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# Progressive deformation of a Coulomb thrust wedge: the eastern Fuegian Andes Thrust–Fold Belt

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**Abstract:** Time-calibrated balanced-cross sections of the eastern Fuegian Thrust–Fold Belt reveal many complex pro- and retro-vergent structures, rooted at the base of Cretaceous and within Paleocene rocks. These structures involve the unconformity-bounded syntectonic sequences of the Austral foreland basin, and accommodate a minimum shortening of *c*. 41.8 km. The complex kinematics of the thrust–fold belt are recorded by: (1) propagation of the basal décollement into the foreland, and forward-directed thrusting during the Ypresian; (2) out-of-sequence thrusting in the Lutetian; (3) subsidence and sedimentation from the Late Lutetian to the Oligocene; (4) backthrusting during the Oligocene; and (5) a renewed stage of forward-directed thrusting between the latest Oligocene and the Early Miocene, probably related to accretion below the sole fault in the hinterland. This thrust sequence is interpreted as the result of critical Coulomb wedge behaviour during the first stage of thrust–fold belt expansion, with accretion of new material that led to a taper decrease. The subsequent period of internal deformation corresponds to a subcritical stage, during which backthrusting accommodates significant shortening (*c*. 15%). After growth and taper increase, the last period of forward thrusting at the wedge's front marks the inception of a new critical stage.

The Fuegian Andes form the southernmost extremity of the South American Andean Cordillera. The mountain front of this portion of the Andes is formed by the Fuegian Thrust–Fold Belt, which has been described in isolated parts of Tierra del Fuego as a thin-skinned wedge that involves Upper Cretaceous to Miocene sequences (Álvarez-Marrón *et al.* 1993; Klepeis 1994*a*; Klepeis & Austin 1997; Ghiglione *et al.* 2002; Torres Carbonell *et al.* 2008*a*). The location of the Fuegian Andes in a complex and still poorly understood geotectonic setting (Dalziel *et al.* 1975; Kraemer 2003; Eagles *et al.* 2005) makes the Fuegian Thrust–Fold Belt a key area for the study and better comprehension of the tectonic evolution of southern South America and Antarctica. In addition, the hydrocarbon significance of the Austral Basin, genetically related to this thrust wedge (Biddle *et al.* 1986; Galeazzi 1998; Rosello *et al.* 2008), strongly encourages further analysis of its detailed structure and stratigraphy.

Even though the geometry and kinematics of the Fuegian Thrust–Fold Belt have been described and analysed in some areas, the timing of its overall structural evolution is still poorly known. Based on the stratigraphic framework known at that time (Olivero & Malumián 1999; Olivero *et al.* 2002, 2003) and on fieldwork in the southeastern part of Tierra del Fuego, Ghiglione & Ramos (2005) proposed the only chronological scheme of thrust front migration known for the area. In this paper, new field data and interpretations are examined, leading to an improved stratigraphic framework (Torres Carbonell *et al.* 2009*a*) and structural database, which allows better constraints on the geometry and kinematics of structures and their age of development.

This work focuses on the tectonics of northern Península Mitre, in SE Tierra del Fuego (Fig. 1), where the best exposures of the eastern Fuegian Thrust–Fold Belt are located. Balanced cross-sections were constructed on the basis of detailed maps of selected sectors in this area, which permit a well-constrained structural geometry for the thrust–fold belt to be established. The kinematic evolution of these cross-sections is time-calibrated with the chronostratigraphy of the syntectonic successions affected by the contractional structures (Olivero & Malumián 2008, and references therein; Torres Carbonell *et al.* 2009*a*). Based on the structural analysis, a comprehensive kinematic model for the thrust–fold belt between Península Mitre and its leading edge at Punta Gruesa (Torres

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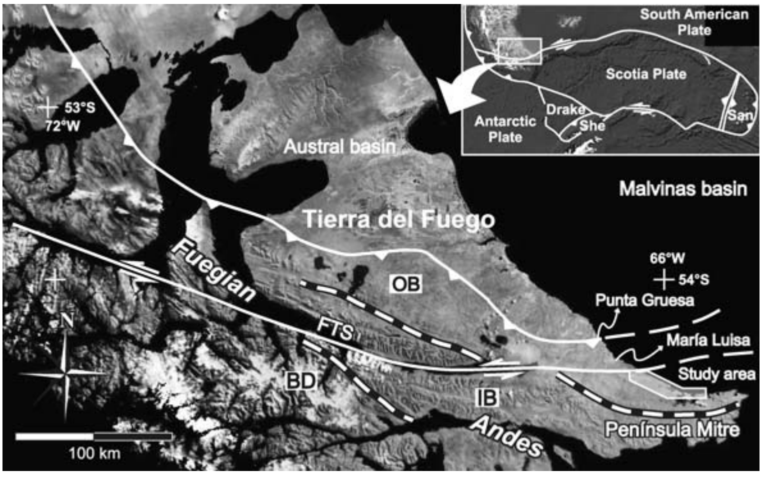


**Fig. 1.** Location of the study area (see Fig. 3) in Tierra del Fuego, and its tectonic setting (inset). Drake, Drake Plate; San, Sandwich Plate; She, Shetland Plate. The dashed heavy lines mark the approximate boundaries between the Upper Palaeozoic–Middle Jurassic basement domain (BD), the Upper Jurassic–'mid' Cretaceous inner orogenic belt (IB), and the Upper Cretaceous–Cenozoic outer orogenic belt (OB). The Neogene sinistral Fagnano Transform System (FTS) cuts the entire Fuegian Andes.

Carbonell *et al.* 2008*a*) is proposed, highlighting the progressive growth history of the Fuegian Andes. This growth history, far from adjusting to standard thrust-sequences, reveals a complex episodic evolution characterized by stages of forward thrusting and interposed out-of-sequence thrusting and back-thrusting stages. The episodic progression of the deformation in the eastern Fuegian Thrust–Fold Belt is explained here in terms of the Coulomb wedge theory. The improved kinematic model developed, plus the complex and distinct thrust-sequence analyzed in terms of a widely applied theory, gives both a local and global topical significance to this work.

The studied area (Fig. 1) is located between Cabo Malengüena (54°32′S; 66°13′W) and Punta Donata (54°39′S; 65°33′W). This remote area is difficult to access, and the outcrops are limited to the coastal cliffs, wave-cut platforms, inland river valleys, and to sectors of nearby hills not covered by vegetation.

## Fuegian Thrust–Fold Belt

The Fuegian Andes evolved since the 'mid' Cretaceous, when a marginal retro-arc basin that had formed from the Late Jurassic–Early Cretaceous closed against the South American southwestern margin (Dalziel *et al.* 1974, 1987; Kraemer 2003). Closure led to intense deformation and tectonic thickening of the marginal basin fill between a parautochthonous magmatic arc and the cratonic margin (Nelson *et al.* 1980; Dalziel 1986; Klepeis 1994*a*). The orogenic belt is separated here into three domains, according to the degree of deformation involved (Fig. 1): The basement domain, located in southwestern Tierra del Fuego, comprises Upper Palaeozoic to Middle Jurassic high to low grade metamorphic rocks affected by several folding stages, and is thrusted over the inner belt with a NE vergence (Nelson *et al.* 1980; Dalziel & Brown 1989; Klepeis 1994*a*). The inner orogenic belt, composed of Upper Jurassic to 'mid' Cretaceous rocks, forms the core of the Fuegian Cordillera and reveals polyphase deformation, isoclinal to tight folding, and slaty cleavage (Bruhn 1979; Caminos 1980; Klepeis 1994*a*). A thin-skinned thrust–fold belt forms the outer orogenic belt, affecting the Upper Cretaceous–Cenozoic sediments deposited in a foreland basin, known as Austral Basin (Biddle *et al.* 1986; Wilson 1991; Álvarez Marrón *et al.* 1993; Klepeis 1994*a*; Ghiglione & Ramos 2005).

The stratigraphic successions involved in the thrust–fold belt have been divided into unconformity bounded sequences (Olivero & Malumián 2008). The bounding unconformities have been recognized throughout the thrust–fold belt and beyond, in the stable cratonic margin of the foreland basin (Malumián *et al.* 1971), and have been linked to tectonic events in the Fuegian Andes (Martinioni *et al.* 1999; Ghiglione & Ramos 2005; Malumián & Olivero 2006; Torres Carbonell *et al.* 2008*a*, 2009*a*).

The youngest structures recognized in the Fuegian Thrust–Fold Belt are the thrust imbricates that crop out at Punta Gruesa (Fig. 1; Torres Carbonell *et al.* 2008*a*), which affect Early Miocene syntectonic strata (Ghiglione 2002; Malumián & Olivero 2006; Ponce *et al.* 2008). Cessation of contractional deformation and freezing of the thrust–fold belt is presumed to have occurred throughout its eastern part by Early Miocene times, according to the age and stratigraphic architecture of undeformed sequences in the foredeep of the Austral Basin, adjacent to the thrust-front (Ponce *et al.* 2008). The end of the contractional tectonics was followed by a period characterized by strike-slip faulting, associated with the development of the transform boundary between the Scotia and South American plates, expressed as the major Fagnano Transform System in Tierra del Fuego (Klepeis 1994*b*; Torres Carbonell *et al.* 2008*b*).

## Stratigraphy

The stratigraphic framework of the studied area is here briefly described, based on the generalized section shown in Figure 2. Most of the sedimentary successions recognized are part of the wedge-top depocenter of the Austral Basin (cf. Torres Carbonell *et al.* 2008*a*, 2009*a*), and therefore they are unconformity-bounded sequences that constrain the age of the contractional stages in the thrust–fold belt.

### *Policarpo Formation (Maastrichtian–Danian)*

The Policarpo Formation (Furque & Camacho 1949; Olivero *et al.* 2002) consists of a mudstone-dominated turbidite succession at least 300 m thick, with ammonites and microfossils from the Maastrichtian–Danian (Fig. 2) (Olivero *et al.* 2002, 2003). It crops out at Punta Donata, Punta Duquesa, and at the northern shore of Laguna Río Bueno (Figs 3 & 4). The base of this unit is not exposed, and the top is formed by an unconformity overlain by the Río Bueno Formation (Lutetian). In other parts of Tierra del Fuego, the Policarpo Formation is unconformably covered by Paleocene strata (Martinioni *et al.* 1999; Olivero *et al.* 2003; Torres Carbonell *et al.* 2008*b*). The unconformity with the Río Bueno Formation reveals an angular relationship of up to 20°, but the magnitude decreases to almost zero in some places.

### *Cabo Leticia and La Barca Formations (Paleocene)*

The Paleocene sedimentary rocks comprise the base of the Río Claro Group, composed of the Cabo Leticia and La Barca Formations, which are separated by a transitional contact (Fig. 2) (Olivero *et al.* 2002; Olivero & Malumián 2008). These formations form a turbidite system with a minimum thickness of 370 m, composed of tuffaceous breccia, conglomerate and sandstone at the base, and mudstone at the top (Olivero *et al.* 2002; Olivero & Malumián 2008). The age of this sedimentary package is constrained by post-Danian foraminiferal and palynological assemblages in the La Barca Formation (Malumián & Caramés 2002; Olivero *et al.* 2002; Torres Carbonell *et al.* 2009*a*). The Cabo Leticia and La Barca Formations crop out at Cabo Leticia and surrounding areas, and at Río Malengüena (Figs 3 & 5).

The base of the Cabo Leticia Formation is not exposed at the studied area, and the contact of the La Barca Formation with the immediately youngest Punta Noguera Formation (Ypresian) is a N-verging gently dipping thrust revealed at Punta Ainol (see below). The La Barca Formation is also covered through an angular unconformity by the Leticia Formation (Upper Lutetian–Priabonian) at Punta Ainol, and by the Río Bueno Formation (Lutetian) at the southern part of Cabo Leticia (Figs 3 & 5).

### *Punta Noguera and Cerro Ruperto Formations (Ypresian)*

The Punta Noguera and Cerro Ruperto Formations form part of the upper Río Claro Group (Fig. 2) (Olivero *et al.* 2002; Olivero & Malumián 2008). The Punta Noguera Formation consists of tuffaceous, sandy gravity flow deposits with a minimum thickness of 380 m at the type area, in the eponymous site (Figs 3 & 4). The age of the Formation is constrained by Ypresian microfossils (Malumián *et al.* 2009; Torres Carbonell *et al.* 2009*a*). The Punta Noguera Formation is also recognized at Río Malengüena, at Punta Ainol, at the wave-cut bench between Punta Noguera and Cabo Leticia, and at the Punta Ancla cliffs (Figs 3–5). The base of the Formation is not exposed, although an unconformity is inferred based on the strong facies and microfaunal differences with the turbidites of the La Barca Formation (Torres Carbonell *et al.* 2009*a*). The top of the Punta Noguera Formation is marked by an angular unconformity with the Río Bueno Formation (Lutetian), exposed at Punta Noguera.

The Cerro Ruperto Formation consists of a minimum of 200 m of marine sandstone and siltstone with an Ypresian palynological content (Olivero *et al.* 2002). The outcrops are restricted to the type area, located between Cerro Ruperto and Punta Cuchillo. The siltstones poorly exposed in the northern foothills of Cerro Las Vacas and eastern foothills of Cerro Piedra are here tentatively assigned to this Formation (Fig. 4). The base of

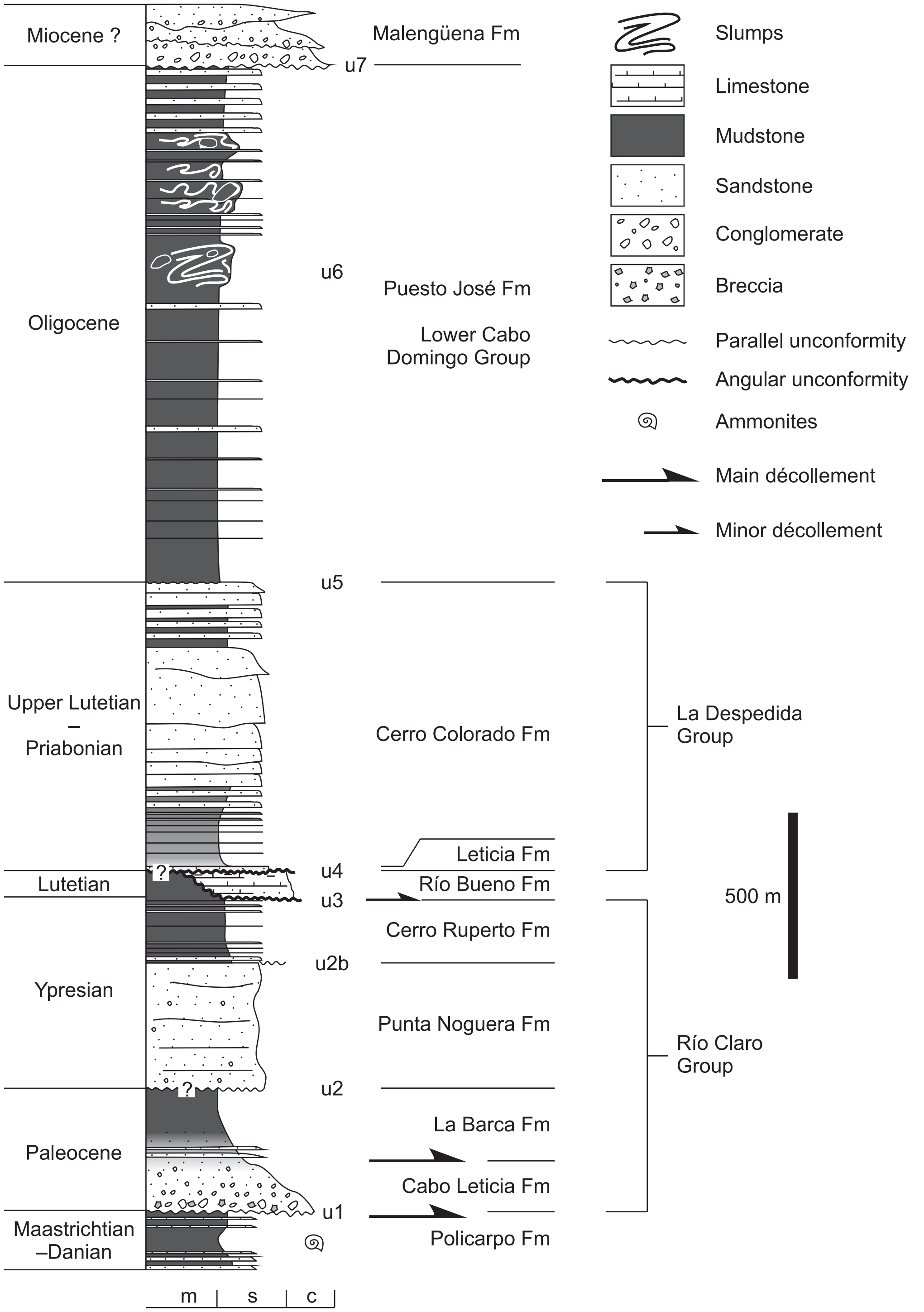


**Fig. 2.** Idealized stratigraphic section of the studied area. m, mudstone; s, sandstone; c, conglomerate. Unconformities (u) 1–7 are shown.

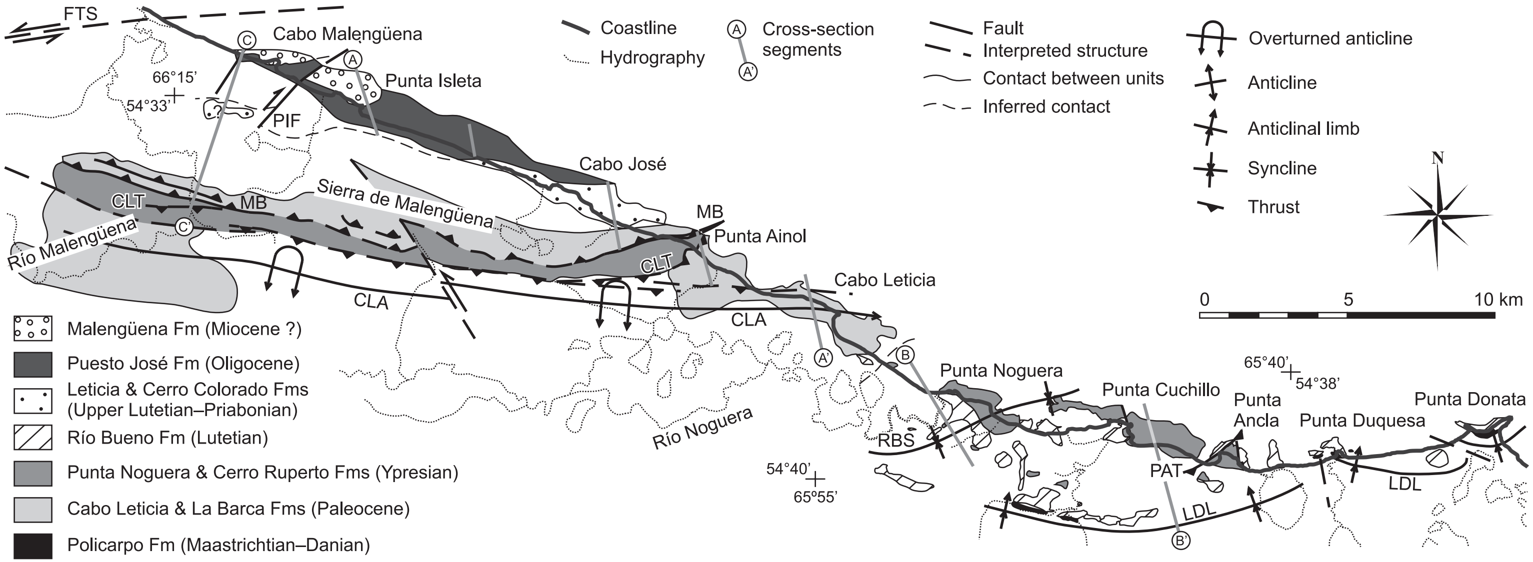


**Fig. 3.** Main geological features of the studied area. FTS, Fagnano Transform System; MB, Malengüena Backthrust; PIF, Punta Isleta Fault; CLT, Cabo Leticia Thrust; CLA, Cabo Leticia Anticline; RBS, Río Bueno Syncline; PAT, Punta Ancla Thrust; LDL, Cordón Largo–Punta Donata Anticlinal Limb. The area is accessed through a track along the coast. The segments of cross-sections in Figures 6 and 7 are indicated. Enlarged maps of the eastern and western portions of the area are shown in Figures 4 and 5, respectively.

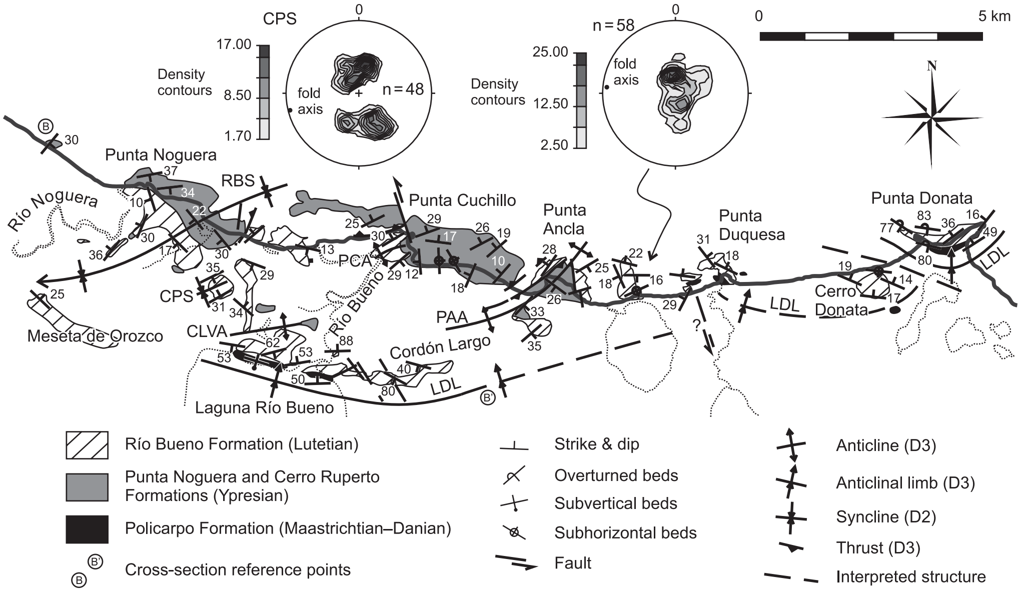


**Fig. 4.** Geological map of the area between Punta Donata and Punta Noguera. Basemap keys as in Figure 3. RBS, Río Bueno Syncline; PAA, Punta Ancla Anticline; PCA, Punta Cuchillo Anticline; CPS, Cerro Piedra Syncline; CLVA, Cerro Las Vacas Anticline; LDL, Cordón Largo–Punta Donata Anticlinal Limb. D2 and D3 structures are distinguished (see text). Stereograms are lower hemisphere, equal area density contour projections of bedding poles of the Río Bueno Formation at the Cerro Piedra Syncline, and at the area between Punta Duquesa and Punta Ancla; n, number of measurements.

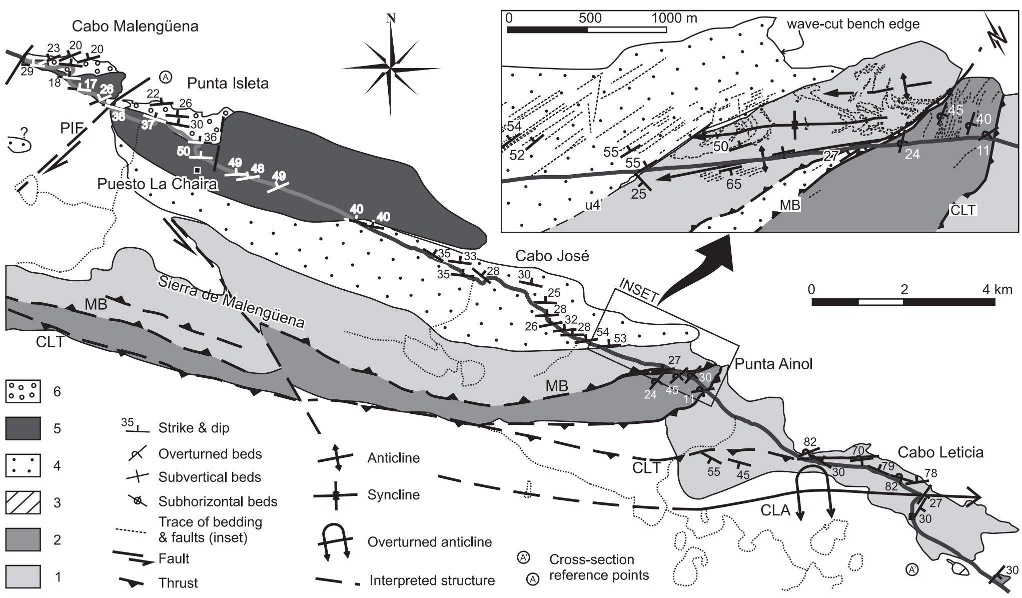


**Fig. 5.** Geological map of the Cabo Malengüena–Cabo Leticia area. Basemap keys as in Figure 3. The inset is a detail of the structures at Punta Ainol, with position of the unconformity u4. PIF, Punta Isleta Fault; MB, Malengüena Backthrust; CLT, Cabo Leticia Thrust; CLA, Cabo Leticia Anticline. Stratigraphic key: 1, Cabo Leticia and La Barca Formations (Paleocene); 2, Punta Noguera Formation (Ypresian); 3, Río Bueno Formation (Lutetian); 4, Leticia and Cerro Colorado Formations (Upper Lutetian–Priabonian); 5, Puesto José Formation (Oligocene); 6, Malengüena Formation (Miocene?).

the Cerro Ruperto Formation is not exposed, but on the basis of facies differences with the older Punta Noguera Formation (Olivero *et al.* 2002), a minor unconformity is inferred between both successions. The top of the Cerro Ruperto Formation is an angular unconformity with the Río Bueno Formation, well exposed at Punta Cuchillo (Fig. 4).

### *Río Bueno Formation (Lutetian)*

The Río Bueno Formation (Furque & Camacho 1949) consists of more than 80 m of shelfal grainstone, calcareous sandstone, marl and micrite (Fig. 2) (Olivero *et al.* 2002; Olivero & Malumián 2008). Its Lutetian age is constrained by microfossils and, according to recent estimations, could be extended to the latest Ypresian (N. Malumián, pers. comm.).

The Formation crops out discontinuously from Punta Donata to the south of Cabo Leticia, and is also exposed along Cordón Largo, at Cerro Las Vacas and at Meseta de Orozco (Figs 3–5). The Río Bueno Formation unconformably covers the Policarpo, La Barca, Punta Noguera and Cerro Ruperto Formations with varying angular relationships at the different outcrops. This feature was interpreted as the evidence of significant contractional deformation prior to the deposition of the Río Bueno Formation (Olivero *et al.* 2002). The top of the unit is not exposed.

### *Leticia and Cerro Colorado Formations (Upper Lutetian–Priabonian)*

The Leticia and Cerro Colorado Formations consist of a coarsening-upwards succession of more than 950 m of sandstone and minor mudstone, with Late Lutetian–Priabonian foraminifers. Both formations form part of the La Despedida Group (Fig. 2) (Olivero & Malumián 1999; Torres Carbonell *et al.* 2009*a*). This succession, as well as the younger units to be described below, were all previously assigned to the Cerro Colorado Formation (Olivero *et al.* 2002), but recent fieldwork and micropaleontological analysis led to a reorganization of the original stratigraphic framework (Torres Carbonell *et al.* 2009*a*).

The Leticia and Cerro Colorado Formations crop out from Punta Ainol to Cabo José. Poor sandstone exposures on a hill a few kilometres SSW of Cabo Malengüena are preliminarily assigned to this package (Fig. 5). The base of the Leticia Formation is an angular unconformity with the La Barca Formation at Punta Ainol, while its contact with the Cerro Colorado Formation is a parallel transgressive unconformity (Torres Carbonell *et al.* 2009*a*). The top of this last formation is an unconformity with the Oligocene Puesto José Formation.

### *Puesto José Formation (Oligocene)*

The Puesto José Formation is composed of a minimum thickness of 1600 m of mudstone at the base and mudstone with turbidite sandstone intercalations at the middle and upper sections (Torres Carbonell *et al.* 2009*a*) (Fig. 2). It bears Oligocene foraminifers that correlate it with the lower Cabo Domingo Group (Malumián & Olivero 2006; Torres Carbonell *et al.* 2009*a*). The Puesto José Formation crops out along the coast between Cabo José and Cabo Malengüena (Fig. 5). Its base is a parallel unconformity with the Cerro Colorado Formation and the top is an erosive unconformity with the Malengüena Formation (Miocene ?).

### *Malengüena Formation (Miocene?)*

The Malengüena Formation consists of a minimum of 216 m of marine conglomerate and sandstone with abundant lithic fragments of sedimentary rocks, amongst other lithologies (Torres Carbonell *et al.* 2009*a*) (Fig. 2). Its age resolution is poor, but estimated as Miocene on the basis of the preserved microfossils (Torres Carbonell *et al.* 2009*a*). The Formation crops out at Cabo Malengüena and Punta Isleta, sites where its unconformable basal contact with the Puesto José Formation is exposed. The top of the Malengüena Formation does not crop out.

## Structure at Península Mitre

### *Unconformities and contractional stages*

The age constraints for the structures exposed at the study area are determined by syntectonic unconformities calibrated with microfossils (mainly foraminiferal assemblages). Otherwise, a relative age (oldest) for the structures is determined by the age of the affected sedimentary packages. The unconformities and related contractional stages recognized are summarized as follows:

*Maastrichtian/Danian–Paleocene unconformity (u1).* An unconformity (u1) between the Policarpo Formation and Paleocene rocks not exposed at the study area has been recognized widely in Tierra del Fuego (Martinioni *et al.* 1999; Olivero *et al.* 2003; Torres Carbonell *et al.* 2008*b*). The u1 unconformity was recognized in eastern Península Mitre, at least 20 km from the study area (Olivero *et al.* 2003), with an apparently angular character (Ghiglione & Ramos 2005).

The development of a pencil structure and incipient foliation in the Policarpo Formation (Torres Carbonell *et al.* 2008*b*, 2009*b*), not recognized in the Paleocene rocks above the u1, reveals more intense strains in the older unit leading to interpret that the unconformity is related to contractional tectonics. Therefore, a contractional period older than the Middle–Late Paleocene (D1) is inferred (Ghiglione & Ramos 2005), although not discussed in this work since it is prior to the development of the structures here described. In the study area, the u1 is inferred to be present in subsurface, at the contact between the Policarpo Formation and the Cabo Leticia and La Barca Formations.

*Base of the Ypresian unconformity (u2).* The contact between the La Barca Formation and the Punta Noguera Formation is not exposed, but an unconformity (u2) is inferred on the basis of significant facies and microfaunal differences between both formations (Malumián & Caramés 2002; Torres Carbonell *et al.* 2009*a*).

A minor unconformity is also inferred within the Ypresian package between the Punta Noguera and the Cerro Ruperto Formations (u2b), whose contact is also not exposed. In this case there is a facies change from gravity-flow deposits to suspensive fall-out deposits and a different palynological content inferred as a shift to shallower, or more restricted depositional environments (Olivero *et al.* 2002).

Both u2 and the minor u2b unconformities are here related to a contractional stage that started at the Paleocene–Eocene boundary and acted in the Ypresian (D2). The early pulses of deformation of the D2 stage are recorded by thrust imbrications in more internal parts of the orogenic belt (Martinioni *et al.* 1999; Torres Carbonell *et al.* 2008*b*). The u2 and u2b may be the expression in the basin of tectonic-related erosion and syntectonic deposition during the formation of those structures. Further deformation during the D2 generated structures that affected both unconformities (Río Bueno Syncline and Cabo Leticia Anticline) described later in this paper. The u2 unconformity is tentatively correlated with the unconformity at the top of the P1 sequence of the western Malvinas Basin (Galeazzi 1998).

Another possible evidence of contractional tectonics during the end of the Paleocene near the study area are clastic dykes exposed at Río Malengüena. These affect the La Barca Formation at the frontal limb of the Cabo Leticia Anticline, and are oriented approximately east–west, parallel to the fold axis, with dips around 65°N (Ghiglione & Ramos 2005). Ghiglione & Ramos (2005) considered the intrusions as seismically induced, relating them to the proximity of the thrust front to this area at the Late Paleocene, although the criteria used to determine the seismic character of the dykes is not discussed in detail in their article.

*Base of the Lutetian unconformity (u3).* The Río Bueno Formation unconformably overlies the older packages (Maastrichtian–Danian to Ypresian) with an angular relationship that varies between 20° with the Policarpo Formation and 5–20° with the Punta Noguera Formation (u3). While the rest of the unconformities described here, except the u4, separate parallel sedimentary packages and are indicated by micropaleontological and sedimentological features, the u3 is an angular unconformity that involves significant hiatuses. This feature is considered the evidence of significant contractional deformation before the deposition of the Río Bueno Formation (Olivero *et al.* 2002). According to our interpretation, this also indicates that while most of the rest of the unconformities recognized were developed synchronously with the contractional stages, the u3 formed by sedimentation after a deformation episode, in this case the D2 stage. The u3, therefore, constrains the earliest age of that stage. The recent estimations of a possible Late Ypresian age for the Río Bueno Formation (N. Malumián pers. comm.), which covers the u3, further constrains the D2 stage to the Ypresian. The u3 is here tentatively correlated with the top of the P2 sequence of the western Malvinas basin (Galeazzi 1998).

*Base of the Upper Lutetian unconformity (u4).* The base of the Upper Lutetian is an unconformity (u4) widely recongnized in the Austral Basin (Malumián *et al.* 1971; Biddle *et al.* 1986). In the María Luisa area (*c.* 25 km NW from the study area, Fig. 1) u4 is an angular unconformity at the base of the Leticia Formation (with an age estimated in *c.* 43.7 Ma, Olivero & Malumián 1999; Torres Carbonell *et al.* 2009*a*), which overlies the Ypresian Punta Torcida Formation (Olivero & Malumián 2008). At the study area, the u4 is recognized at Punta Ainol, defined by the strongly angular contact (up to 85°) between the La Barca and the Leticia Formations (Fig. 5).

The unconformities u2 to u4 are here related to a period of enhanced growth of the Fuegian Andes between the Paleocene and the Lutetian (60–40 Ma, Klepeis 1994*a*; Kohn *et al.* 1995), associated with the D2 and D3 stages. The u4 is the expression of erosion after the last pulse of contraction (D3) at the end of this orogenic period. As well as the u3 unconformity, the u4 is covered by a succession (Leticia and Cerro Colorado Formations) that does not show evidence of synchronous contractional deformation. The u4 is here correlated with the top of the P3 sequence of Galeazzi (1998).

*Uppermost Priabonian–lowermost Oligocene unconformity (u5).* The parallel unconformable contact between the Cerro Colorado and the Puesto José Formations is related to a significant facies change from channelized sandstones to massive mudstones, and is also indicated by a shift in paleoenvironments recorded by the microfossil assemblages (Torres Carbonell *et al.* 2009*a*). This unconformity (u5) is correlated with the one mentioned by Malumián & Olivero (2006) between the Cerro Colorado Formation and the earliest Oligocene Tchat-chii Conglomerate at central Tierra del Fuego and at the coastal sector in the María Luisa area (Fig. 1).

The u5 unconformity was related to a shift to deep marine settings in the foreland basin due to eustatic and tectonic processes (Malumián & Olivero 2006; Scarpa & Malumián 2008), and was locally associated with the development of the Campo del Medio Anticline, a fault-bend fold formed above a backthrust (Torres Carbonell *et al.* 2008*a*). Uplift and erosion at the hinterland during development of the u5 is inferred from the provenance analysis of the Tchat-chii Conglomerate (Jurassic, Cretaceous and Palaeogene source rocks; cf. Malumián & Olivero 2006). Therefore, a contractional stage (D4) that occurred at the thrust front near María Luisa and at the inner Fuegian Cordillera, is related to the development of the u5 in the latest Priabonian–earliest Oligocene.

*Oligocene syntectonic strata (u6).* Several large synsedimentary folds are recognized at the upper section of the Puesto José Formation, within a coarsening-upwards succession with turbidites and chaotic sandstones (slumps) in its uppermost part (Torres Carbonell *et al.* 2009*a*). These features are interpreted as a syntectonic package deposited during a new contractional stage (D5). Although there are no exposures of a discrete unconformity surface, the slumps occur in a stratigraphic interval of at least 500 m, and define the boundary (u6) between massive mudstones at the base of the Puesto José Formation to gravelly and sandy turbidites at the top. The age of the D5 contractional stage is estimated at the 'mid' Oligocene on the basis of foraminiferal biostratigraphic markers (Torres Carbonell *et al.* 2009*a*).

*Miocene ? unconformity (u7).* The youngest unconformity recognized in the study area (u7) separates the Puesto José and Malengüena Formations, with significant erosion of the top of the former. Although the unconformity is apparently parallel, it laterally involves a hiatus of at least the entire Upper Oligocene succession (Torres Carbonell *et al.* 2009*a*), and is related to a contractional stage (D6) that uplifted part of the older sedimentary packages. Erosion of these previous successions is indicated by the composition of coarse facies above the unconformity, with abundant clasts and reworked microfossils from the Upper Cretaceous–Palaeogene beds (Torres Carbonell *et al.* 2009*a*). The age of the D6 is younger than the Late Oligocene, and most probably Miocene.

### *Geometry and kinematics of the structures*

A detailed structural survey allowed the construction of 1:50 000 scale maps, from which a regional-scale north–south balanced cross-section was made, depicting the subsurface geometries of the major structures across northern Península Mitre. The studied part of the thrust–fold belt is separated in five distinctive structural zones (Fig. 3): (1) to the north, a north-dipping backthrust sheet (Malengüena Backthrust) involves Paleocene to ?Miocene strata, and is affected by (2) a strike-slip fault system at its northern termination (Punta Isleta Fault System); (3) in the north-central zone, a north-verging fault-propagation fold (Cabo Leticia Anticline) is formed above a major thrust that affects the Paleocene and Ypresian packages (Cabo Leticia Thrust); (4) in the south-central zone, a syncline at the rear of the Cabo Leticia Anticline is formed in the Ypresian succession and is covered unconformably by the Lutetian package (Río Bueno Syncline); and finally (5) in the southernmost zone, an arcuate roughly east–west, north-dipping structure forms the northern limb of an anticline cored by the Maastrichtian–Danian succession (Cordón Largo–Punta Donata Anticlinal Limb).

The balanced cross sections (Figs 6 & 7) show a décollement for these structures located within the Paleocene. This layer has been identified as a décollement in the Cerro Malvinera sector, less than 50 km WNW from northern Península Mitre (Torres Carbonell *et al.* 2008*b*), and in previous schematic cross-sections of the study area that show a décollement for the main structures around the same level (Ghiglione & Ramos 2005). In the study area the mudstones of the La Barca Formation act as a décollement for the Malengüena backthrust (Figs 5 & 6), supporting the interpretation of a regional sole fault associated with this suitable level.

*Malengüena Backthrust.* The Malengüena Backthrust (Figs 3 & 5) is the base of a south-vergent thrust sheet composed of the La Barca, Leticia, Cerro Colorado, Puesto José and Malengüena Formations, and is exposed as a fault that cuts the frontal limb of the Cabo Leticia Anticline. The backthrust was previously interpreted as an out-of-sequence thrust (Ghiglione & Ramos 2005), but it is reinterpreted in this paper on the basis of the improved structural mapping (Fig. 5) and biostratigraphical ages recently obtained for the successions involved in deformation (Torres Carbonell *et al.* 2009*a*).

At Punta Ainol, the Malengüena Backthrust dips *c.* 27°N, and is exposed as a couple of splays that

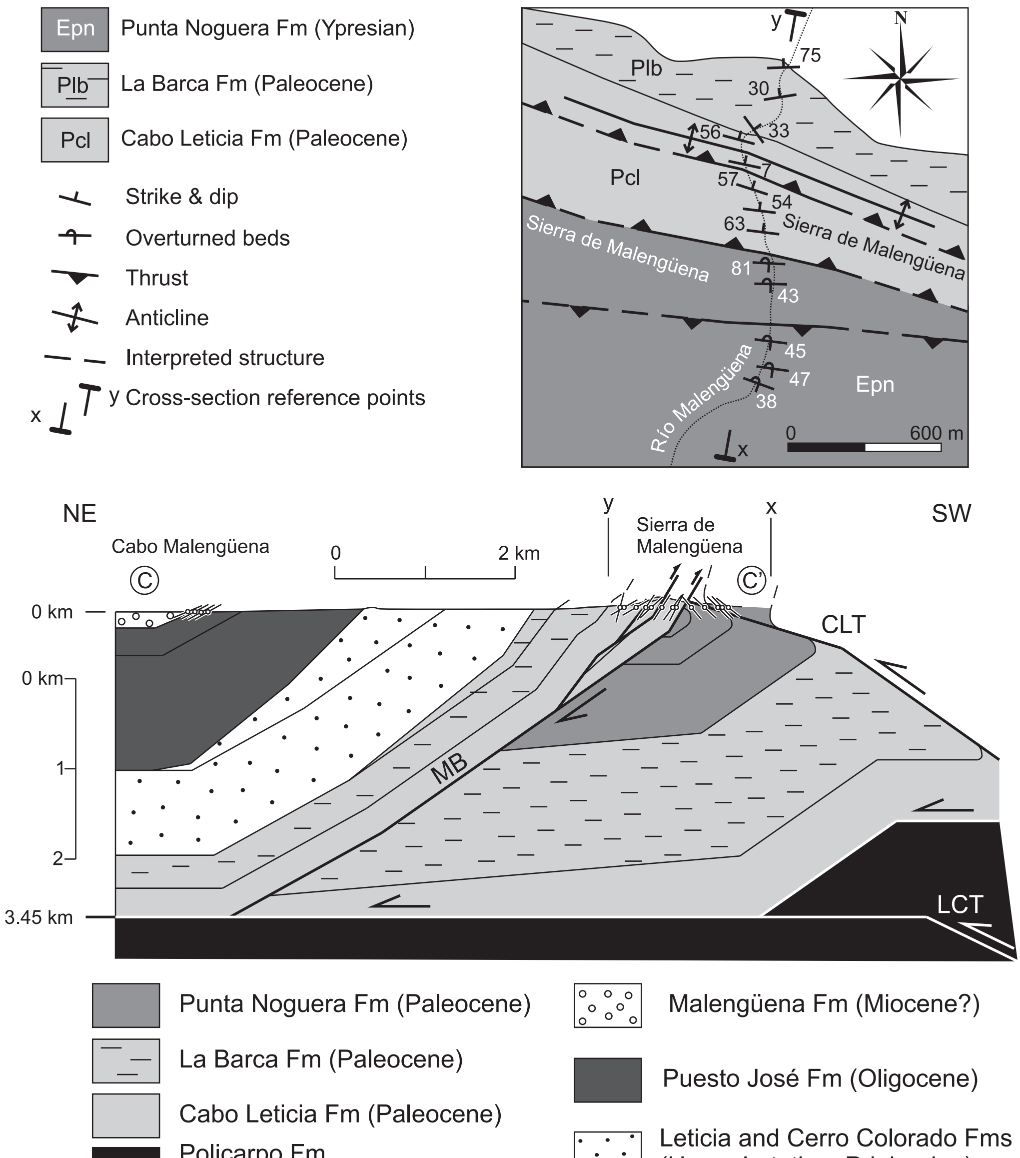


**Fig. 6.** Geological map and balanced cross-section of the valley of the Río Malengüena. See location of cross section (C–C′) in Figure 3. Basemap key as in Figure 3. LCT, La Chaira Thrust; CLT, Cabo Leticia Thrust; MB, Malengüena Backthrust.

locally repeat the La Barca and Leticia Formations (Fig. 5). At this site, the Leticia Formation is thrusted above overturned beds of the Punta Noguera Formation, leading to the problem of explaining younger beds thrusted over older beds. This feature is interpreted assuming significant erosion of the Punta Noguera Formation to the north of the Cabo Leticia Anticline, followed by deposition of the Leticia Formation directly above the La Barca Formation (covering the u4 unconformity). After its deposition, the Leticia Formation was thrusted over the Punta Noguera Formation due to the Malengüena Backthrust (Figs 7 & 11).

At Río Malengüena, the backthrust is also exposed as a set of fault splays that dip between 60°NE and 30°NE (Fig. 6). There, the Cabo Leticia

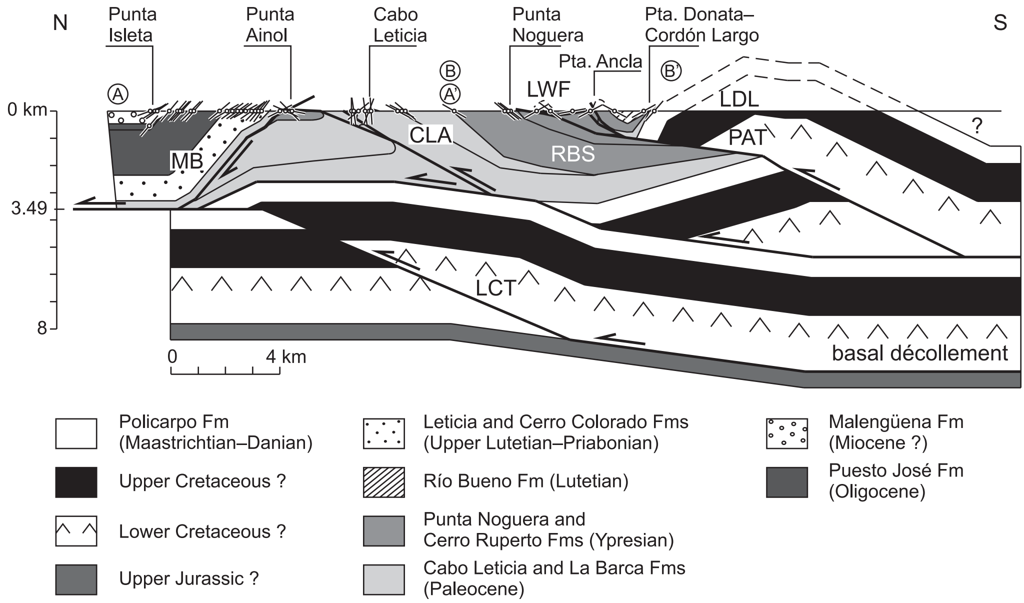


**Fig. 7.** Balanced cross-section between Punta Isleta and Punta Donata–cordón Largo. See location of reference points (A–A′ and B–B′) in Figures 3–5. The parts A–A′ and B–B′ were constructed combining partial segments normal to the main structures, as shown in Figure 3. MB, Malengüena backthrust; CLA, Cabo Leticia Anticline; RBS, Río Bueno Syncline; PAT, Punta Ancla Thrust; LDL, Cordón Largo–Punta Donata Anticlinal Limb; LCT, La Chaira Thrust; LWF, Low-wavelength folds.

and La Barca Formations are thrusted over south-dipping overturned beds of the Punta Noguera Formation.

Only the backlimb of the Malengüena Back-thrust sheet is exposed, with beds consistently dipping to the north with moderate angles (30–40°N) except in its northernmost part, where the Puesto José Formation dips 50°N just south of Punta Isleta (Fig. 5). These steep dip angles, higher than the moderate dips expected in the back-limbs of simple thrust-sheets (Boyer & Elliott 1982; Suppe 1983; Suppe & Medwedeff 1990), are suggestive of further rotation of the original backthrust sheet. Successive thrust imbrications, frequent in piggyback thrust sequences, normally generate partial rotation of the original moderately dipping thrust sheets. Since no evidence of minor scale (parasitic) folds is seen in the well exposed back-limb of the Malengüena Backthrust sheet between Punta Ainol and Punta Isleta, we consider the interpretation of rotation by multiple thrusting stages as the most effective way to explain the recognized geometry. The structure responsible for partial rotation of the Malengüena Backthrust sheet is further described and discussed later in this article.

The balanced cross-section (Figs 6 & 7) shows a décollement for the Malengüena Backthrust at *c*. 3.5 km below sea level, within the Paleocene succession, associated with the La Barca Formation as seen at Punta Ainol.

*Punta Isleta Fault System.* At Cabo Malengüena and Punta Isleta, a system of subvertical faults (Punta Isleta Fault System) affects the Puesto José and Malengüena Formations, disconnecting the outcrops of both sites (Fig. 8). The fault system is composed of three sets of faults, each with a strike-slip apparent displacement in map view. These sets strike NNE, NE and NNW.

The NNE set, exposed in the cliffs and wave-cut bench of Cabo Malengüena and Punta Isleta, has a dominant right-lateral slip sense with a minor (apparent) normal component, determined by stratigraphic offsets in plan view (tens of metres) and cross-section (metre scale), respectively (Fig. 8). The faults of this set also affect the terrain near Cabo Malengüena, generating a fault scarp of about a kilometre length and one metre height. The scarp affects the post-glacial deposits (Holocene, cf. Heusser 2003), apparently playing an important role on the hydrographic control of the area. A dry circular lake adjacent to the coast (less than 500 m in diameter) was probably drained towards the sea due to activity of the fault system (Fig. 8). This inference is supported by a rectilinear stream that flows

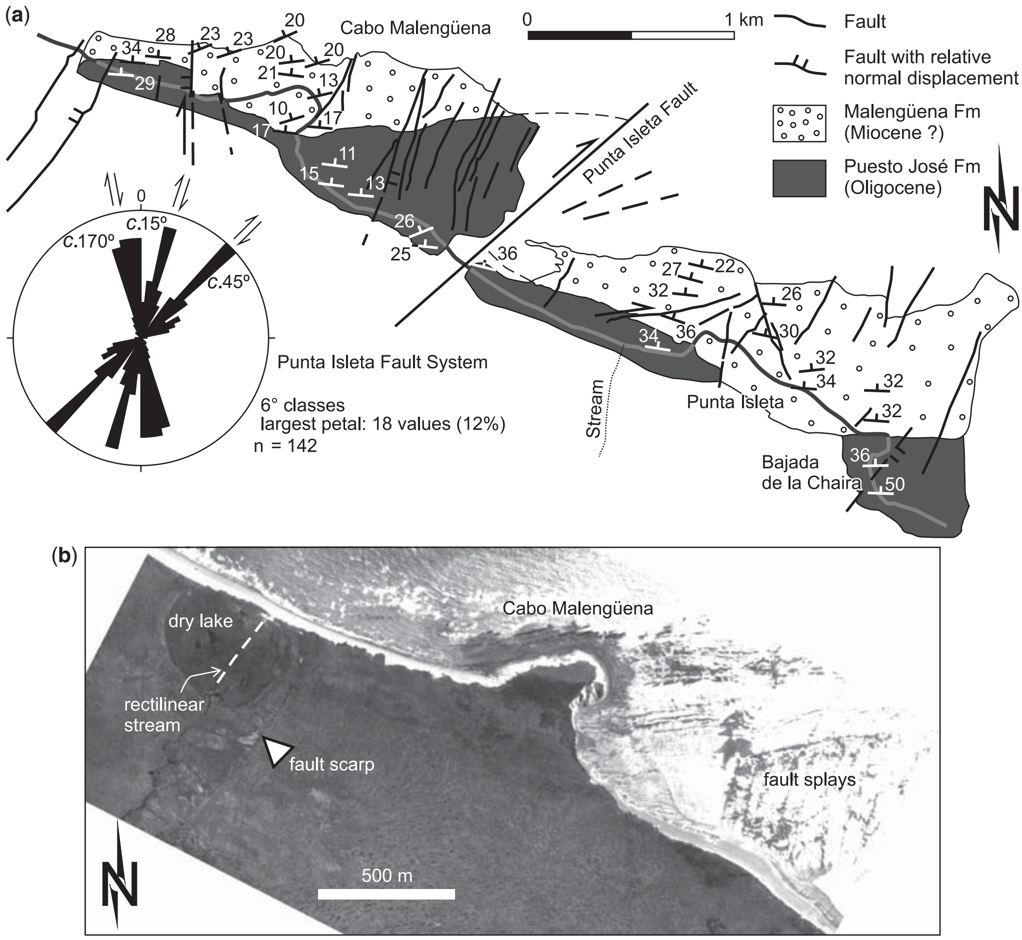


**Fig. 8.** (**a**) Geological map of the Cabo Malengüena–Punta Isleta area, basemap key as in previous figures. The rose diagram shows the strikes of the three fault sets that compose the Punta Isleta Fault System, n: number of measurements. (**b**) Aereal photograph of Cabo Malengüena, showing major morphological features related to the Holocene NNE fault set.

to the sea crossing the dry lake along a fault splay, which is exposed continuously up to the wave-cut platform. The age of the NNE fault set, therefore, is younger than the Malengüena Formation (?Miocene), most probably Holocene, according to the control of the faults on the terrain morphology.

The NE set includes a main fault located at the bay between Punta Isleta and Cabo Malengüena, which combined with the NNE set produces, in map view, a right-lateral offset of at least 600 m, and probably up to 1000 m, to the contact of the Puesto José and Malengüena Formations (Fig. 8).

The NNW faults are also exposed in the cliffs and wave-cut bench at both sites, although they are less frequent. Both the NNW and NNE sets bound blocks formed by the Puesto José and Malengüena Formations, which reveal attitude changes from block to block interpreted as relative rotations due to the apparent minor oblique-slip observed in the NNE faults.

Following Coulomb fracture criterion (Twiss & Moores 2007), the maximum compressive stress ($\sigma_1$) has a different orientation for each of the three fault sets analyzed separately, which in turn may suggest that they formed diachronously. Assuming dominant strike-slip, the $\sigma_1$ direction for the NNE faults should be approximately oriented N225°; for the NE faults N255°; and for the NNW faults N200°. These three maximum compression directions are SW–NE oriented, which is consistent with the approximately NW–SE strike of the major contractional tectonic features in the region. On the other hand, if a regional north–south right-lateral shear is assumed, with a $\sigma_1$ oriented at N45°, then only the NNE and NNW sets would show compatible kinematics since they could be interpreted as R and P synthetic shear fractures, respectively.

Furthermore, another interpretation can be proposed for the formation of the NNE faults. The location of segments of the active Fagnano Transform System at the Río Irigoyen valley, about 10 km westwards from the Cabo Malengüena area (Figs 1 & 3; Torres Carbonell *et al.* 2008*b*), and the estimated young age of the NNE faults, may suggest that these latter and the Fagnano Transform System are genetically related. Since the NNE set is oriented at 75° to the left-lateral east–west Transform System, it can be interpreted as an antithetic Riedel fracture set. Nevertheless, this interpretation is still preliminary since the main synthetic Riedel shear fractures, that should be oriented N75°, are apparently lacking.

*Cabo Leticia Anticline.* The Cabo Leticia and La Barca Formations are involved in an asymmetrical anticline (Cabo Leticia Anticline), with a north–NE vergence, recognized at Cabo Leticia and partly at Río Malengüena (Figs 3 & 5). The structure is inferred to be continuous between both sites, with morphological expression along the southern border of the Sierra de Malengüena.

At Cabo Leticia the exposed core of the anticline is formed by subvertical beds of the Cabo Leticia Formation. Both limbs are formed by the La Barca Formation. The southern limb (backlimb) dips around 30°SE, and the northern limb (frontal limb) is subvertical to overturned, and is cut by many faults oriented east–west (Figs 6 & 7). The anticlinal hinge is recognized at Cabo Leticia, and reveals an axis plunging 20° to the east. In this site the fold has an interlimb angle of 60° (close fold), and exposed width of 3 km.

This anticline is related to the Cabo Leticia Thrust, which dips to the south with a moderate angle and is interpreted to root at the same décollement as the Malengüena Backthrust (within the Paleocene). The Cabo Leticia Thrust has several splays exposed from the northern coast of the eponymous cape up to the south of Punta Ainol, where, although the outcrops are scarce and isolated, a change in the fault attitude to a very gentle dip is revealed. Low dip fault splays are also exposed at Río Malengüena south of the Malengüena Backthrust trace, affecting overturned beds of the Punta Noguera Formation, which comprise the frontal part of the Cabo Leticia Anticline there (Fig. 6). Farther to the south along Río Malengüena, outcrops of the La Barca Formation (Ghiglione 2003; Olivero *et al.* 2007) may form part of the inner frontal limb of the anticline.

A drag fold is recognized in the footwall of the Cabo Leticia Thrust affecting beds of the Punta Noguera Formation at Punta Ainol and at Río Malengüena as well. In the first site the drag fold is formed by overturned sandstones dipping from 40–11°S, revealing a strong rotation (Fig. 5). At Río Malengüena the Punta Noguera beds dip from 45–19°S also in overturned position (Fig. 6).

*Río Bueno Syncline.* The Río Bueno Syncline is a fold recognized between Cerro Ruperto and Punta Noguera. It is formed by the Punta Noguera and Cerro Ruperto Formations (Figs 3, 4 & 7), and is covered with an angular unconformity (u3) by the Río Bueno Formation (Fig. 9a).

The half-wavelength of the syncline is of *c.* 7 km in the northern limb. That limb comprises the Punta Noguera Formation, and has an average dip of

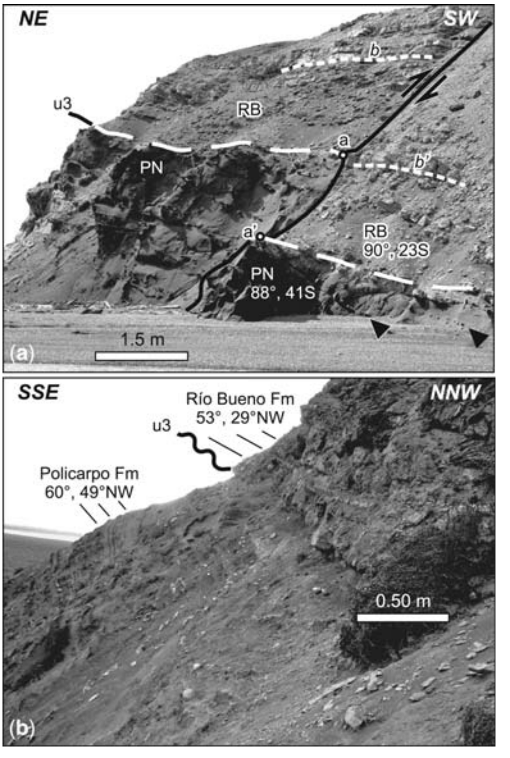


**Fig. 9.** (**a**) Angular unconformity (u3) in the northern limb of the Río Bueno Syncline (at Punta Noguera) between the Punta Noguera sandstones (PN) and the Río Bueno basal marls (RB). The dashed line *b* marks a reference horizon within the Río Bueno marls. A fault (subvertical, note that the angle of the photo generates an apparent dip to the left) affects both formations downthrowing the SW block. Note that this geometry could be caused either by a right-lateral or a dip–slip displacement. The black triangles mark horizons in the PN clearly truncated by the u3. (**b**) Detail of the angular unconformable contact between the Policarpo and Río Bueno Formations at Punta Donata.

37–40°SSE at Punta Noguera. The southern limb, although being obliterated by minor order deformation (see below), could be measured in the wave cut bench near Punta Cuchillo, where it dips *c*. 20°NW, and is formed by the Cerro Ruperto Formation (Fig. 10a). The Punta Noguera Formation comprises the external part of the southern limb at Punta Ancla (Fig. 4). The interlimb angle is of *c*. 120° (open fold). The Río Bueno Syncline surface trace is located in the southern part of Punta Noguera, where it closes forming a rounded hinge with an axis plunging 27° to the SW.

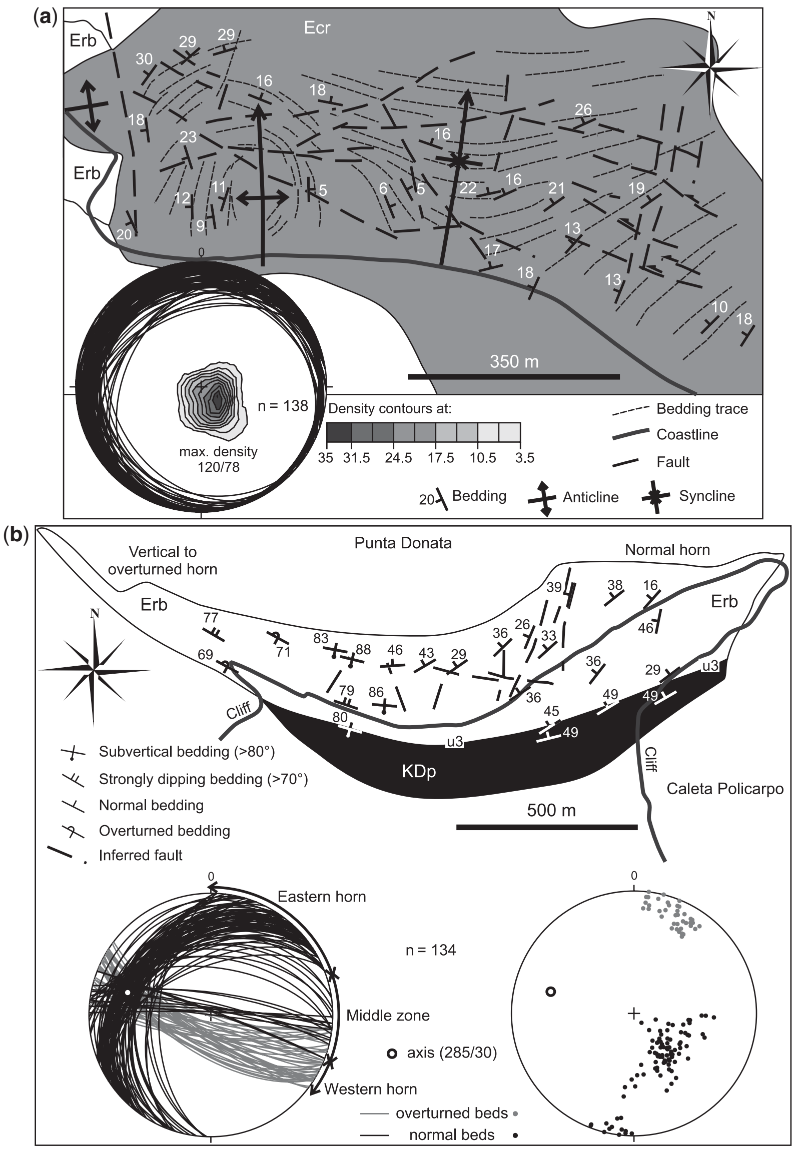


**Fig. 10.** (**a**) Geological map of Punta Cuchillo–Cerro Ruperto wave-cut bench, and lower hemisphere, equal area stereographic plot of the Cerro Ruperto Formation bedding (density contours for poles) showing an average moderate dip towards the NW. Erb, Río Bueno Formation; Ecr, Cerro Ruperto Formation. (**b**) Geological map of Punta Donata. Erb, Río Bueno Formation; KDp, Policarpo Formation. The stereonets are lower hemisphere, equal area projections of bedding planes (left diagram: planes; right diagram: poles) of the Río Bueno Formation at Punta Donata, indicating the polarity (normal, inverted) and location of the measured planes. The estimated axis of rotation of the beds in the western horn is shown.

The southern limb of the Río Bueno Syncline is affected by a gently dipping thrust, called Punta Ancla Thrust, related to low wavelength folds and minor fault splays that accommodate deformation above it. The Punta Ancla Thrust and its related minor structures partly obliterate the original geometry of the Río Bueno Syncline (Fig. 7), and although these structures are associated with a younger deformation stage (see below), they are described here since they form part of the southern limb of the Río Bueno Syncline.

The low wavelength folds related to the Punta Ancla Thrust (LWF in Fig. 7) affect the Punta Noguera, Cerro Ruperto and Río Bueno Formations. The most significant structures related to the Punta Ancla Thrust are the Punta Cuchillo Anticline and the Punta Ancla Anticline (Fig. 4). The first one is formed on beds of the Río Bueno Formation and cored by the Cerro Ruperto Formation; it is symmetrical with both limbs dipping 32°–35° and a subhorizontal axis trending N243°, with a rounded hinge, a wavelength of about 500 m and an interlimb angle of 118° (open fold). The Punta Ancla Anticline is cored by the Punta Noguera Formation and flanked by the Río Bueno Formation; it is also nearly symmetrical, with limbs dipping 30°–34° and an axis plunging 5° towards N221°, a wavelength of about 850 m and an interlimb angle also of 118°. The limbs of the Punta Ancla Anticline are cut by several high-angle minor faults with probable normal dip–slip displacements. The south limb (back limb) of the Punta Ancla Anticline is also recognized in the hills located to the SW of Punta Ancla (Fig. 4). The north limb (frontal limb) of this anticline is cut by a splay of the Punta Ancla Thrust, which dips 60°SE and has striae plunging towards N140°–N160°. The reverse displacement along this fault is indicated by drag folds in its footwall.

The inland area between Río Noguera and Río Bueno is characterized by low hills frequently topped by exposures of the Río Bueno Formation (Fig. 4). These exposures show low wavelength folding, equivalent to that recognized in the coast formed above the Punta Ancla Thrust. The most notable inland folds are the Cerro Las Vacas Anticline and the Cerro Piedra Syncline (Fig. 4). The first one is cored by siltstones here assigned to the Cerro Ruperto Formation, its south limb dips nearly 57°S, but its frontal limb is badly exposed, and its wavelength is in the order of 1000 m. The Cerro Piedra Syncline is formed by the Río Bueno Formation, with limbs dipping 30°SSE and 42°NNW, a subhorizontal axis gently plunging towards N256°, an interlimb angle of 113° (open fold) and a wavelength of almost 300 m.

A recent different structural analysis of this region of Tierra del Fuego proposes reactivation of high-angle normal faults to explain this evidence of contractional deformation, mainly based on the interpretation of the Punta Noguera Formation as a synrift succession. This interpretation is principally supported by apparent thickness variations of that formation at Punta Noguera (Ghiglione *et al.* 2008). These authors propose that the normal faults associated with the rifting stage were later inverted as reverse faults uplifting the Río Bueno Formation.

Nevertheless, the detailed stratigraphy (Furque & Camacho 1949; Olivero *et al.* 2002) and structural analysis at the Punta Noguera area reveal that: (a) the interpreted thickness variations in the Punta Noguera Formation are a consequence of an incorrect definition of the basal unconformity of the Río Bueno Formation (u3), since Ghiglione *et al.* (2008) wrongly assigned the basal marls of this later unit to the top of the Punta Noguera Formation, therefore incorrectly placing the u3 within the Río Bueno Formation; and (b) the normal faults, which are subvertical and strike north–NNE (data omitted by Ghiglione and collaborators), affect both the Punta Noguera and Río Bueno Formations with no evidence of inversion. They generate a neat apparent downdip displacement of *c.* 2–3 m to both formations (Fig. 9a). A more feasible interpretation, therefore, is that these faults postdate the Río Bueno Formation, instead of being synchronous with the Punta Noguera sandstones. Moreover, since no directional data (e.g. slikenline orientations) were presented by Ghiglione *et al.* (2008), a strike-slip component of displacement is also possible (Fig. 9a).

The interpretation of Ghiglione *et al.* (2008) also proposes a pop-up anticline in the Punta Noguera Formation with a trace located in the exact position where we place the axial trace of the Río Bueno Syncline. That interpretation is not even consistent with the data shown on their maps, which reveal the synclinal open hinge at Punta Noguera like our map does (Fig. 4). The clear evidence of contractional tectonics in northern Península Mitre during the Early Eocene (Ghiglione & Ramos, 2005; this work), for example, the Cabo Leticia Anticline that formed during or after deposition of the Punta Noguera Formation and before the development of the u3 unconformity, also argues against the interpretation of an extensional setting during these times.

*Cordón Largo–Punta Donata Anticlinal Limb.* Between the northern shore of Laguna Río Bueno, along Cordón Largo and towards the east up to Punta Donata, the Río Bueno Formation beds keep a dip of 50–35°N, NNE and NW (Fig. 4). These beds unconformably cover the Policarpo Formation (u3) with an angle of 20° at Punta Donata (Fig. 9b) and almost zero at Laguna Río Bueno. This long structure, with a general east–west orientation that varies from WNW to ENE, is interpreted as the

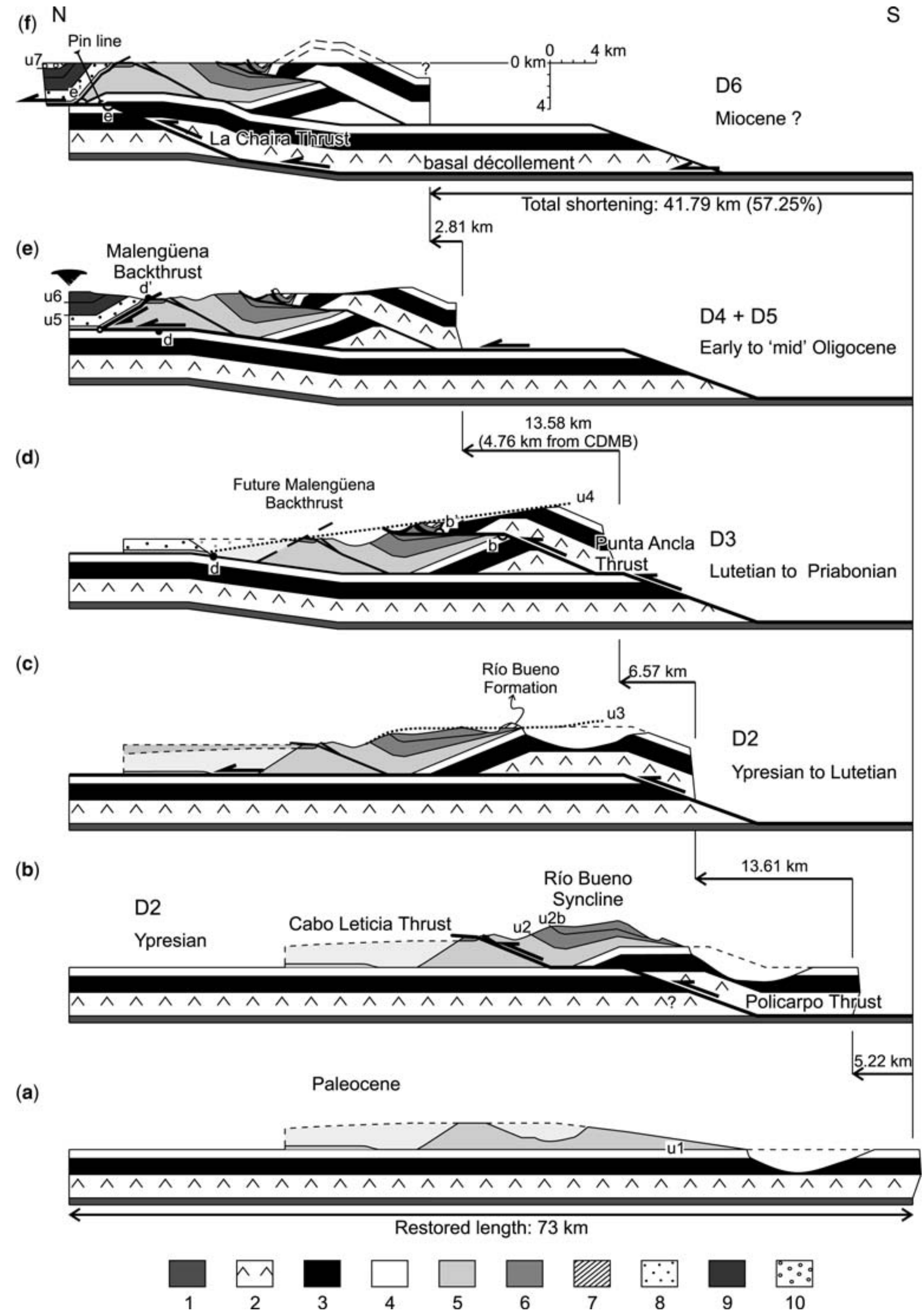


**Fig. 11.** Kinematic evolution of the balanced cross-section of Figure 7. CDMB, Campo del Medio Backthrust. Stratigraphic key: 1, ?Upper Jurassic; 2, ?Lower Cretaceous; 3, ?Upper Cretaceous; 4, Policarpo Formation; 5, Cabo Leticia and La Barca Formations; 6, Punta Noguera and Cerro Ruperto Formations; 7, Río Bueno Formation; 8, Leticia

frontal limb of an anticline. The core of this anticline is not exposed at the study area. The northern limit of the Cordón Largo–Punta Donata Anticlinal Limb is preserved at Cerro Donata, where an open syncline is recognized (Fig. 4). Part of this syncline is laterally represented by subhorizontal to gently dipping beds east of Punta Ancla, and towards Laguna Río Bueno, where the northern limb of the syncline steepens to form the backlimb of the Cerro Las Vacas Anticline.

The Cordón Largo–Punta Donata Anticlinal Limb reveals several changes in orientation along its strike. At Punta Donata, where this is more pronounced, this structure is arcuate and the bedding changes its strike from NE at the eastern salient to NW at the western salient, forming a map-view curve with its concave side facing north. The convex side of the curve is formed by the Policarpo Formation, whereas the concave part and both salients or horns are formed by the Río Bueno Formation (Figs 4 & 10b). The beds in the eastern horn dip moderately to the NW (30–40°), the middle zone varies from north-dipping to subvertical, and the beds in the western horn are slightly overturned, steeply dipping to the SW (Fig. 10b). This complex structure was previously interpreted as a syncline with a north–south oriented axis (Olivero *et al.* 2002; Ghiglione 2003), but it is here reinterpreted as part of an originally NW dipping succession (with its original attitude preserved only at the eastern horn) that has been bent by clockwise rotation of the beds in the western horn on a plunging axis. The possible axis of rotation, with 30° of plunge towards N285°, is obtained from the bedding stereogram (Fig. 10b).

Between Punta Ancla and Punta Duquesa, the Río Bueno Formation reveals flat lying beds affected by several faults and gentle parasitic folds, which define a folding axis plunging 6° towards N275° (Fig. 4). These gently folded beds are inferred to form part of the northern (frontal) syncline of the Cordón Largo–Punta Donata Anticlinal Limb.

It is here interpreted that the Cordón Largo-Punta Donata Anticlinal Limb constitutes the northern flank of an anticline formed in the Policarpo and Río Bueno Formations. This anticline is not exposed at the study area, but is recognized to the east at Caleta Falsa (Ghiglione & Ramos 2005), where its core crops out and has a SW trend. This anticline is interpreted in this paper as related to the Punta Ancla Thrust, which forms the upper segment of a fault-ramp that cuts the backlimb of the Río Bueno Syncline. The anticline was transported above that thrust, and shortening in the hanging wall in front of the Cordón Largo–Punta Donata Anticlinal Limb generated the low wavelength folds and minor thrusts previously described in the backlimb of the Río Bueno Syncline. The Cordón Largo–Punta Donata Anticlinal Limb is connected to these low wavelength folds by means of its frontal syncline in the Río Bueno Formation, as observed between Punta Ancla and Punta Duquesa, and at Laguna Río Bueno where that syncline is tighter.

According to this interpretation, the time of formation of the Cordón Largo–Punta Donata Anticlinal Limb is the same as the Punta Ancla Thrust and its genetically related low wavelength folds, which postdate the u3 unconformity and the deposition of the Río Bueno Formation (D3). The deformation that obliterates the anticlinal limb and produces its rotation at Punta Donata, on the other hand, is considered to be produced by a later deformation stage. Due to the lack of exposures, the kinematics and structures related to this younger stage cannot be evaluated with certainty, so the geometry was simplified in the balanced cross-section (Fig. 7).

*Balanced cross-section restoration and kinematics.* On the basis of the structural data, a balanced cross-section of northern Península Mitre was constructed (Fig. 7). It depicts an interpretation of the complex structures recognized in this part of the Fuegian Thrust–Fold Belt, constrained by the geometries already described. There is no local subsurface information (well-logs or seismic data) available in order to better constrain the geometries, but reasonable results were achieved with the data obtained by intensive mapping. In addition to these abundant structural data, the cross-section kinematics were time-calibrated with the biostratigraphic ages published elsewhere (Olivero & Malumián 2008; Torres Carbonell *et al.* 2009*a*).

For the construction of the cross-section and subsequent restoration, several geological assumptions concerning the mechanisms of deformation were made. Folding by flexural slip was assumed for the Paleocene–?Miocene beds, according to models by Suppe (1983) and Suppe & Medwedeff (1990). Restoration of these structures was made, therefore, assuming conservation of bed lengths. In the Cretaceous–Danian package, on the other hand, unknown amounts of internal strain are likely in highly deformed areas affected by more than one contractional stage. To restore these parts of the section, therefore, a combined bed length and area balancing technique was used (Fig. 11).

**Fig. 11.** (*Continued*) and Cerro Colorado Formations; 9, Puesto José Formation; 10, Malengüena Formation. Light shaded areas indicate eroded parts. Thicker lines indicate active faults and solid lines mark previous faults. Unconformities 1–7 (u1–u7) are indicated, as well as contractional stages D2–D6. See text for explanation.

Two main décollement levels are present in the cross-section. The shallower one has been already described, and is located within the Paleocene. A deeper décollement is placed at the base of the Cretaceous package. This layer does not crop out in nearby regions, but it was proposed as a detachment level in other parts of Tierra del Fuego (Klepeis 1994*a*). This inference is also necessary in order to be consistent with the approximate thickness of Cretaceous rocks in the Fuegian Andes (Klepeis 1994*a*; Olivero & Martinioni 2001).

The evolution of the structures shown in the cross-section starts in the Ypresian (late D2) with the propagation of the basal décollement of the thrust–fold belt from the deeper level to the Paleocene succession (Fig. 11a, b). The connection of both décollements implies the formation of a thrust-ramp called the Policarpo Thrust (Fig. 11b). The importance of the Policarpo Thrust in the evolution of the thrust–fold belt is here highlighted, since it ultimately connects the sole fault to the base of the post-Danian sedimentary fill of the foreland basin, leading to further accommodation of the tectonic shortening above the shallower décollement. Displacement over the Policarpo Thrust results in the formation of an anticline cored by the Policarpo Formation and older rocks (Fig. 11b). The emplacement of the Policarpo Thrust occurs after the initial phases of the D2 stage, which had already given birth to the u2 unconformity, and is probably synchronous with the deposition of the Punta Noguera and Cerro Ruperto Formations.

Part of the shortening transferred to the foreland by the emplacement of the Policarpo Thrust sheet (5.22 km) is accommodated above the shallower décollement by a fault-propagation fold (Cabo Leticia Anticline) that affects the Cabo Leticia, La Barca and Punta Noguera Formations (Fig. 11b). The Río Bueno Syncline is formed between the frontal limb of the Policarpo fault-bend fold and the Cabo Leticia Anticline, affecting also the Cerro Ruperto Formation. The Cabo Leticia Anticline evolves initially as a fault-propagation fold with a backlimb dip of *c.* 30°, and is later transported above a further thrust with a dip of 22° and a gently dipping upper flat. Beneath this thrust, a drag structure with overturned beds is formed in the footwall, as observed in the Punta Noguera Formation at Punta Ainol and at Río Malengüena. The two-stage evolution of the Cabo Leticia Anticline (first fault-propagation and then fault-bend folding) is consistent with models of deformation in heterolithic turbidite successions (Butler & McCaffrey 2004). The age of the Policarpo Thrust sheet and the Cabo Leticia Anticline during the D2 is constrained by the Early Ypresian age estimated for the Punta Noguera Formation. The D2 stage continues by the ongoing displacement above the Policarpo Thrust, which accommodates a shortening of 13.6 km after the formation of the Cabo Leticia Anticline, transferring deformation to the foreland (Fig. 11c). Partial erosion of the D2 structures produces the unconformity observed at the base of the Río Bueno Formation (u3, Fig. 11c), which also constrains the earliest age of the D2 structures to the Late Ypresian, and defines a short period of erosion and sedimentation after D2.

Continued contraction after deposition of the Río Bueno Formation leads to renewed thrusting in an out-of-sequence scheme (D3), forming the Punta Ancla Thrust. This thrust is also rooted at the décollement in the Paleocene succession, and offsets the core of the earliest Policarpo Thrust sheet (Fig. 11d), accommodating almost 6.6 km. The stage D3, constrained in age between the Early Lutetian and 43.7 Ma (u4), is responsible for the uplift of the Policarpo Formation to a higher structural level, for the low wavelength folding of the Punta Noguera, Cerro Ruperto and Río Bueno Formations in the backlimb of the Río Bueno Syncline, and for favored erosion of the uplifted thrust–fold belt.

The enhanced erosion after D3 gives rise to the major unconformity u4, while the increase in tectonic load by the repetition of a thick Cretaceous–Danian package at the southern part of the section (imbrication of the Policarpo and Punta Ancla thrust sheets) enhances flexural subsidence (Fig. 11d). Since the amount of subsidence is unknown, and also difficult to estimate with the available data, we constrained it using the maximum reasonable slope for the u4 unconformity. This slope was calculated from the thickness of the sedimentary succession deposited above u4, taking into account the original position of that succession and its estimated pinch-out before the inferred kinematics of the Malengüena Backthrust, which later affects these rocks. The slope is consistent with the angle of truncation of the equivalent unconformity below the Middle Eocene in the foreland, offshore Tierra del Fuego (unconformity P3 of Galeazzi 1998). Although this constraint on the magnitude of subsidence may be somewhat inaccurate, the approximation is plausible, and allows good geometrical results that can be improved if coupled with geophysical information. Furthermore, a significant aeromagnetic and gravimetric low is observed to the north of the Cordón Largo–Punta Donata Anticlinal Limb (Lodolo *et al.* 2007; Ghiglione *et al.* 2008), supporting the inference of a flexural deflection in the sector.

The development of the u4 unconformity involves significant erosion of the previous succession, generating a chronostratigraphic hiatus that can reach up to 12 Ma (cf. chronostratigraphic chart by Gradstein *et al.* 2004). This is manifest at Punta Ainol where the Leticia Formation covers the La Barca Formation. Following the development of the u4, a thick sedimentary succession is deposited during the Late Lutetian–Priabonian (Fig. 11d). After the deposition of the Leticia and Cerro Colorado Formations (*c.* 950 m) an unconformity (u5) is formed above the latter, caused by the contractional stage D4 that is characterized by backthrusting in the foreland (to the north of the area involved in Fig. 11) in the earliest Oligocene (Campo del Medio Backthrust, Torres Carbonell *et al.* 2008*a*). The deformation caused by the D4 is recognized by unconformities through the outer orogenic belt, with their best expression at the base of the earliest Oligocene Tchat-chii Conglomerate, which consists of up to 70 m of conglomerate and coarse sandstone with abundant clasts derived from Jurassic, Cretaceous and Palaeogene rocks of the Andean Cordillera (Malumián & Olivero 2006). The D4 is interpreted to be intimately related to the next contractional stage that affects the studied area (D5).

The stage D5 acts in the 'mid' Oligocene leading to the formation of a second backthrust (Malengüena Backthrust) generated in response to the delamination of the sequence above the décollement in the Paleocene rocks (Fig. 11e). The stage D5 is coincident with the development of u6 and the progradational deposition of the syntectonic upper part of the Puesto José Formation (Fig. 11e).

The Malengüena Backthrust evolves by displacement of the footwall towards the foreland, resembling the work of a chisel against the passive hanging wall. The backthrust's branch line and the syncline above it are displaced towards the north (Fig. 11d, e). Such a backthrust sheet could not evolve without a basal décollement in continuous propagation in order to accommodate the tectonic push from the hinterland (Butler 1987). In this case, the necessary basal décollement formed during the late D2 by the continued emplacement of the Policarpo Thrust Sheet, after formation of the Cabo Leticia Anticline (Fig. 11c). Therefore, the backthrust is able to evolve by continuous delamination as long as other mechanical instabilities restrain further deformation.

The Campo del Medio and Malengüena Backthrusts accommodate *c.* 13.6 km of shortening, uplifting and exposing to erosion a thick succession of sedimentary rocks from the foreland basin fill. The shortening involved in the Campo del Medio Backthrust (*c.* 4.8 km) (Torres Carbonell *et al.* 2008*a*) is accounted for in Figure 11 by displacing the hanging wall of the décollement towards the north (cf. reference point 'd' in Fig. 11d, e), previous to the development of the Malengüena Backthrust (offset of reference point 'd' in Fig. 11e), which in turn accommodates *c.* 8.8 km. The estimated shortening transferred to the foreland during D4, however, is poorly constrained since the structural disconnection between the northern and southern structures produced in the Neogene by the Fagnano Transform System (Torres Carbonell *et al.* 2008*b*) hinders the estimations. For this reason, the relative proportions of shortening of the Campo del Medio and Malengüena Backthrusts should be considered a rough approximation, while the total shortening produced by the combined result of both structures (13.6 km) is better constrained and more accurate.

Renewed deformation generates thrusting in the footwall of the basal décollement, within the Cretaceous–Danian sequence (D6; Fig. 11f). The new thrust branches from the lower flat of the Policarpo Thrust (deeper décollement) and rejoins the upper décollement forming a horse in the Cretaceous–Danian rocks (Figs 7 & 11f). This splay is called the La Chaira Thrust, and its lower flat forms the new sole for this portion of the thrust–fold belt. Displacement along the La Chaira Thrust produces further deformation of the already folded Paleocene–Oligocene successions. The stage D6 is responsible for the steepening of the Malengüena Backthrust sheet (see description), which is incorporated to the frontal limb of the La Chaira fault–bend anticline. The La Chaira Thrust sheet is emplaced after or during the formation of the u7 unconformity, covered by the ?Miocene Malengüena Formation, and it accommodates a shortening of less than 3 km, being probably the last stage of the contractional tectonic regime (Fig. 11f). Unfortunately, there is no accurate geochronological data to constrain the timing of this stage in relation to deformation in the foreland at the Early Miocene (Ghiglione 2002; Ponce *et al.* 2008). Additionally, the different amounts of shortening estimated for the La Chaira Thrust and the Late Oligocene–Early Miocene thrusting in the foreland (Torres Carbonell *et al.* 2008*a*), may suggest along-strike variations in the forward transference of shortening in the thrust–fold belt.

The structural geometry of the final cross-section can be depicted as a large duplex horse within the Cretaceous–Danian strata bounded by the La Chaira and Policarpo Thrusts and by a roof thrust within the Paleocene, above which there is a set of thrusts of opposite vergence. The total shortening estimated is of 41.8 km, which represents 57% of the initial section's length. Analysing the kinematic history of this section, it is important to recall the out-of-sequence style of the propagated thrusts above the shallower décollement between D3 and D5, since it indicates a long-lived stage of internal deformation and thickening of the thrust wedge, explained below using the Coulomb wedge theory.

## Kinematics of the eastern Fuegian Thrust–Fold Belt: progressive growth of a Coulomb thrust wedge

The structures of northern Península Mitre are here linked with previous work that depicts the geometry and kinematics of the eastern Fuegian Thrust–Fold Belt deformation front (Torres Carbonell *et al.* 2008*a*), which is located *c*. 50 km northwards (Fig. 1). This permits the description of the thrust–fold belt's complete structural history and to propose a model for the evolution of the thrust wedge in terms of the Coulomb wedge theory (Davis *et al.* 1983). The thrust sequence recorded at the thrust–fold belt leading edge, outside the study area (cf. Torres Carbonell *et al.* 2008*a*), can be summarized as follows: (a) folding of the Punta Torcida Formation (Ypresian) before the Late Lutetian, most probably during the Ypresian coinciding with the D2 stage; (b) backthrusting of the Punta Torcida, Leticia and Cerro Colorado Formations in the earliest Oligocene by development of the Campo del Medio Backthrust (D4), which branches from the basal décollement and evolves by delamination analogous to the Malengüena Backthrust; and finally (c) foreland and upward propagation of the sole fault and frontal thrusting between the latest Oligocene and the Early Miocene (D6?), forming an imbricate thrust system that is now exposed at the Punta Gruesa area in the Atlantic coast (Punta Gruesa Imbricates).

The thrust sequence observed reveals stages of forward propagation of the thrust front (D2 and D6?), separated by stages of out-of-sequence thrusting and backthrusting within the wedge (D3–D5, Fig. 12). This history of progressive deformation can be understood in terms of the Coulomb wedge theory, as a general approximation to the incremental buildup of the outer Fuegian orogenic belt. According to that theory, thrust–fold belts are considered analogous to a homogeneous wedge with a taper angle that is the sum of the topographic slope ($\alpha$) and the basal décollement dip ($\beta$) (Davis *et al.* 1983). The taper angle is referred to a critical value, dependant on the coefficient of friction at the base of the wedge and the strength of the rocks that compose it. When the taper angle is below that value, the wedge is subcritical and deforms internally to increase taper, until the critical geometry is reached. If the critical wedge is forced to accrete new material (e.g. by syntectonic sedimentation) it will continuously deform to maintain its critical taper (Davis *et al.* 1983; Dahlen & Suppe 1988). Also, variations of the composition and basal friction of the wedge produce different critical taper angles, thus controlling its internal dynamics (Dahlen 1984). Physical factors such as erosion and sedimentation play an important role in changing the taper angle, therefore affecting the state (critical or subcritical) of the wedge (Dahlen & Suppe 1988).

The model to be introduced here describes the Ypresian–Miocene history of the eastern Fuegian Thrust–Fold Belt. Before this period, the orogenic wedge had grown since the 'mid' Cretaceous, after the closure of the Late Jurassic–Early Cretaceous marginal basin (Dalziel & Palmer 1979; Nelson *et al.* 1980; Dalziel & Brown 1989; Kohn *et al.* 1995), and its thrust front was located southwards from the studied area (Ghiglione & Ramos 2005). This thrust front involved Upper Cretaceous to Paleocene sedimentary units deformed during the early stages of the D2 episode.

During the Ypresian, the incremental growth of the outer orogenic wedge begins with the foreland propagation of the sole décollement, which ramps from a previous deeper level at the base of the Cretaceous up to the Paleocene succession, forming the Policarpo Thrust (stage D2). The shortening becomes then accommodated above this shallower décollement by the development of thrust-related structures within the wedge (Cabo Leticia Thrust, Fig. 13a). The folding of the Punta Torcida Formation (Torres Carbonell *et al.* 2008*a*), here considered Ypresian, is assumed to accommodate the last pulse of emplacement of the Policarpo Thrust Sheet (Fig. 11c) during the end of the D2 stage (Fig. 13b). The D2 stage is the result of a critical wedge that grows towards the foreland by forward thrusting, accreting material (foreland sedimentary deposits) at its toe. The forward expansion of the wedge tends to decrease the angle $\beta$, while active sedimentation at its toe and erosion at the hinterland impede the proportional $\alpha$ increase to maintain the critical taper. This forms a very thin frontal orogenic wedge, with a low taper angle that causes it to become subcritical, restraining continued forward thrusting (Fig. 13a, b).

As no further horizontal growth is possible, the following thrusting stage (D3) tends to increase the taper angle in the Lutetian, deforming the clastic infill of the foreland basin in an out-of-sequence fashion (Punta Ancla Thrust, Fig. 13c). The D2 and D3 stages are coincident with a regional period of tectonic contraction, orogenesis and sedimentation in the Fuegian Andes (Klepeis 1994*a*; Kohn *et al.* 1995; Olivero & Martinioni 2001; Olivero & Malumián 2008; Barbeau *et al.* 2009).

The emplacement of thrust sheets at the hinterland of the thrust wedge enhances tectonic load, which in turn leads to flexural subsidence increasing the décollement slope $\beta$. The flexural subsidence also favors the deposition of a thick clastic succession above the u4 unconformity during the Late Lutetian to Priabonian, adding fresh material at the front of the wedge which in turn flattens its upper slope (Fig. 13d).

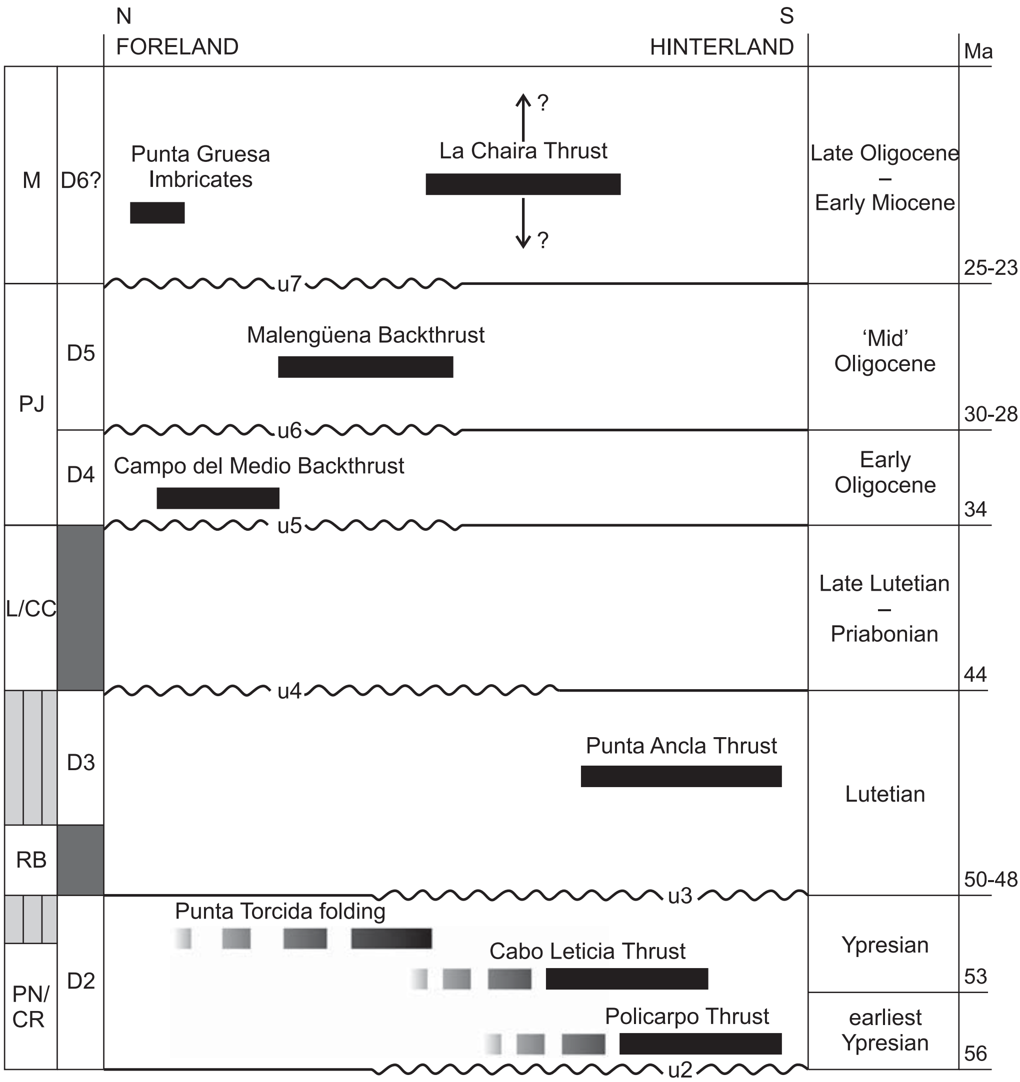


**Fig. 12.** Chronological evolution of the structures recognized in the eastern Fuegian Thrust–Fold Belt, constrained by the ages of the syntectonic successions and their bounding unconformities (u2–u7), and related to successive contractional stages (D2–D6?). Stratigraphic key: PN/CR, Punta Noguera and Cerro Ruperto Formations; RB, Río Bueno Formation; L/CC, Leticia and Cerro Colorado Formations; PJ, Puesto José Formation; M, Malengüena Formation. Vertical lined shading indicates hiatuses, dark shading indicates pauses between contractional stages. Note the cyclicity concerning the location of deformation within the thrust wedge.

Since the wedge continues to be subcritical, further contraction is accommodated above the sole décollement by backthrusting (D4 and D5), coincidently with the deposition of the Oligocene package. Backthrusting evolves due to delamination in a piggyback fashion, forming a hinterlandward leading imbricate system (Fig. 13e). The first structure formed is the Campo del Medio Backthrust (D4), starting with a branch line several kilometres south from the tip line of the décollement (previously formed during the D2 stage). The backthrust's branch line migrates northwards, folding the hanging wall succession until it reaches the décollement's termination, causing the backthrust to stick. Further deformation is then accommodated by the development of the Malengüena Backthrust (D5) towards the hinterland, which evolves in a similar way. The backthrusting stage in the

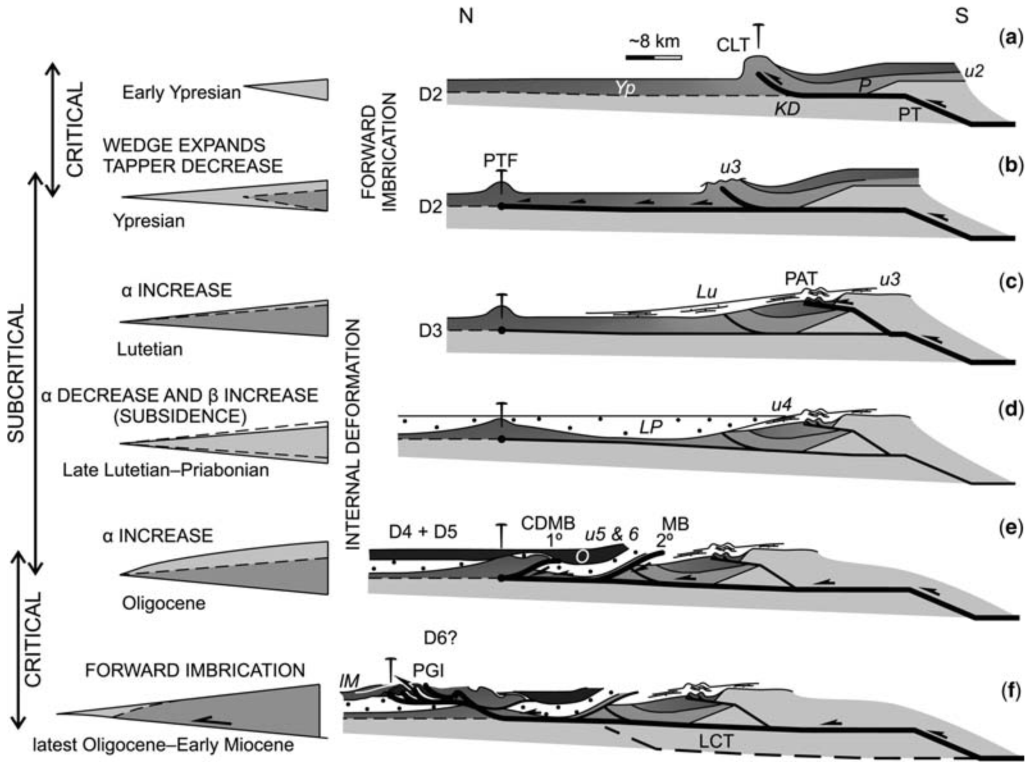


**Fig. 13.** Schematic evolution of the eastern Fuegian Thrust–Fold Belt through contractional stages D2–D6?, according to the Coulomb wedge theory. This cartoon shows the thrust wedge configuration before the emplacement of the Fagnano Transform System (cf. Torres Carbonell *et al.* 2008*b*). KD, Cretaceous–Danian; P, Paleocene; Yp, Ypresian; Lu, Lutetian; LP, Upper Lutetian–Priabonian; O, Oligocene; lM, Lower Miocene; PT, Policarpo Thrust; CLT, Cabo Leticia Thrust; PTF, folding of the Punta Torcida Formation; PAT, Punta Ancla Thrust; CDMB, Campo del Medio Backthrust; MB, Malengüena Backthrust; PGI, Punta Gruesa Imbricates; LCT, La Chaira Thrust. Thick lines indicate the active faults at each stage.

Oligocene accommodates a minimum shortening of *c*. 15% within the thrust–fold belt, significantly building up the surface slope of the orogenic wedge.

After the taper increase produced between D3 and D5, the wedge attains its critical geometry permitting foreland sliding over the sole décollement with deformation localized at the leading edge. The décollement termination propagates to a higher structural level, causing the development of the Punta Gruesa imbricate fan between the latest Oligocene and the Early Miocene (Fig. 13f), as recorded by syntectonic strata (Ghiglione 2002; Ponce *et al.* 2008). There is a possible correlation between the stage D6 that acts during the emplacement of the La Chaira Thrust in the ?Miocene and the development of the Punta Gruesa Imbricates. In that sense, the latest contractional pulses in the thrust front in the Early Miocene could be related to growth of the wedge with accretion below the sole by emplacement of the La Chaira Thrust, as a way to maintain the taper. Nevertheless, the precise age of u7, which constrains the age of the La Chaira Thrust, has not been estimated yet, and its relative age in relation to the syntectonic Lower Miocene beds in the thrust front is therefore not known.

## Conclusions

A detailed study of the structures at the eastern Fuegian Thrust–Fold Belt has led to an improved kinematic model that reveals a complex and distinct thrust-sequence for this portion of the Andes. The analysis of this model in terms of the Coulomb wedge theory reasonably explains the progressive deformation of the thrust wedge, linking it to sedimentation in the Austral foreland basin.

The eastern Fuegian Thrust–Fold Belt at northern Península Mitre reveals complex pro- and retro-vergent structures rooted at the base of the Cretaceous and within the Paleocene, which affect the unconformity-bounded syntectonic sequences of the Austral foreland basin system. These structures accommodate a minimum shortening of *c.* 41.8 km, assuming fault-related folding mainly by flexural slip, restored by the combination of bed-length and area conservation techniques.

The kinematic evolution of the eastern Fuegian Thrust–Fold Belt unveils a progressive behaviour with several contractional stages: (a) during the Ypresian the décollement propagates into the foreland (Policarpo Thrust), ultimately connecting the sole fault to the base of the post-Danian sedimentary fill of the Austral Basin; (b) continuing in the Ypresian, thrusting occurs in a forward-directed fashion, expanding the wedge towards the foreland (Cabo Leticia Anticline and folding of the Punta Torcida Formation); (c) during the Lutetian, out-of-sequence thrusting acts hinterlandwards from the deformation front (Punta Ancla Thrust); (d) significant subsidence and sedimentation take place from the Late Lutetian–Oligocene; (e) backthrusting occurs in the Oligocene (Campo del Medio and Malengüena Backthrusts); (f) from the latest Oligocene to the Early Miocene, foreland-verging thrusting acts at the leading edge (Punta Gruesa Imbricates), probably related to renewed thrusting on Cretaceous–Danian rocks below the sole fault in the hinterland (La Chaira Thrust).

This progressive thrust sequence indicates critical Coulomb wedge behaviour during the Ypresian, with horizontal growth of the wedge by forward directed thrusting into the foreland syntectonic successions, which accretes new material. The increased length causes a diminished taper angle, and the subsequent subcritical wedge progressively grows by internal deformation from the Lutetian–Oligocene. Backthrusting in particular proves to be an important mechanism to accommodate significant shortening (*c.* 15%) during the subcritical stage. After the internal deformation and creation of the topographic slope, the thrust wedge again reaches a critical geometry in the Late Oligocene. The second critical stage causes renewed foreland propagation of the thrust front between the latest Oligocene and the Miocene. This last stage is short lived in comparison to the previous subcritical stage, and ends apparently during the Early Miocene.

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