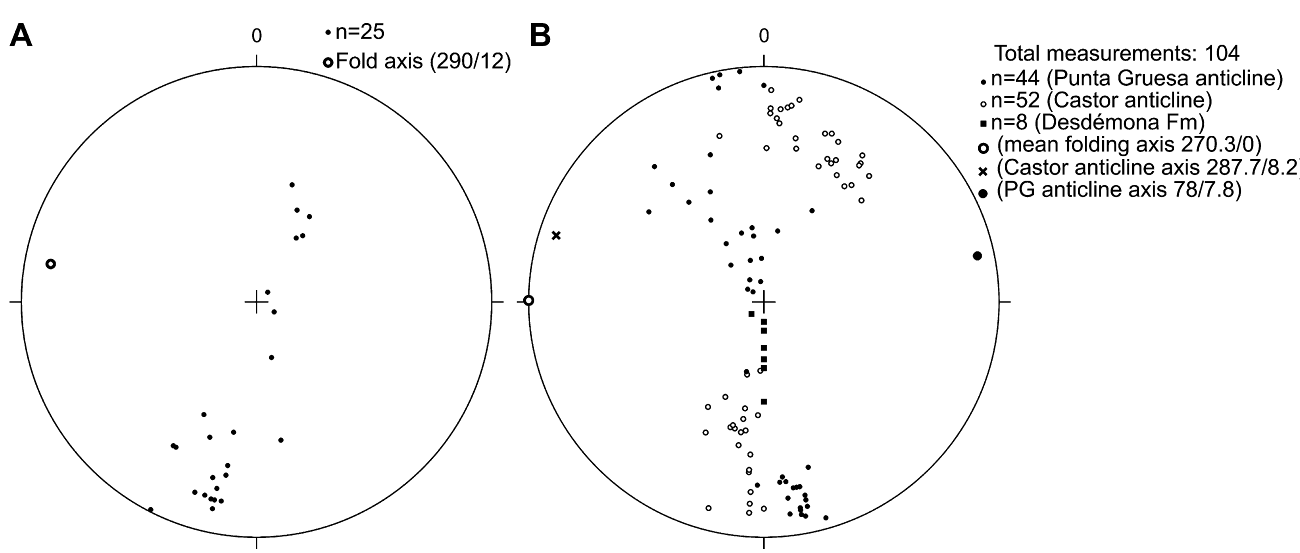

Fig. 13. Equal area, lower hemisphere stereographic projections. (A) Poles to planes of stratification of Punta Torcida Formation near Río Azara mouth, forming the La Fueguina syncline. Bigger dot marks the axis line of the fold. (B) Smaller dots (white, black) and gray squares are poles to planes of stratification of the structures at Punta Gruesa (Punta Gruesa anticline, Castor anticline and Desdémona growth structure). Bigger dots and cross mark the axis line of folds.

fault, evidenced by disturbed beds towards its termination (some of them overturned). As expressed before, it is also possible that towards the west this fault also turns to the SW, following the trace of the Punta Gruesa anticline, and rejoining its basal detachment. The dip of the fault could not be measured accurately, but it is estimated to be at least 70°S in the cliff's exposure, where the apex of the curved trace of the fault is located. The dip angle of the thrust might decrease towards both terminations of the fault, according to the highly curved trace indicative of low angle thrusts.

Below this thrust the Puesto Herminita Beds form the Castor anticline, whose limbs dip 64°S and 49°N with an approximate E–W strike, defining an apparent south-vergence (Fig. 13B). The core of the Castor anticline is formed by sandstones here assigned to the Estancia María Cristina Beds. To the east, the southern limb of the anticline bends changing its strike slightly to the SE (Figs. 5 and 13B), and reveals overturned sandstone beds dipping to the NE. This deformation is due to the drag against the Fueguina fault zone, and consistent with its kinematics (Ghiglione et al., 2002).

To the north of the anticline the slope mudstones of the Desdémona Formation crop out with a buried base. These mudstones record a slight dip decrease towards the north from ~19°N at the base of the succession to about 6°N at the top keeping a constant strike of ~N90° (Fig. 13B). They form a succession of growth strata related to syntectonic sedimentation evidenced by the occurrence of synsedimentary folds and N–S oriented clastic-dike swarms affecting their whole thickness, supporting the idea of pulses of deformation coeval with the sedimentation of the Formation (Ghiglione, 2002; Ghiglione and Ramos, 2005). The Desdémona Formation is covered to the north by several north-prograding clinothems of Miocene age, without evidences of compressive deformation, interpreted as the fill of the Austral basin Miocene foredeep (Ponce et al., 2005).

4.2.2. Balanced construction

The same criteria presented for the cross-section A was used to balance this cross-section, supporting the assumptions in own field observations. The reconstruction of the structure in depth shows a common decollement for the thrusts involved in deformation, at about 1.1 km below sea level (Fig. 14). It is assumed that this decollement is connected with the upper flat of the North thrust in cross-section A (see Fig. 11).

Three ramps branch from the decollement, forming an imbricate thrust system responsible for the deformation in the thrust-fold belt front. The oldest and southernmost thrust is the Punta Gruesa thrust, which ramps with an original angle of 20° dipping to the south. This thrust generates a fault-propagation fold (Punta Gruesa anticline) that sticks after an early stage of evolution. After that, the thrust breaks through upwards with the same original angle, and propagates to the paleosurface transporting the fold northwards (Fig. 14). The second thrust is a north verging blind thrust that branches from the basal detachment with an original angle of 38°. This fault propagates producing the Castor anticline, and deforms at the same time the previous Punta Gruesa anticline and Punta Gruesa thrust. Afterwards, a final blind thrust propagates from the decollement with an angle of 35°, deforming both previous anticlines and their related thrusts.

There is no outcrop evidence for these last thrust and fold, but to explain reasonably the high-dipping angles of Punta Gruesa thrust at its apex (see description above) and the back limb of Castor anticline, a frontal anticline that deforms these structures is necessary. The geometry of this structure was defined to maintain reasonable shear angles in the restored section. The development of this thrust must have been coincident, at least during its last stages, with deposition of the Desdémona mudstones, generating the growth structure observed in the field. Moreover, to the north of this cross-section, the strata at the top of Desdémona Formation are slightly folded (Ghiglione, 2002, 2003), indicating the cessation of compressive deformation at an early-Miocene time. In Fig. 14, the unconformable contact between Desdémona Formation and the previous units, including the erosive surface at the top of the frontal buried anticline, is schematic. It does not affect the balanced construction, as for the restoration of the section the geometry of the buried structures was considered continuous (see dotted line in Fig. 14). The restoration of cross-section B shows an undeformed length of 5.67 km and a total shortening of 1.68 km (29.63%; Fig. 14). Also, the shear presented in the shortening profile is of about 32°.

The eastern foreland thrust-fold belt of the Fuegian Andes can be classified following Morley (1986) as a buried thrust front of type II (with blind frontal thrust). The tip of this thrust front may be represented by the blind thrust generated in the last compressive deformation pulse, evidenced by the Desdémona Formation growth structure. Assuming the Punta Gruesa imbricate system described in cross-section B as a product of the last stages of deformation in cross-section A (displacement on North thrust), the shortening of almost 53% recorded in the latter can be considered as the maximum shortening for the frontal 16 km of the Fuegian thrust-fold belt at the study area.

4.3. Differences with previous models

The geometry of the structural model introduced here strongly differs from those presented elsewhere for the same study area, particularly with the model of Ghiglione et al. (2002). The cross-section shown by these authors only coincides with our model in having a decollement within the Paleocene units, which they assume as the Tertiary–Cretaceous contact. Their model postulates a mudstone dominated succession for the Paleocene acting as a very weak detachment that favors the generation of detachment folds. The kinematics of those folds, following these

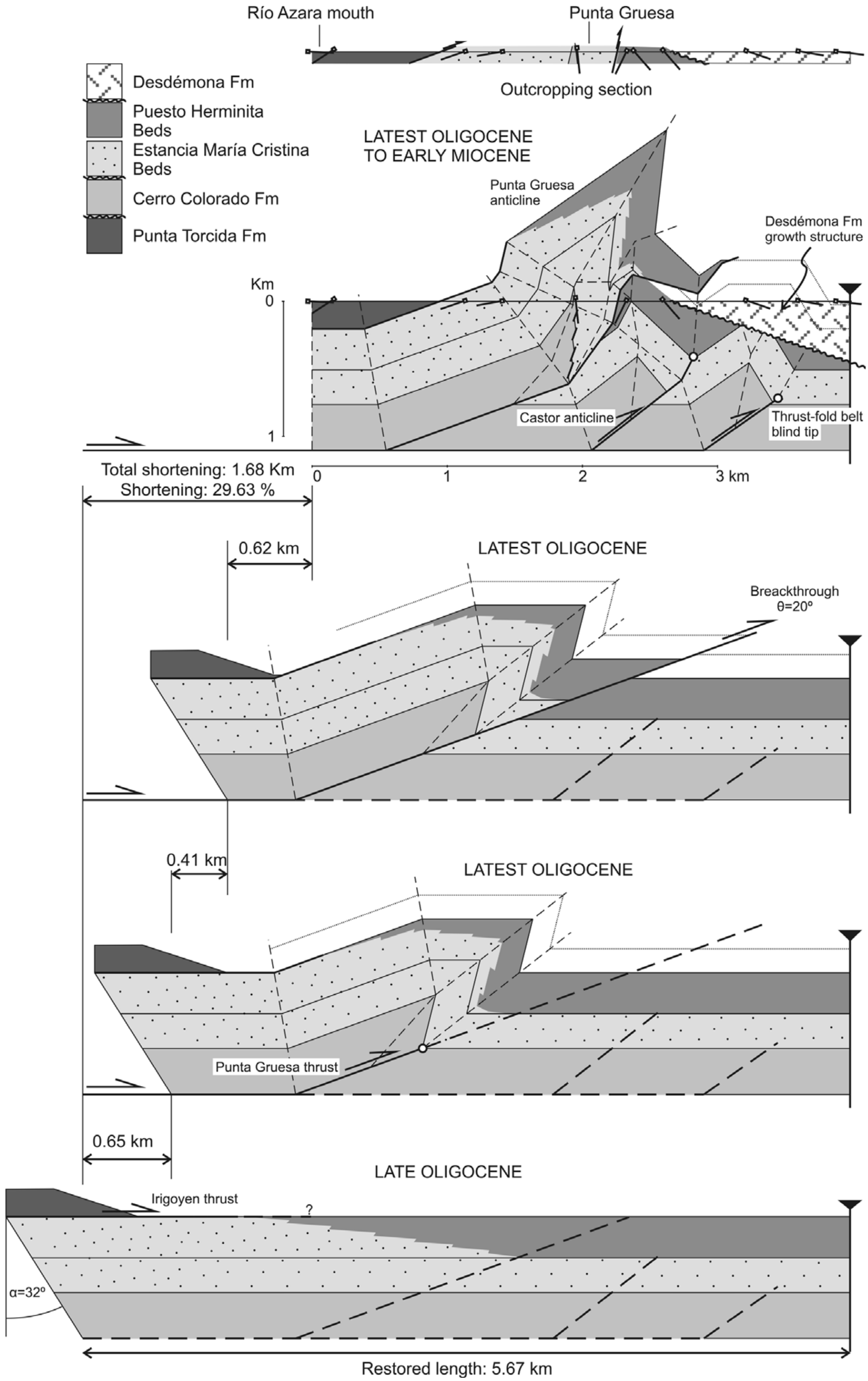

Fig. 14. Geometry and kinematics of balanced cross-section B (see location in Fig. 5). Basal unconformity of Desdémona Formation is schematic. Dotted line is used as reference for line-length balancing.

authors, has been recorded by the growth strata at the top of the Punta Torcida Formation and at the base of the Leticia Formation.

We differ with this model in several aspects: a mudstone dominated succession for the base of the Tertiary is not supported by field evidence, as the Paleocene units recognized in the Atlantic coast of Tierra del Fuego are dominated by sandstones (Río Claro Group, Olivero et al., 2002; Olivero and Malumián, in press), and only about 100 m of the La Barca Formation and 250 m of the Punta Torcida Formation (the latter in the study area) are mudstone dominated within an overall Paleocene section of at least 950 m (Olivero et al., 2002). While it is certainly possible that a mudstone dominated layer acted as a favorable detachment level, it is not valid to state a whole ductile succession for the base of the deformed sequence at the study area. In this sense, Ghiglione and Ramos (2005) postulated fault-propagation folds affecting the Río Claro Group between cabo Leticia and cabo Malengüena, instead of accounting for a ductile detachment and decollement folds.

Secondly, we have shown that the growth strata inferred by Ghiglione et al. (2002) at Cabo Campo del Medio can be interpreted as sedimentary major scale structures (Figs. 6 and 8) for the top of the Punta Torcida Formation, and that the base of the Leticia Formation records an angular unconformity representing a hiatus of at least 7 Ma (Fig. 3B and C; see Malumián and Olivero, 2006; Olivero and Malumián, in press) rather than a syntectonic unconformity. Also, we point out that the outcrops previously assigned to the Leticia Formation at Cabo Irigoyen (Olivero and Malumián, 1999; Ghiglione et al., 2002) are instead part of the Cerro Colorado Formation, that there are no evidences for growth strata developed there, and that the structure observed records deformation at the footwall of a thrust (Figs. 9 and 10).

The second part of the model by Ghiglione et al. (2002) postulates late Eocene–Oligocene north-directed thrusting of the previously formed detachment folds. At least in the case of the Campo del Medio fold, it is evident from the attitude data (Figs. 5, 7 and 11) that the vergence of the fold is towards the south, i.e. towards the hinterland. This supports backthrusting and fault-bend folding rather than foreland propagation of thrusts, as a more efficient geometric model for this fold. Also, the cross-section presented by Ghiglione et al. (2002) shows thrusts with angles of dip up to 55° (consistent with the southern limb of Campo del Medio anticline) that would imply high amounts of shear within the competent layers (Suppe, 1983; Woodward et al., 1985; Suppe and Medwedeff, 1990; Mitra, 1990), not recorded in the field. Therefore, it is preferable to constraint the model with gently dipping thrusts.

Finally, Ghiglione (2002) proposed a transpressional regime with reactivation of the frontal structures of the thrust-fold belt (Punta Gruesa and Castor thrusts), supported by the orientation of clastic dikes between punta Gruesa and cabo San Pablo affecting Miocene strata. We differ with that model, pointing out that there is no evidence for such statement. As we discussed before, the orientation of clastic dike swarms presented by Ghiglione (2002) is averaged between N165° and N175°, which should be the direction of the main vectors of the stress field (Ghiglione, 2002; Twiss and Moores, 2007). The structures at Punta Gruesa record an E–W directed average folding axis (Figs. 5 and 13B), hence it is better to interpret these structures as formed under a fully compressive regime, with main stresses oriented N–S. Additionally, kinematic analysis from Diraison et al. (2000) in our study area presents data from only two stations near Cabo Irigoyen (TdF18 and TdF19), which throw a calculated shortening axis (λ_3) of (azimuth/inclination angle) 166°/50° and 011°/21°, respectively. These values are consistent with an intermediate N–S compressive direction. Nevertheless, Diraison et al. (2000) kinematic analysis is from minor faults constrained in age between "Late Cretaceous to Tertiary" (Diraison et al., 2000, p. 100), which is a time span that does not permit to define if faults are formed during the compressive stage of the Fuegian Andes thrust-fold belt formation (Klepeis, 1994a; Ghiglione, 2003; Ghiglione and Ramos, 2005) or during the transcurrent stage that affected the Cordillera forming the Fagnano transform system (Klepeis, 1994b; Torres Carbonell et al., 2008). Therefore, although data from these workers seems to be coincident with our assumptions, further detail in location and timing of faults should be needed to define kinematics accurately.

5. Thrust-fold belt evolution: paleogeographic implications

The analysis of the structural features shown in this work together with the previous knowledge on the chronostratigraphy of the rocks exposed in the area (Olivero and Malumián, 1999; Malumián and Olivero, 2006) allow us to reconstruct a reasonable path of evolution for the foreland thrust-fold belt of the Fuegian Andes, and its relation to the paleogeography of the Austral foreland basin system. This system is here defined as the broad region of sediment accommodation related to the development of a flexure in the lithosphere (cf. DeCelles and Giles, 1996) due to the tectonic load created by the formation of the Fuegian-Southern Patagonian orogen (Winslow, 1982; Biddle et al., 1986; Wilson, 1991).

The presence of some kind of structural relief bounding a late-middle Eocene sub-basin is necessary to explain the wedging to the north of the upper-middle Eocene succession (Leticia Formation) in the Cabo Campo del Medio-Punta Torcida area, as discussed before (see Fig. 3). According to the observed angular unconformity between the Punta Torcida and Leticia Formations, this structural high should have been developed by a pulse of deformation that affected Paleocene to lowermost Eocene rocks (Punta Torcida Formation and previous units of Río Claro Group).

Restoring the Península Mitre to its early Eocene position by removal of post-Oligocene strike-slip motion of the Fagnano–Magallanes fault system (see Klepeis, 1994b; Olivero and Martinioni, 2001; Torres Carbonell et al., 2008), it can be observed that the first outcrops south of the study area are those of northern Península Mitre region (between Punta Ancla and Punta Donata areas; Fig. 15). In this sector, Paleocene to lowermost Eocene rocks are folded (Grupo Río Claro), and the angular unconformity between Paleocene–lowermost Eocene and Eocene rocks is also exposed (Olivero et al., 2002). The structures in this area can be considered as part of the late Paleocene–earliest Eocene deformation front of the Fuegian thrust-fold belt (Ghiglione and Ramos, 2005). By earliest Eocene times, northward of this deformation front it has been developed a foredeep filled with sediments originated by erosion of the growing Andean orogen at the south (Olivero, 2002). The only exposed rocks of this foredeep at the study area are represented by the Punta Torcida Formation, which records the deepest facies of the Paleocene to lowermost Eocene regressive succession of Península Mitre (Olivero and Malumián, in press).

In the late-early Eocene, the deformation front migrated northwards reaching the Cabo Campo del Medio area. This evolutionary stage of the thrust-fold belt is partly included in the Río Bueno thrusting stage of Ghiglione and Ramos (2005). The deformation front migration involved a main detachment propagated below or within the Paleocene to lowermost Eocene succession. This succession was folded above the detachment's tip (Fig. 15B), forming an antiformal structure that acted as the leading edge high of a sub-basin with active deposition at least up to the northern Península Mitre area. There, the Río Bueno Formation (Olivero et al., 2002) represents the shelf deposits at the southern part of this sub-basin (cf. Olivero and Malumián, in press). The lack of outcrops to the north of Península Mitre (the area that now forms part of the Atlantic Shelf) obscures the knowledge of the structural geometry within this sub-basin.

The sub-basin was filled by late-middle Eocene to Oligocene sediments of Andean provenance (Olivero, 2002), and it acted as a wedge-top basin as it was developed over the propagated detachment slice (cf. DeCelles and Giles, 1996). It is unknown if the Eocene sedimentary fill was passive or coincident with tectonic activity in the frontal part of the detachment, due to lack of structures within the upper-middle Eocene to upper Eocene succession that could reveal syntectonic sedimentation at the studied area. The fill of this sub-basin has excellent exposures between the Punta Torcida and the Cerro Colorado, where the complete succession crops out (the Leticia and Cerro Colorado Formations and the María Cristina-Puesto Herminita Beds). This depozone, named here María Luisa sub-basin after the nearby farm, was an integral portion of the Austral foreland basin system defined before. To the north of the early Eocene anticline that bounds María Luisa sub-basin it was located the late-middle Eocene foredeep, which was filled also by the Leticia and Cerro Colorado Formations and by the María Cristina and Puesto Herminita Beds (Fig. 15).

The paleocurrent data obtained indicates that there was a strong component of sedimentary dispersion towards the east within the María Luisa sub-basin (Figs. 3 and 15). This is consistent with the roughly E–W orientation of the regional folding axis (Ghiglione, 2003; Olivero et al., in press), and actually it is also coincident with the dominant trend of the rivers in Tierra del Fuego that nowadays drain into the Atlantic. The north-dispersed sediments yielded by the erosion of the Fuegian Andes must have been reoriented by the former structural-controlled morphology, and driven to the east (Fig. 16).

During the latest Eocene to Oligocene, the deformation front was reactivated along with the deposition of the uppermost part of the Cerro Colorado Formation and the Estancia María Cristina Beds. A backthrust has cut the sub-basin succession near its limit against the foredeep, generating the Campo del Medio anticline (see Fig. 12). The time constraint used for this anticline is the erosive unconformity between the Cerro Colorado Formation and the María Cristina Beds (Malumián and Olivero, 2006), and the decrease in bed dip between the base and the top of the María Cristina and Puesto Herminita Beds conformable succession (Fig. 7). Later sticking of the backthrust produced the foreland propagation of the thrust front, leading to the formation of a north-vergent imbricate thrust system that affected the southern limit of the late-middle Eocene to Oligocene foredeep. The propagation of the deformation front started with the development of the Irigoyen thrust, and then continued with the formation of a ramp in the original sole detachment, propagating the thrust front to a higher structural level (North thrust, Fig. 12). An imbricate system branched from this new decollement level generating successively the Punta Gruesa and Castor anticlines in the latest Oligocene (after deposition of the Puesto Herminita Beds), ending with the development of a frontal tip anticline by the Oligocene–Miocene limit (Fig. 14). This final deformation stage generates the growth structure of the uppermost Oligocene–lowermost Miocene Desdémona Formation. According to our model, these syntectonic deposits previously interpreted by Ghiglione (2002) as a Miocene wedge-top depocenter, form indeed part of the early Miocene foredeep adjacent (in front of) the deformation front, with evidences of syntectonic deformation only in its southern margin (Ponce et al., 2005).

The foredeep that had begun to evolve in the late-middle Eocene has migrated to the north as the deformation front did, acquiring its final position north of the thrust-fold belt leading edge (as recorded by seismic lines, see Galeazzi, 1998) after cessation of compressive deformation by earliest Miocene (Fig. 15). Following the compressive deformation freezing, the foredeep continued to act as an active depocenter being filled by prograding successions during the rest of the Neogene (Galeazzi, 1998).

The presence of clastic dike swarms cutting the lowermost Miocene succession cropping out north of Punta

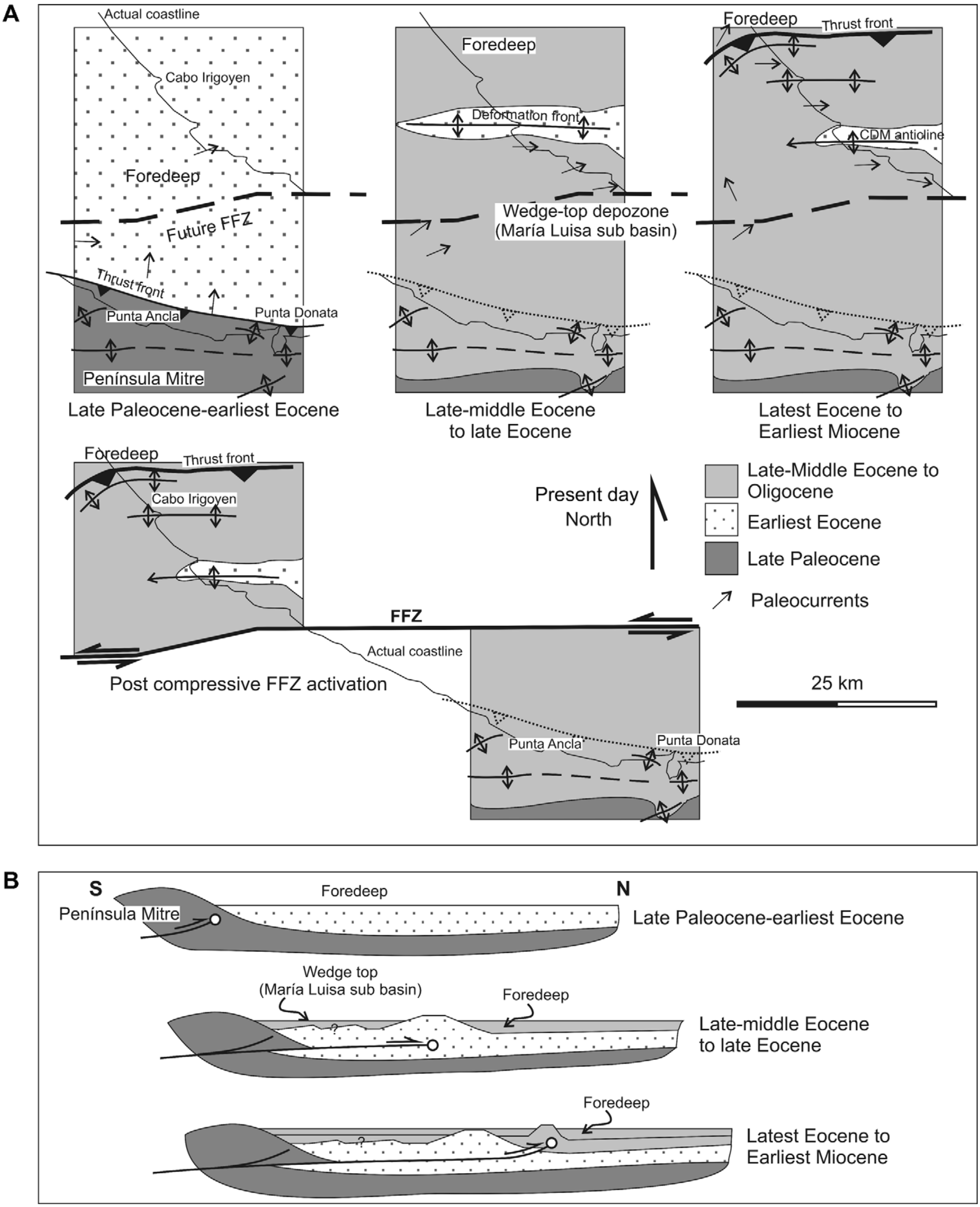

Fig. 15. (A) Map diagrams depicting the evolution of the foreland thrust-fold belt and the Austral basin system. The first three maps show the configuration of the area before activation of the strike-slip Fagnano fault zone (FFZ). CDM, Campo del Medio. Paleocurrent data south of FFZ is extrapolated from the actual coast outcrops. (B) Schematic cross-sections of the model shown in (A), depicting evolution of the thrust-front in relation to the foreland basin system.

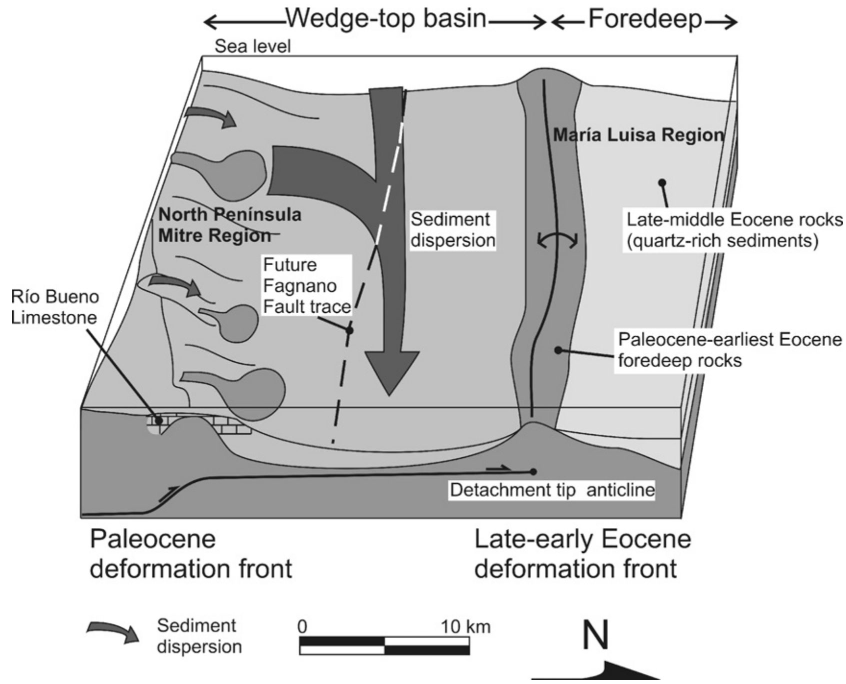

Fig. 16. Block diagram of the model of sedimentary dispersion in the wedge-top sub-basin, according to the paleocurrent data from field measurements.

Gruesa, with dominant N–S strike, was interpreted by Ghiglione (2002) as evidence for syntectonic sedimentation associated to a transpressive tectonic regime. We agree with the syntectonic triggering model for the clastic dikes, but our interpretation is that a pure compressive stress field could be responsible for the generation of extension fractures with the observed orientation and the interpreted N–S principal stress direction (see Section 4.3). In this sense the same stress field that produces the final stages of deformation in the thrust front would have been responsible for the N–S pure compression, without further evidence supporting transpression.

The balanced cross-sections constructed here, in addition to the knowledge of the subsurface geometry in the Austral and Malvinas basins (Robbiano et al., 1996; Galeazzi, 1998) allow to reconstruct an entire schematic section of the Austral–Malvinas foreland basin between the Estancia María Luisa sector and the foreland offshore area (Fig. 17). These reconstructions depict the existence of three foredeep depocenters. The oldest and southernmost one, of late Paleocene–earliest Eocene age, corresponds to that filled by the Río Claro Group as mentioned above. It is also equivalent to the Paleogene trough described by Galeazzi (1998) for Malvinas basin, with the difference that it is here described as a foredeep *sensu stricto*, yielded by the Andean orogeny and the early development of the foreland basin system. We consider that the wedge-shaped trough described by Galeazzi (1998) should be the northern termination of this foredeep, while the deepest part of this basin is located within the thrust-fold belt, as seen in Fig. 17.

The second foredeep schematized in Fig. 17 is the one developed in front of the deformation front by late-middle Eocene times. This foredeep migrated to the north until compression ceased in the early Miocene and tectonic configuration in southern South America changed, being partly affected by the development of the frontal thrust-fold belt structures (Irigoyen thrust, North thrust and Punta Gruesa imbricate system, Figs. 12 and 14). Its deepest part is located ~10 km north of the deformation front, according to seismic lines from Galeazzi (1998). The third foredeep is the one developed in front of the thrust front after compression stopped, during Miocene times (Ponce et al., 2005; Malumián and Olivero, 2006).

The two oldest foredeeps are separated by the Paleocene–earliest Eocene to late-middle Eocene major unconformity, product of a compressive event that has been associated with major changes in the tectonic convergence rates and orientations between Nazca-Farallón Plates and southern South America (see Ghiglione and Ramos, 2005). This tectonic stage has caused an important shift on the Fuegian Andes orogenic wedge foreland propagation, evidenced by the uplift of high-grade metamorphic rocks within the Fuegian Cordillera between 60 and 40 Ma (Kohn et al., 1995), which are involved in the thrust-fold belt evolution (Klepeis, 1994a). The northward migration of depocenters observed within the foreland basin system, therefore, is a consequence of the Fuegian Andes orogenic wedge forward propagation (Ghiglione and Ramos, 2005). Hence, the Austral basin reveals a foreland-propagating scheme of depocenters typical of foreland basin systems (DeCelles and Giles, 1996; Olivero and Malumián, 2002).

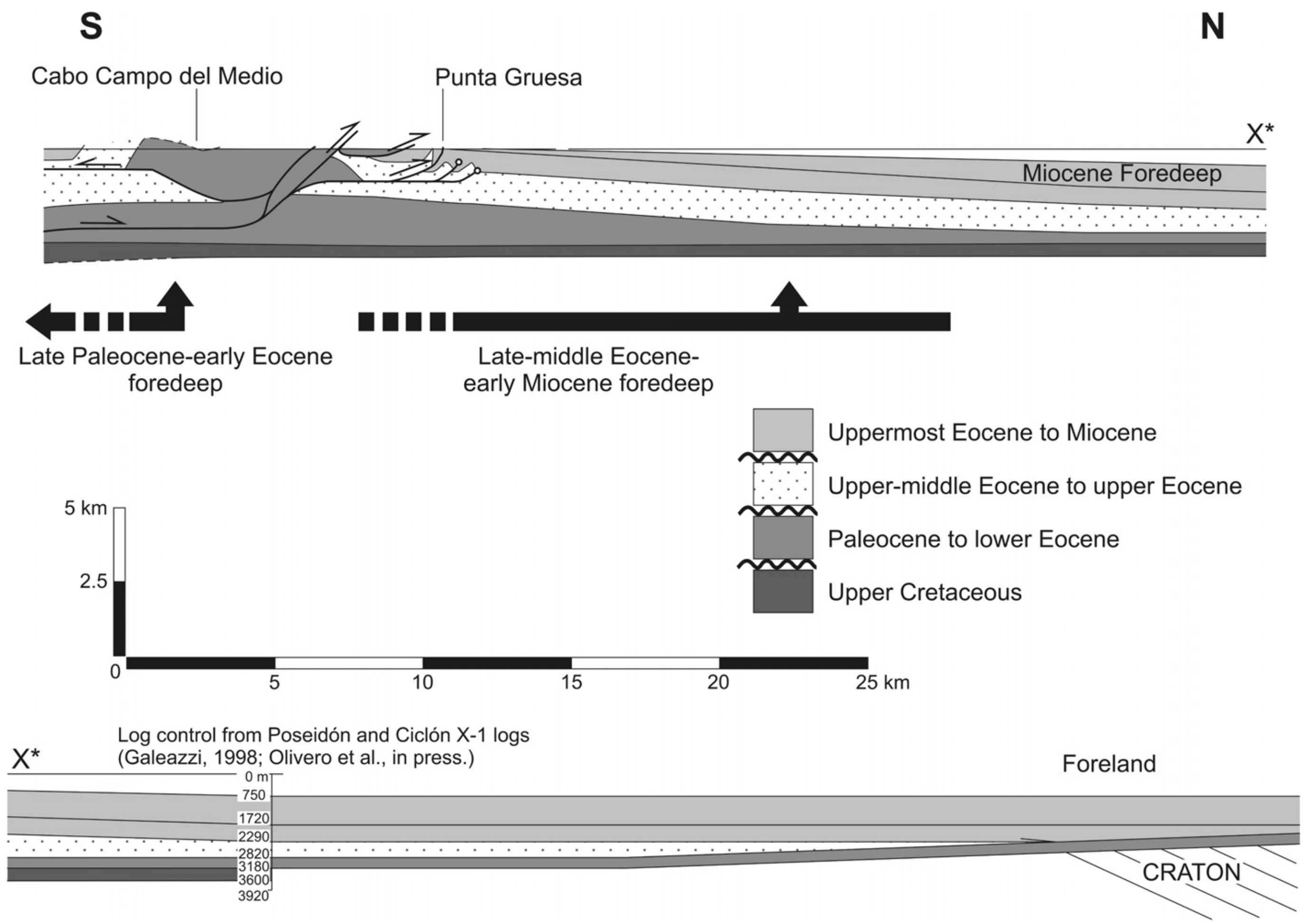

Fig. 17. Schematic cross-section between Estancia María Luisa area and the foreland offshore of Tierra del Fuego (location of section in Fig. 1). The section combines the structural balanced cross-sections presented in this work, log information from the undeformed basin and seismic lines shown in Galeazzi (1998). Location of Paleocene–earliest Eocene, late-middle Eocene–early Miocene and Miocene foredeeps is shown. Note that there is no vertical scale exaggeration. Structures affecting the basement, such as normal and reactivated rift faults (Galeazzi, 1998), are not shown for simplification.

6. Conclusions

The structural sections constructed here reveal a first balanced approach to the subsurface geometry of the frontal Fuegian Andes thrust-fold belt in the Atlantic coast sector of Tierra del Fuego. Based on these palinspastic reconstructions, we have described the structural and paleogeographic evolution of the thrust front and the foreland basin system, respectively, both of which are strongly related.

After the early formation of a foredeep in the late Paleocene–earliest Eocene Austral basin, the evolving thrust-fold belt front migrated to the north in response to a major compressive stage that affected the Fuegian Andes at about 50–40 Ma. The resultant deformation front bounded a wedge-top depozone to the south (María Luisa sub-basin), and formed the southern border of the new foredeep of the foreland basin system. The María Luisa sub-basin evolved as a wedge-top depozone from late-middle Eocene to at least early Oligocene, while the foredeep continued to evolve until cessation of the compressive tectonic regime by the earliest Miocene, later acting as a passive depozone.

The kinematics of the late-middle Eocene–Miocene thrust front changed from backthrusting of the María Luisa sub-basin in the late Eocene–early Oligocene to the development of an imbricate north-vergent thrust system from late? Oligocene to earliest Miocene. Both thrust systems branch from the same sole detachment, formed within Paleocene rocks during the 50–40 Ma compressive stage. The younger imbricate thrust system, however, transfers deformation to a higher structural level than the backthrust, forming the blind leading edge of the thrust-fold belt. The total shortening calculated for the frontal 16 km of the foreland thrust-fold belt is about 15.2 km. That amount means ~52.7% of a restored total length of 28.9 km.

Two successive foredeeps are depicted in this paper for the Tertiary of the Austral basin within the thrust-fold belt: a Paleocene–earliest Eocene one located from the study area to the south, and a late-middle Eocene to early Miocene one located to the north. A third Miocene foredeep that formed after compression ceased is present north of the thrust front. The migration of the foredeep to the north (forelandward) in the basin system in relation to the propagation of the orogenic load is consistent with foreland basin system models. Also, the presence of a wedge-top depozone (María Luisa sub-basin) described for the first time in the Austral basin adds new insights concerning the paleogeographic framework of Southern South America.

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