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Tectonophysics 405 (2005) 25–46
TECTONOPHYSICS
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Progression of deformation and sedimentation in the southernmost Andes

Matías C. Ghiglione*, Victor A. Ramos

Laboratorio de Tectónica Andina, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria C1428EHA, Buenos Aires, Argentina

Received 8 August 2004; received in revised form 30 April 2005; accepted 9 May 2005
Available online 11 July 2005

Abstract

The chronology of thrust motion in the Fuegian thin-skinned fold-thrust belt was established using data from the Atlantic coast of Tierra del Fuego. A set of original structural–geological maps showing the distribution of structures, unconformities and synorogenic sequences in the last tip of the Andes reveals the cratonward propagation of thrusts and sedimentary depocenters. A succession of syntectonic angular and progressive unconformities occur in the studied zone: (1) an angular unconformity between Danian and Late Paleocene sequences, (2) a series of progressive and syntectonic angular unconformities developed from the Late Early Eocene to the Late Eocene, and (3) a Lower Miocene syntectonic unconformity. Additional evidence for the time–space location of the thrust-front is provided by the presence of seismically triggered sand intrusions in Late Cretaceous, Late Paleocene and Middle Miocene sequences.

The integration of data shows that faulting occurred in three main episodes: San Vicente thrusting, ca. 61–55 Ma, Río Bueno thrusting, ca. 49–34, and Punta Gruesa strike-slip event, ca. 24–16 Ma. San Vicente thrusting represents the onset of thrust propagation onto the foreland craton. The thrust-front endured a major cratonward migration through the Río Bueno thrusting, and remained steady afterward. Punta Gruesa constitutes a strike-slip event, associated with the phase of wrench deformation that influences the southernmost Andes since the Oligocene. Although the overall pattern of faulting was progressively younger cratonward, several episodes of out-of-sequence thrusting and folding occurred.

Other features in the southernmost Andes can be linked to these three deformation events to broadly characterize the behavior of the Fuegian orogenic wedge in terms of critical taper models. The Fuegian Andes underwent at least three cycles between subcritical, critical and supercritical stages of behavior in terms of deformation, erosion, and sedimentation.

Keywords: Chronology of thrust motion; Foreland basins evolution; Growth strata; Progressive and syntectonic angular unconformities; Crustal deformation; Critical taper model; Clastic dikes; Southernmost Andes; Fuegia Andes

* Corresponding author.
E-mail address: mghiglione@hotmail.com (M.C. Ghiglione).

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doi:10.1016/j.tecto.2005.05.004

1. Introduction

It is generally accepted that the southernmost Andes from Tierra del Fuego expanded continuously from the Late Cretaceous to the Neogene. The earliest orogenic stage in the Late Cretaceous involved the closure of the Rocas Verdes marginal basin (Fig. 1; Dalziel et al., 1974; Hervé et al., 1981), followed by the uplift of basement blocks (Nelson, 1982; Ramos et al., 1986; Kohn et al., 1995). Afterward, shortening propagated cratonward, sustained by the offsetting effects of continuous basement uplift in the hinterland (Nelson, 1982; Kohn et al., 1993; 1995) and thrust imbrication in the thin-skinned fold-thrust belt (Fig. 1; Cagnolatti et al., 1987; Wilson, 1991; Alvarez-Marrón et al., 1993; Klepeis, 1994a; Diraison et al., 2000; Ghiglione et al., 2002a).

An accurate but imprecise timing of thrust motion in the Fuegian Andes can be obtained using regionally distributed data from unconformities located within synorogenic deposits from the associated Austral (Magallanes) foreland basin (Klepeis, 1994a; Klepeis and Austin, 1997; Ghiglione et al., 2002a; Kraemer, 2003). At least four deformational events can be deduced from the presence of unconformably bounded tectonostratigraphic units (Biddle et al., 1986; Klepeis, 1994a; Kraemer, 2003). However, it is not possible to establish the precise spatial location of the deformational front using regional unconformities. Although the causal relation between the uplift of the basement-involved hinterland and the thrust propagation in the thin-skinned fold-thrust belt has been suggested previously (Kohn et al., 1995; Klepeis and Austin, 1997; Ghiglione et al., 2002a), the step-by-step progression of events through the Tertiary was not possible to establish because of the lack of more precise spatial information.

We present a set of original structural–geological maps from the southernmost tip of the Andes showing the distribution of structures, unconformities and synorogenic sequences that indicate the cratonward propagation of thrusts and sedimentary depocenters (Figs. 2 and 3). The addition of data from continuous exposures along the Atlantic coast in Tierra del Fuego results in a thrust chronology that is more precise, although not entirely independent of assumptions

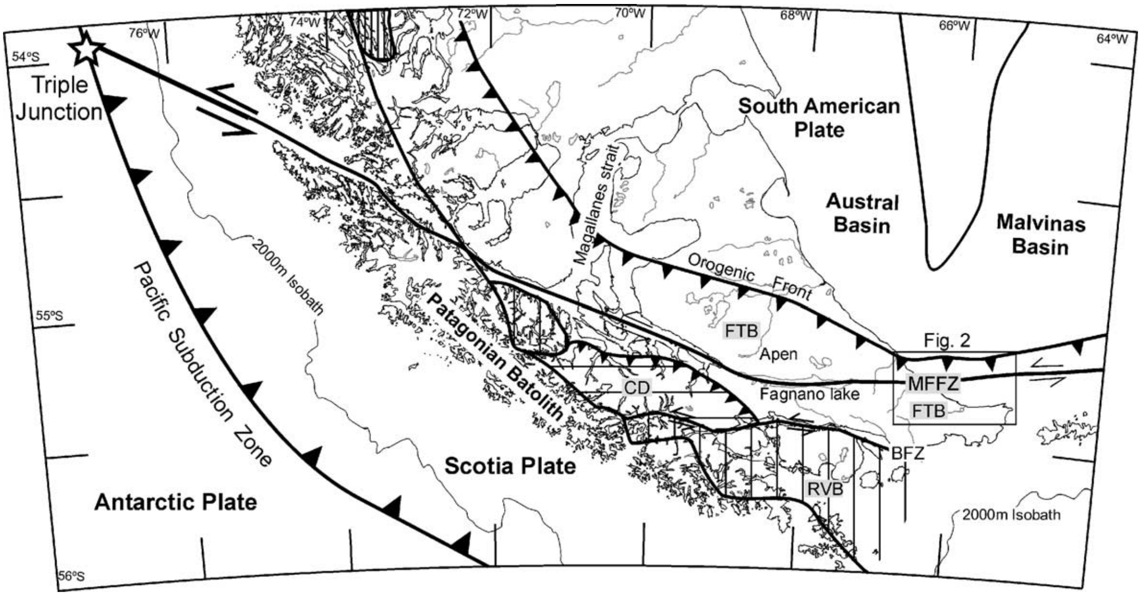

Fig. 1. Map of the Southernmost Andes showing five main tectonic provinces and their boundaries (after Klepeis, 1994a; Diraison et al., 2000; Barker, 2001). The internal domain, with basement-involved contractional deformation, includes the Patagonian Batolith, Cordillera Darwin (CD), and the Rocas Verdes Basin (RVB). The thin-skinned fold-thrust belt (FTB) constitute the external domain. The eastern boundary between these two domains is the basement thrust called Beagle Fault Zone (BFZ) (Klepeis, 1994a; Cunningham, 1994, 1995; Kraemer, 2003). The Magallanes–Fagnano fault zone (MFFZ) is the boundary between the South American and Scotia Plates. The orogenic front separates the Fueguian foreland fold-thrust belt to the S–SW from the Austral and Malvinas basins to the N–NE.

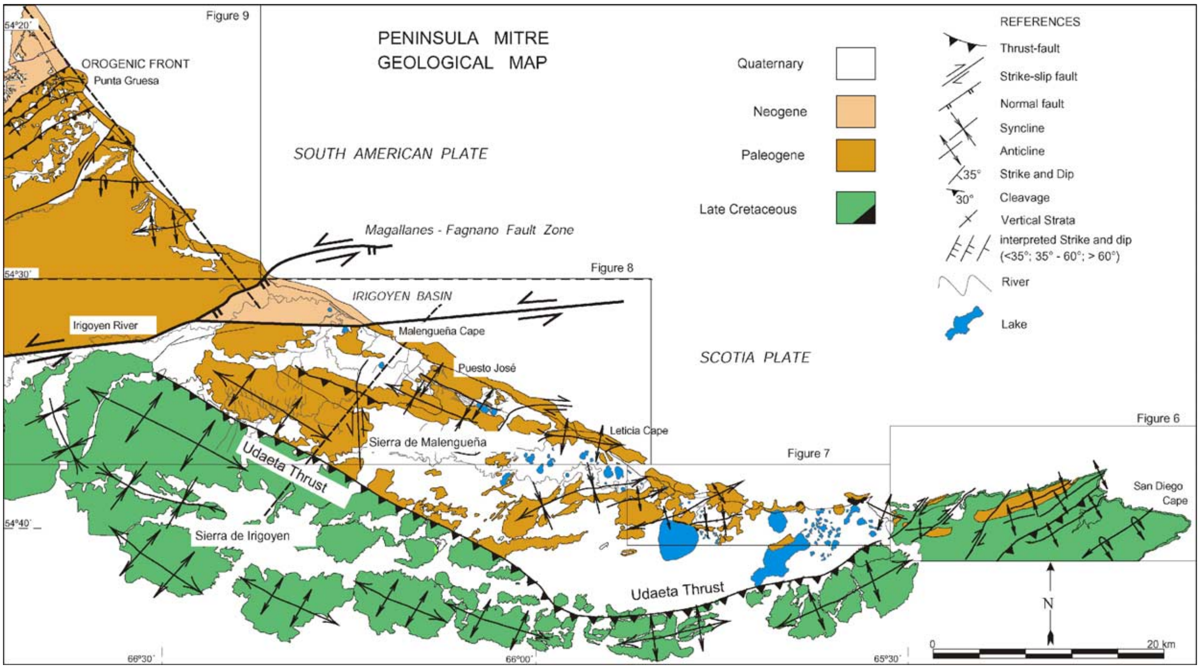

Fig. 2. Structural map of the Peninsula Mitre. The Udaeta thrust fault is the boundary between the southern domain and the central and northern domains. The Magallanes–Fagnano fault zone is the boundary between the South American and Scotia Plates and divides the northern domain in a southern and northern sector. Dashed line indicates location of cross-section from Fig. 3. Boxes indicate position of Figs. 6–9. For stratigraphic references see Fig. 5. For map location, see Fig. 1.

about foreland basin dynamics. The presence of growth strata and seismic-related sand intrusions provide additional evidence on the time–space distribution of deformation (Fig. 4). Data from previous studies of the Fuegian Andes have been synthesized with data obtained in the present study to illustrate the causal relation between hinterland uplift and thrust propagation in the foreland. In light of the new findings, the evolution of the Fuegian orogenic wedge is discussed in the context of a symptomatic approach

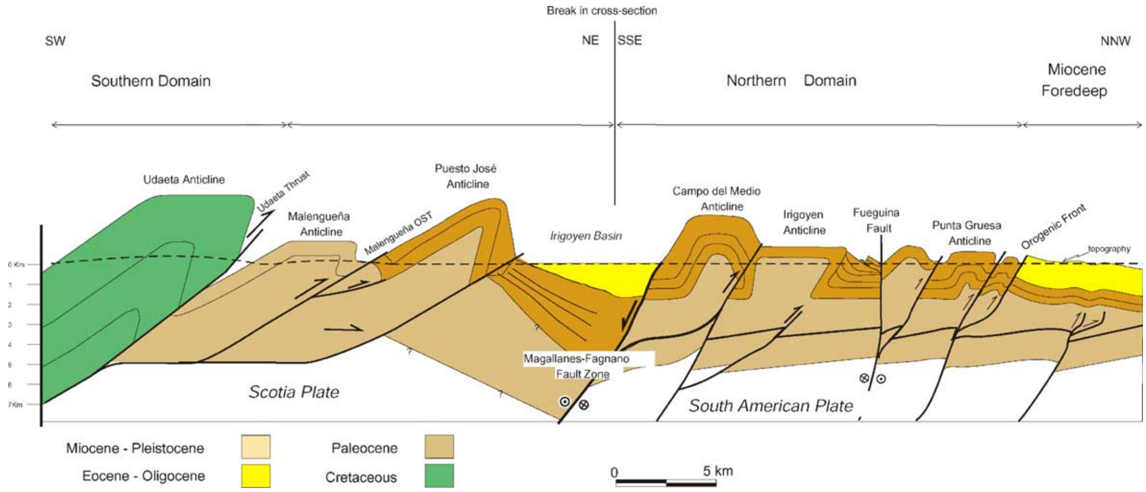

Fig. 3. Structural cross-section. For location, see Fig. 2.

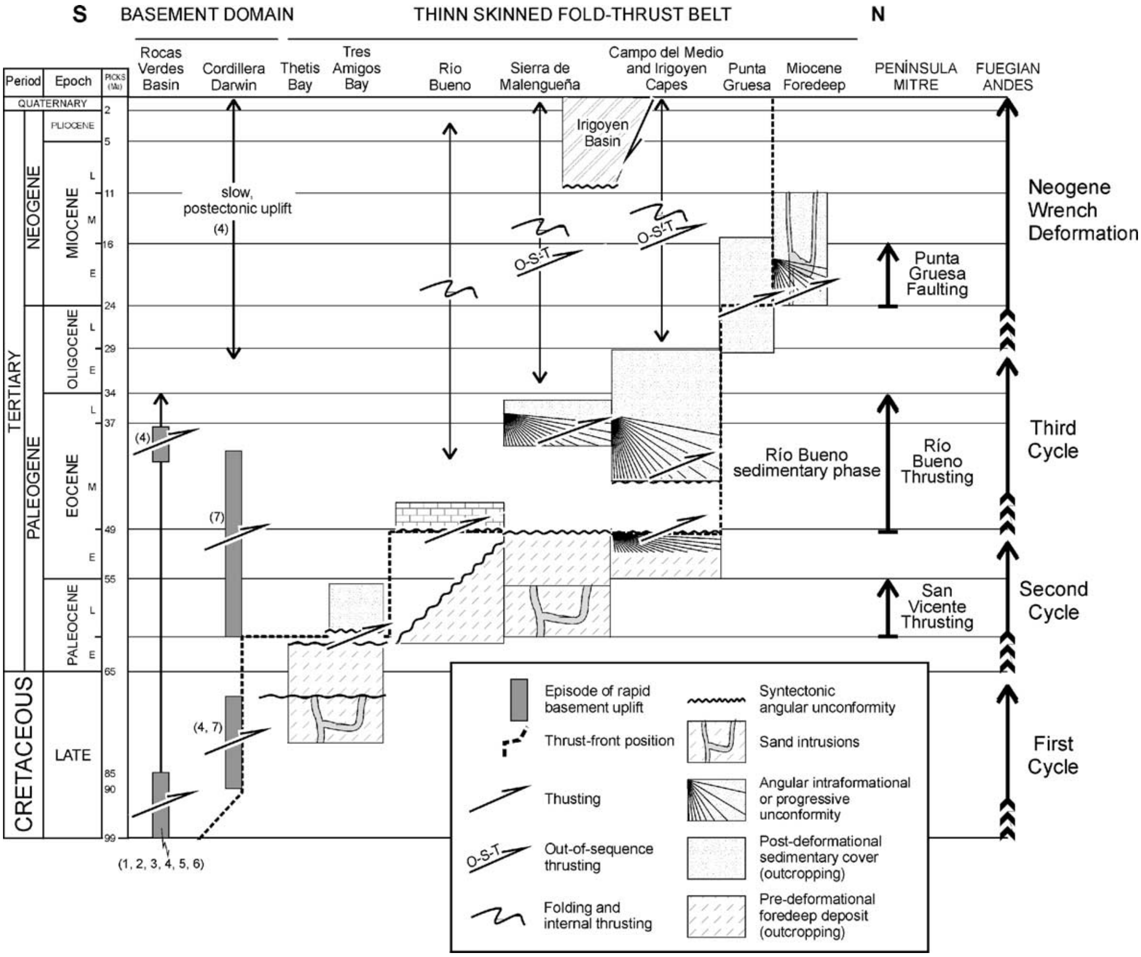

Fig. 4. Schematic time–space section through the Fuegian orogenic wedge in Peninsula Mitre illustrating patterns of faulting, uplift, sedimentation, and erosion. The uplift history of Rocas Verdes basin and Cordillera Darwin is compiled from (references are indicated with numbers in the figure): 1, Halpern and Rex, 1972; 2, Natland et al., 1974; 3, Hervé et al., 1981; 4, Nelson, 1982; 5, Ramos et al., 1986; 6, Cunningham, 1994; 7, Kohn et al., 1995. Time scale is from the 1999 Geological Time Scale (GSA).

(DeCelles and Mitra, 1995) in which wedge behavior is inferred from the time–space distribution of basement uplift in the hinterland, and thrust faulting, erosion and sediment accumulation in the foreland.

2. Geological history and tectonic setting

The southernmost Andes can be divided into two sections (Fig. 1): one section with a north–south orientation (Patagonian Andes) and a second section that runs east–west (Fuegian Andes). Since the Late Paleozoic, these mountains have been affected by changing tectonic regimes and multiple phases of spatially superimposed deformation (e.g. Klepeis and Austin, 1997): (1) Subduction along the Pacific margin of Gondwana formed an accretionary prism from the late Paleozoic to the early Mesozoic, which currently comprises the metasedimentary and metavolcanic basement of the southernmost Andes (Dalziel and Cortés, 1972; Nelson et al., 1980; Dalziel, 1981; Hervé et al., 1981; Dalziel, 1985; Mpodozis and Ramos, 1990; Mukasa and Dalziel, 1996). In Tierra del Fuego, basement rocks are concentrated in Cordillera Darwin (Fig. 1), a high-grade metamorphic complex (Dalziel et al., 1974; Hervé et al., 1981;

Nelson, 1982; Kohn et al., 1995). (2) The southernmost Andes were dominated by crustal stretching during the early stages of supercontinent break up in the Triassic–Early Cretaceous, (Dalziel, 1981; Biddle et al., 1986). Widespread silicic volcanism and deposition of silicic volcaniclastic rocks accompanied thinning of the South American craton by normal faulting (Natland et al., 1974; Bruhn, 1979; Biddle et al., 1986; Wilson, 1991; Pankhurst et al., 2000). These events, as well as the development of a proto-marginal basin along the Pacific margin of the continent (Wilson, 1991; Mukasa and Dalziel, 1996), mark the beginning of an extensional phase in the development of the Austral (or Magallanes) basin (Fig. 1; Biddle et al., 1986). With further extension, the siliceous proto-marginal basin magmatism gave way to the development of oceanic crust and the onset of the Rocas Verdes marginal basin extending from the Sarmiento Complex in the NW to the Weddell Sea in the SE (Katz, 1973; Dalziel et al., 1974; Dalziel, 1981; Mukasa and Dalziel, 1996). Deformed remnants of this basin and its coarse to fine clastic infill are now exposed as the upper part of ophiolite complexes in the hinterland (Fig. 1, Katz, 1973; Wilson, 1991; Mukasa and Dalziel, 1996). (3) The Cordilleran orogenic belt became tectonically consolidated with the closure of the Rocas Verdes marginal basin during Late Cretaceous time (Halpern and Rex, 1972; Natland et al., 1974; Hervé et al., 1981). Afterward, forward propagation of deformation was maintained by the offsetting effects of constant basement uplift in the hinterland (Nelson, 1982; Kohn et al., 1993, 1995; Klepeis, 1994a) and forward imbrication in the thin-skinned fold-thrust belt (Winslow, 1982; Cagnolatti et al., 1987; Wilson, 1991; Alvarez-Marrón et al., 1993; Klepeis, 1994a; Ghiglione et al., 2002a; Kraemer, 2003). The continuous advance of deformation produced a systematic cratonward propagation of the Austral foreland basin depocenters (Yrigoyen, 1962; Biddle et al., 1986; Wilson, 1991; Ramos, 1996; Galeazzi, 1998; Olivero and Malumian, 1999; Ghiglione et al., 2002a). The expansion of the orogenic wedge continued until the Late Eocene–Oligocene (Caminos et al., 1981; Winslow, 1982; Alvarez-Marrón et al., 1993; Ghiglione, 2002), or Neogene (Diraison et al., 1997, 2000; Kraemer, 2003). (4) Contractional deformation in the southernmost Andes slowed dramatically and changed in character to transpressional during the Neogene, (Winslow, 1982). The development of the seismically active transform plate boundary between South America and Scotia plates (Magallanes–Fagnano fault zone) produced the strike-slip deformation observed throughout the mountain belt since the Oligocene (Cunningham, 1993; Klepeis, 1994b; Cunningham et al., 1995; Ghiglione, 2002). Extensional faulting and rifting concentrated along the Magellan Strait and still active today started during this period (Diraison et al., 1997). The initiation of Late Tertiary wrench faulting can be related to reorganization of the South American, Antarctic, and Scotia plates motions (Winslow, 1982), and the acceleration of the opening of Drake's Passage between South America and Antarctica (Cunningham et al., 1995; Barker, 2001).

3. Structure and geology

The Fuegian Andes comprise (Fig. 1): (1) an internal domain, with basement-involved contractional deformation, and (2) a thin-skinned external domain (Klepeis, 1994a; Klepeis and Austin, 1997; Kraemer, 2003). The boundary between these two domains is the basement thrust-front that bounds the northern side of Cordillera Darwin and continues eastward along the Beagle Channel (Fig. 1; Klepeis, 1994a; Kraemer, 2003). The studied geological transect in the external domain includes the thin-skinned Fuegian foreland fold-thrust belt, the Magallanes–Fagnano fault zone, the orogenic front and the Lower Miocene foredeep (Figs. 2, 3 and 5).

The Fuegian foreland fold-thrust belt is subdivided here in (1) a southern domain with north vergent thrusts rooted at the base of the Cretaceous units (Figs. 3 and 6); (2) a central domain characterized by gently folded Lower Middle Eocene sequences unconformably overlying tighter-folded Cretaceous to Lower Eocene units (Fig. 7); and (3) a northern domain composed of Paleogene to Neogene units affected by north vergent thrusts with a basal decollement situated within the Tertiary units (Figs. 3, 8 and 9). The left-lateral Magallanes–Fagnano fault zone cuts the northern domain along the Irigoyen River, forming a transtensional domain where the Irigoyen pull-apart basin is emplaced (Figs. 2, 3 and 8; Ghiglione, 2003). The orogenic front located at Punta

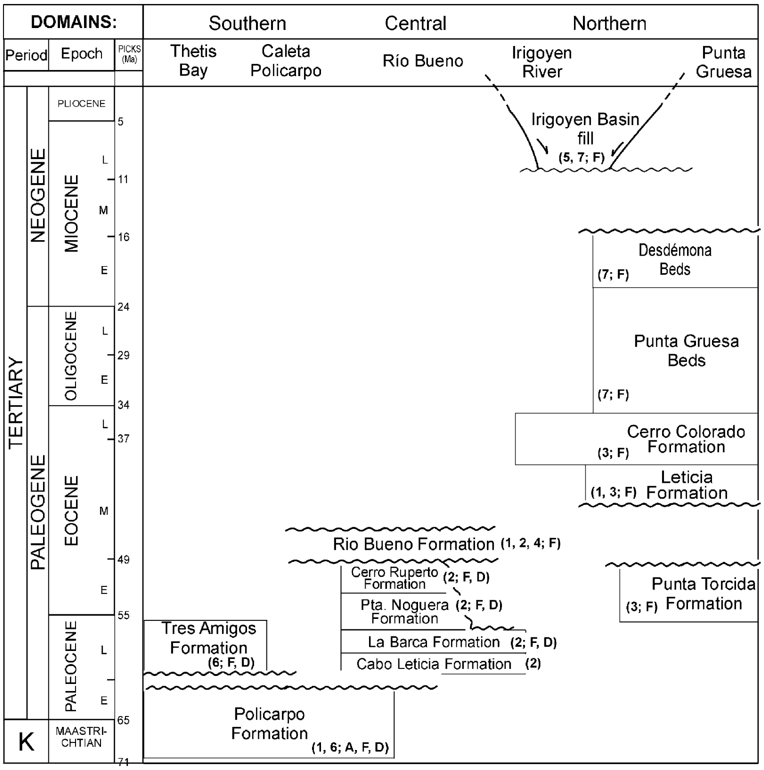

Fig. 5. Late Cretaceous to Cenozoic stratigraphic columns for the Fuegian fold-thrust belt in Peninsula Mitre after (references are indicated with numbers in the figure): 1, Furque and Camacho, 1949; 2, Malumián and Olivero, 1998; 3, Olivero and Malumian, 1999; 4, Olivero et al., 2002; 5, Ghiglione, 2003; 6, Olivero et al., 2003; 7, Malumián and Olivero, 2005. Abbreviations indicate fossils used for chronology: A, ammonites; D, dinocysts; F, foraminifera; I, Inoceramus. Time scale is from the 1999 Geological Time Scale (GSA). For location, see Figs. 1, 2, 6–9.

Gruesa separates the foreland fold-thrust belt to the south from the foredeep of the Austral foreland basin to the north (Figs. 3 and 9).

The main features that reveal the timing of deformation in the study zone are described in the following sections. The specific structural characteristics and details from each of the three domains are expressed in the enclosed maps (Figs. 2, 6–9).

3.1. Fuegian foreland fold-thrust belt

3.1.1. Southern domain

The southern domain forms an arched region between San Diego Cape and Sierra de Irigoyen composed mainly of Late Cretaceous units, and limited exposures of Paleogene rocks (Figs. 2 and 5; Olivero et al., 2003). The most relevant features use to reveal the chronology of deformation in this domain are (1) the widespread development of seismic-related sand-intrusions within the upper-Campanian–Maastrichtian sedimentary sequences, and (2) the development of an angular unconformity between the Late Paleocene to Eocene rocks and the Cretaceous to Danian units.

The Maastrichtian tabular sand intrusions are clustered along the coast east of Thetis Bay and their concentration decreases outward from than point (Fig. 6). In general, the clastic dikes are vertical with a N–S orientation and crosscut the sedimentary sequence (Fig. 10a). The presence of laminar flow surfaces along the edges of the dikes is consistent with an upward-directed hydraulic force of short duration. The characteristics of these sand intrusions meet a set of criteria (Obermeier, 1996) developed for determining whether observed sediment deformation was triggered by seismically induced liquefaction. The most important criterion is that seismic liquefaction origin

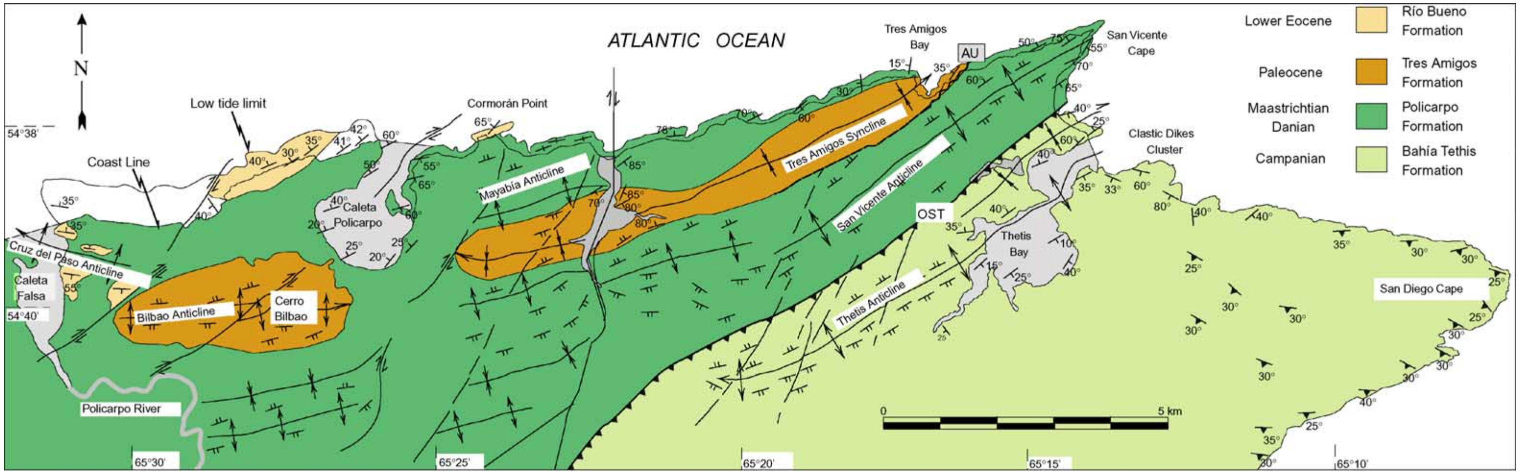

Fig. 6. Structural–geological map of the southern domain. Abbreviations are CDC: clastic dikes cluster, OST: out of sequence thrust, STU: syntectonic unconformity. For map location, explanations and symbols see Fig. 2. For stratigraphic references see Fig. 5.

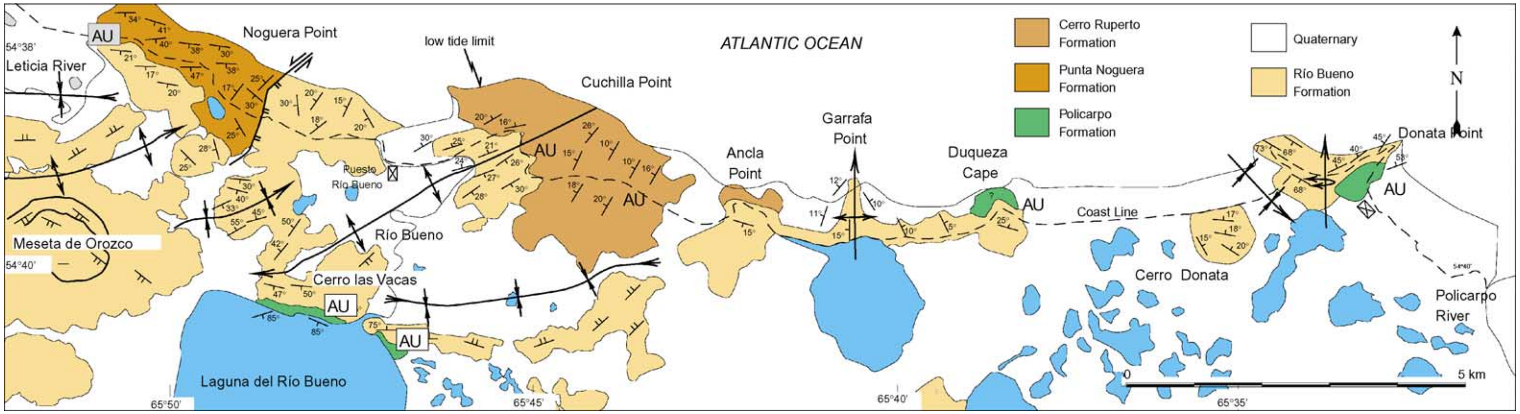

Fig. 7. Structural–geological map of the central domain. Abbreviation is AU: angular unconformity. For map location, explanations and symbols see Fig. 2. For stratigraphic references see Fig. 5.

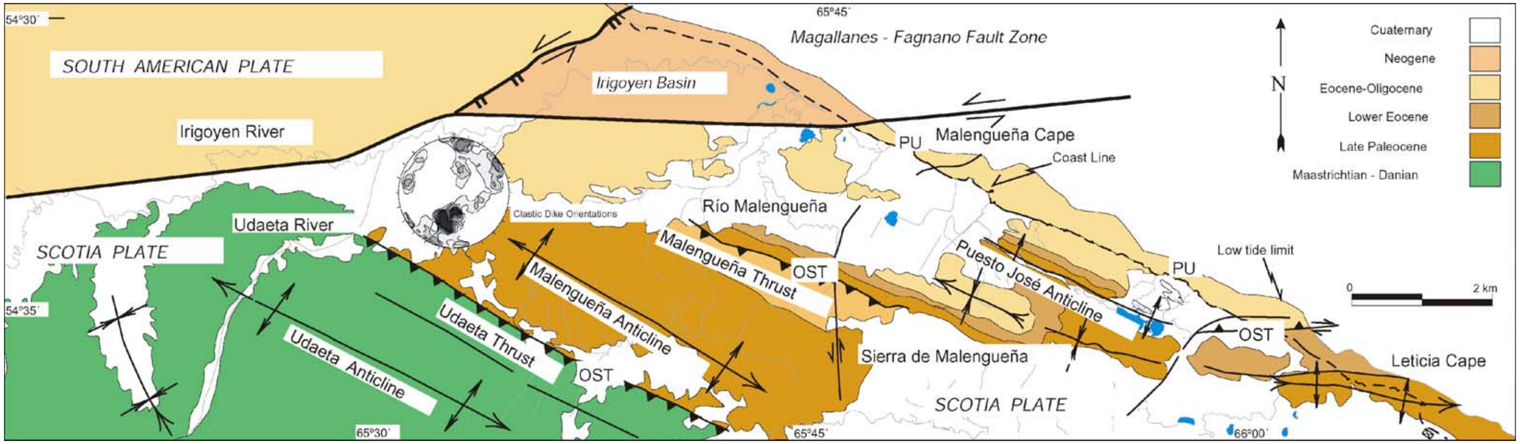

Fig. 8. Structural–geological map of the southern northern domain. Abbreviations are CDC: clastic dikes cluster, OST: out of sequence thrust, STU: syntectonic unconformity. For map location, explanations and symbols see Fig. 2. For stratigraphic references see Fig. 5.

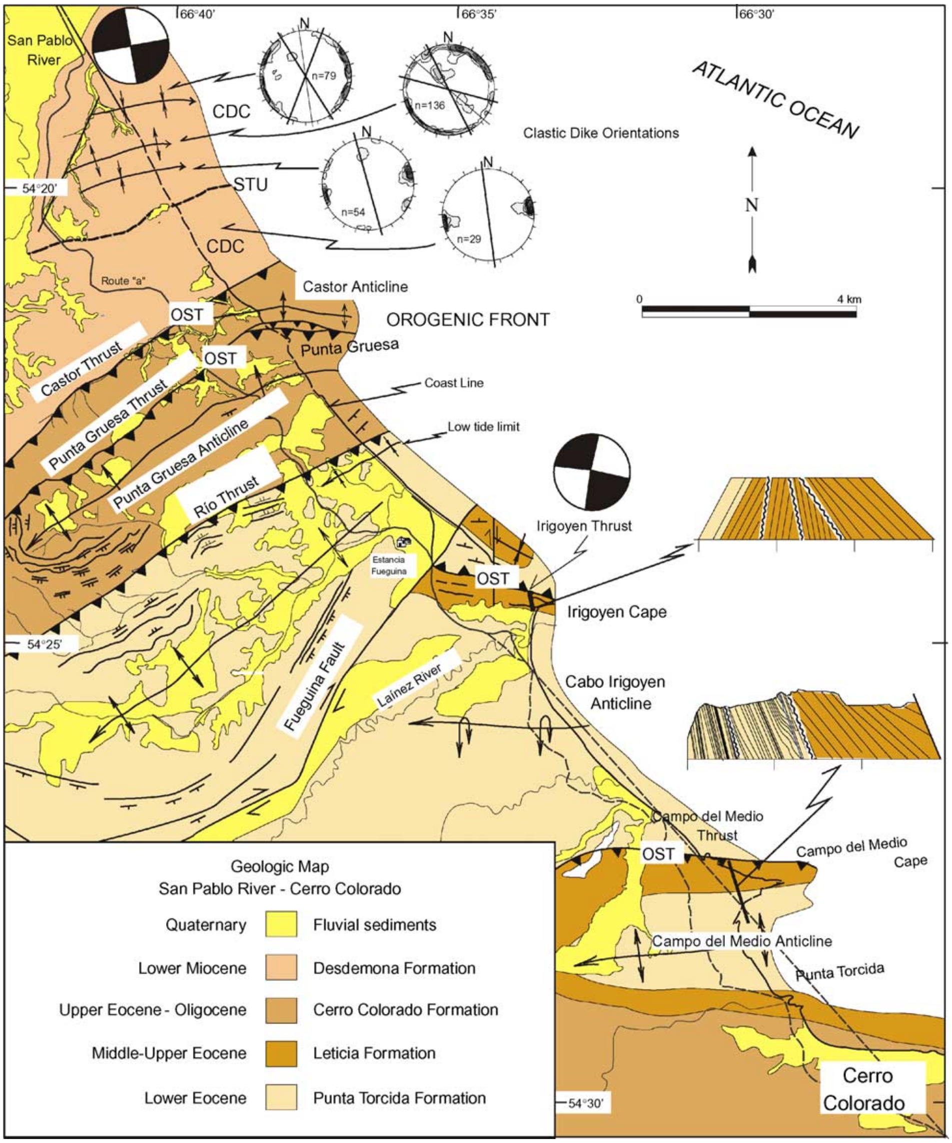

Fig. 9. Structural and geological map of the northern domain. The diagrams of clastic dikes orientation are after Ghiglione (2002). Abbreviations are CDC: clastic dikes cluster, OST: out of sequence thrust, PU: progressive unconformity, STU: syntectonic unconformity. Geological sections show the decreasing dip up-section of unconformably bounded syntectonic sequences from the Campo del Medio and Irigoyen anticlines. Stereograms show clastic dike orientations intruded in the foredeep. Kinematic stereograms from fault fault-slip data are from Diraison (1998). For map location, explanations and symbols see Fig. 2. For stratigraphic references see Fig. 5.

implies widespread, regional development of features around a core area where the effects are more severe (Obermeier, 1996). In addition, the features must have a morphology that is consistent with a very sudden application of a large hydraulic force (Obermeier, 1996). Clastic dike swarms with similar characteristics are intruded into equivalent Maastrichtian sequences in the western side of Tierra del Fuego, north of the basement thrust-front (Winslow, 1983; Schmitt, 1991; Diraison et al., 2000). The structural features of these dike swarms and their geometric relations with other structures suggest rapid, single-phase injection (Win-

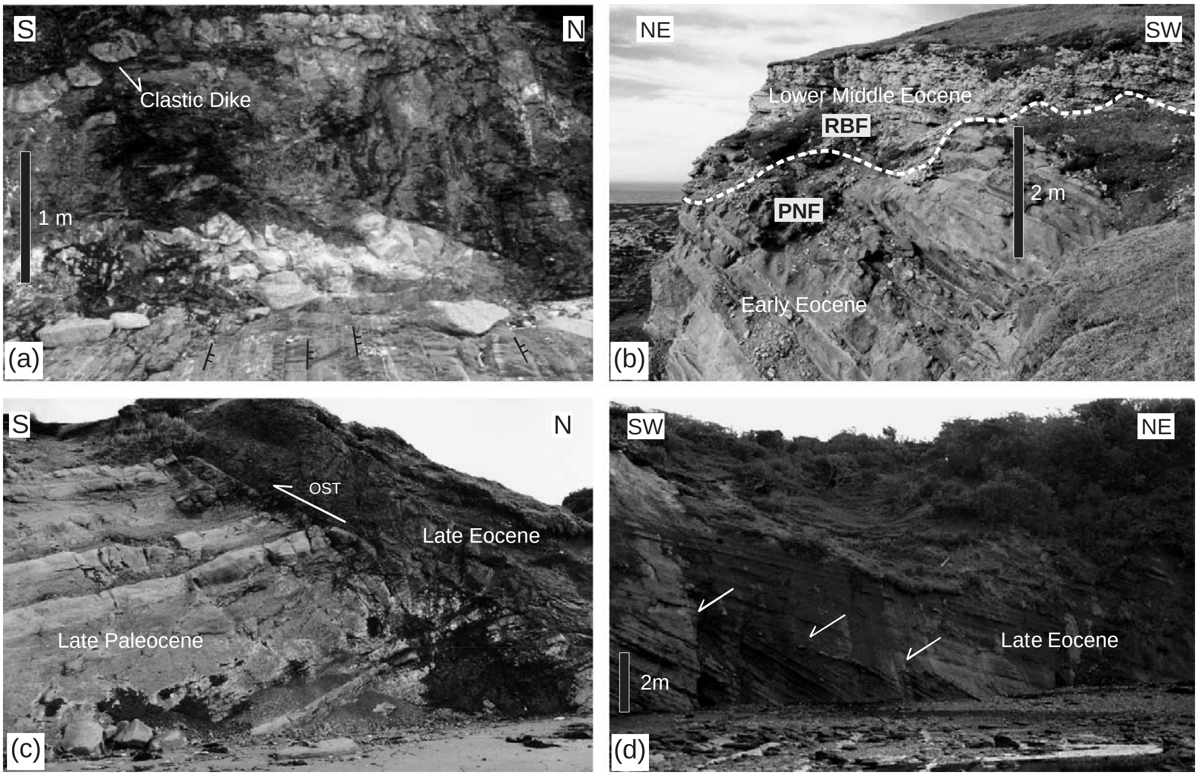

Fig. 10. (a) Sandstone dike intruded within the heterolithic upper Campanian–Maastrichtian sequence from Bahía Thetis Formation in the cliff east of Thetis Bay. The sedimentary sequence dips 80° S and is cut by the clastic dike. View to the east; for location see Fig. 6. (b) Angular unconformity between the Early Middle Eocene Río Bueno Formation (RBF, dipping 20° S) and the Early Eocene Punta Noguera Formation (PNF, dipping 45° S) at Noguera Point. View toward the southeast; for location, see Fig. 7. (c) South vergent out-of-sequence back-thrust that cuts the northern limb of Leticia anticline and places the Late Eocene member of the Cerro Colorado Formation against older late Paleocene units. (d) Syntectonic unconformity (arrows) in the Oligocene Cerro Colorado Formation on the northern limb of Puesto José Anticline. View toward the northwest; for location see Fig. 8.

slow, 1983). Dike injection may be attributed to high pore pressure generated during rapid tectonic loading by thrusts advancing on the sedimentary pile (Winslow, 1983), released during a severe seismic event. The presence of seismically triggered sand intrusions in Late Cretaceous sequences suggests the proximity of the thrust-front during its deposition, probably along the adjacent northern border of the basement-involved internal domain.

An angular unconformity is particularly well developed in the frontal limb of the San Vicente anticline where the Late Paleocene sandstones from the Tres Amigos Formation dip 35° NW over Danian strata from the Policarpo Formation dipping 60° NNW (Figs. 4 and 6). The angular relation shows that during the Late Paleocene the Policarpo Formation was folded, eroded and onlapped by the Tres Amigos Formation (Fig. 4). A similar angular unconformity bounds units of Late Cretaceous and Early Paleocene age north of Fagnano Lake in Sierra de Apen (Fig. 1; Martinioni et al., 1999).

The widespread distribution of Late Cretaceous to Early Paleocene sedimentary units (Figs. 2, 4 and 6) indicates that the southern domain was an important depocenter during that period. In contrast, the lack of post-Paleocene sequences reveals that sedimentation began to decrease after the orogenic front reached this domain in the Early Paleocene.

3.1.2. Central domain

This domain is mainly composed of Late Paleocene strata to early middle Eocene with restricted

Maastrichtian outcrops (Figs. 5 and 7; Furque and Camacho, 1949; Malumián and Olivero, 1998; Olivero et al., 2002). An unconformity is particularly well developed at the base of the Río Bueno Formation and shows angular relations owing to thrust-related deformation and uplift (Figs. 7 and 10b). The youngest strata beneath the carbonate member are the lower Eocene sandstone from the Cerro Ruperto Formation in Cuchilla and Ancla Points (Figs. 5 and 7; Olivero et al., 2002). The Upper Paleocene–Lowest Eocene Punta Noguera Formation is tilted ~30° beneath a NW-dipping angular unconformity at the outlet of the Leticia River (Fig. 10b; Furque and Camacho, 1949; Malumián and Olivero, 1998; Ghiglione et al., 2002a). Towards the south and east of the central domain at Donata Point, Duqueza Cape and Cerro Las Vacas, the carbonate member rests in angular unconformity upon Upper Cretaceous pelitic rocks (Figs. 4 and 7). These unconformities are the result from erosion associated with regional shortening, deformation and uplift that took place during the Early and Middle Eocene (Fig. 4).

The abundance of Late Paleocene to Middle Eocene sequences (Figs. 2, 4 and 7) suggests that the central domain was an important depocenter during that period. After the onset of deformation and the deposition of the Río Bueno Formation, sedimentation began to decrease.

3.1.3. Northern domain

The northern domain is composed of imbricated thrust sheets rooted within the Tertiary units (Fig. 3). The southwest dipping Udaeta thrust outlines the boundary between the southern and northern domains in Sierra de Irigoyen (Figs. 2, 3 and 8). Its northern limit is the last emergent thrust cropping out at Punta Gruesa (Figs. 2 and 9). This domain is cut-through by the Magallanes–Fagnano fault zone along the Irigoyen River and subdivided into two sectors, one that includes the Sierra de Malengueña between Leticia and Malengueña Capes (Fig. 8), and a second sector from Cerro Colorado to Punta Gruesa (Fig. 9). The presence of several syntectonic and progressive unconformities, together with growth strata, out-of-sequence thrusts and seismically triggered clastic intrusions reveal the timing of deformation in this domain (Fig. 4).

3.1.4. Leticia Cape—Sierra de Malengueña

The Malengueña anticline present tabular sand dikes intrusions in its frontal limb. The preferred orientation of the clastic dikes is 270° dipping 65° N, approximately parallel to the fold axis (Fig. 8), at low-angle with respect to the sedimentary layers orientated 275° and dipping 45° N. The clastic dikes are intruded in the Late Paleocene with similar diagnostic characteristics than the Maastrichtian sand intrusions suggesting seismically induced liquefaction. The presence of co-seismic triggered sand intrusions suggests the proximity of the thrust-front in the Late Paleocene, probably along the northeastern border of the southern domain.

Along the coast 2 km north of Leticia Cape, a south vergent out-of-sequence back-thrust places the Late Eocene member of the Cerro Colorado Formation against older Late Paleocene units (Figs. 8 and 10c). These Late Eocene marine sediments located in the frontal limb of Puesto José anticline include progressive unconformities (Fig. 10d) revealing syntectonic sedimentation.

3.1.5. Magallanes–Fagnano fault zone—Irigoyen basin

The subhorizontal sequences of a 5 km wide basin named the Irigoyen Basin are exposed along the Magallanes–Fagnano fault zone. These sequences are horizontal to gently folded and offset by small normal faults between the Malengueña Cape and the Cerro Colorado (Figs. 8 and 11a; Ghiglione, 2003). The upper sequences of this basin are Miocene?–Pliocene in age (Fig. 5; Malumián and Olivero, 2005). It has been proposed that the kinematics of the Irigoyen basin changed from compressive (thrust top basin) during the Paleogene to pull-apart since the Oligocene–Miocene (Ghiglione, 2003). The first evolutionary stage as a thrust-top basin started at least during the Late Eocene-development of the Puesto José anticline marked by syntectonic unconformities in its northeastern limb (Figs. 4, 8 and 10d). The Late Paleocene activity of the Malengueña anticline to the southwest is reflected by the presence of seismically induced sand intrusions (Figs. 3 and 8), suggesting that some kind of tectonic load and subsidence in the Irigoyen basin could have existed from that time. Due to its location along the plate boundary, the Pliocene infill of the basin is associ-

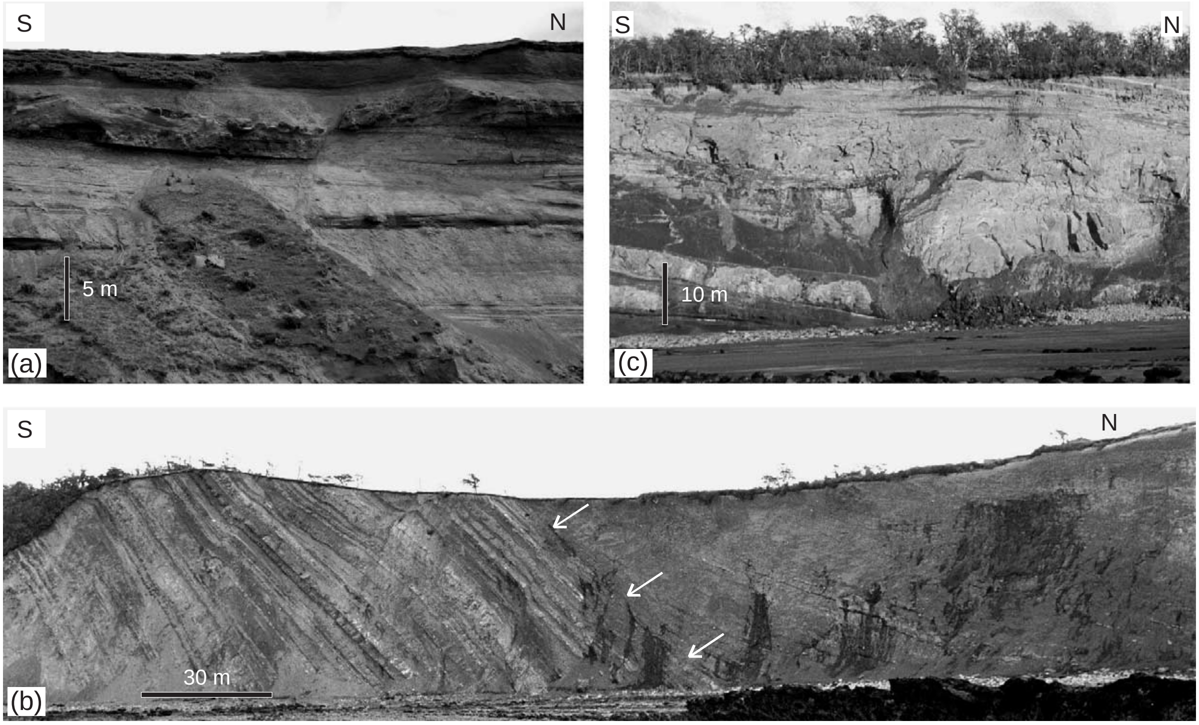

Fig. 11. (a) Subhorizontal Pliocene sequences from the Irigoyen basin south of Cerro Colorado, affected by normal faults. View toward the west; for location see Fig. 9. (b) Syntectonic unconformity-forced regression (arrows) within the Punta Torcida Formation (Early Eocene) in the northern limb of the Campo del Medio Anticline. Strata below and above the unconformity dip 56° and 36° N, respectively. View toward the west; for location see Fig. 9. (c) Lower Miocene deltaic sequences south of Ladrillero Cape. The numerous clastic dikes and the main sand body (~20 m long by ~10 m tall) are interpreted as the products of co-seismic sand liquefaction. View toward the west.

ated with the transtensive kinematics of the Magallanes–Fagnano fault zone. Similar basins have been found along this plate-boundary in the Magallanes Strait (Klepeis and Austin, 1997), in the Fagnano Lake and in the Argentine continental shelf (Lodolo et al., 2003). The Pacific character of the Pliocene foraminiferal assemblage from the Irigoyen basin suggests a direct connection between the Atlantic and Pacific oceans along the structural depression of the Magallanes–Fagnano fault system (Malumián and Olivero, 2005).

3.1.6. Cerro Colorado—Punta Gruesa

Early Eocene to Oligocene sequences out crop in this zone (Fig. 5; Olivero and Malumian, 1999; Ghiglione et al., 2002a). The presence of growth strata in the frontal limbs of the Campo del Medio and Irigoyen anticlines evidence lower to middle Eocene syntectonic sedimentation.

The northern limb of Campo del Medio anticline presents three unconformably bounded syntectonic sequences that show a decreasing dip up-section from ~57° to ~7° (Figs. 9 and 11b). An angular unconformity within the Lower Eocene sequences indicates the initial deformation of Campo del Medio anticline (Figs. 4 and 11b). The growth of the structure continued throughout the Middle Eocene as evidenced by angular and progressive unconformities within the Leticia Formation of upper Middle Eocene age (Figs. 4 and 12).

Sequential restoration methods and forward modelling applied to these growth strata demonstrate folding kinematics and geometry of the Campo del Medio anticline at various stages (Ghiglione et al., 2002a). The study revealed that the structure evolved akin to a faulted detachment fold (Mitra, 2002), involving a transition in deformational behavior from detachment folding with frontal limb rotation

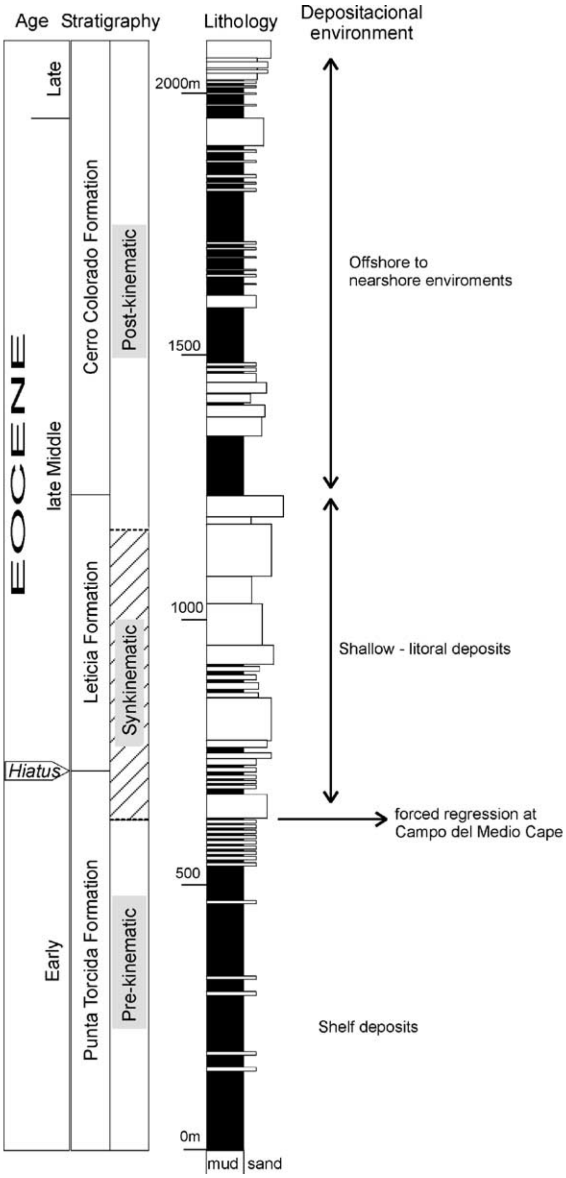

Fig. 12. Composite stratigraphic section of the Eocene formations from the northern domian showing lithological and environmental features and the kinematic stages (after Olivero and Malumian, 1999; Ghiglione et al., 2002a,b).

to fault propagation with increasing shortening (Fig. 13). The decollment in the first stage was the pelitic basal member of the Punta Torcida Formation while later the propagation thrust fault came from deep crustal levels, probably as a result of basement reactivations (Fig. 13). The northern limb of the Irigoyen anticline contains four angular-unconformably bounded sequences that show a decreasing dip upsection (Olivero and Malumian, 1999; Ghiglione et al., 2000). The first sequence includes the overturned boundary between the Punta Torcida Formation and the Leticia Formation (Fig. 9). The three angular unconformities are of upper middle Eocene age and show that deformation in Irigoyen anticline started later that in Campo del Medio anticline.

The Eocene sequences from the northern domain show an important sedimentary response to the onset of deformation (Fig. 12). The synkinematic sequences at Campo del Medio Cape are from a littoral setting, while the pelitic to heterolitic pre-kinematic units located beneath are mainly shelf deposits (Fig. 12; Olivero and Malumian, 1999). We interpret this abrupt change in the sedimentary environment as a forced regression that shows the relative sea-lowering and increased sedimentation produced for the initial uplift.

The SW trending Punta Gruesa and Castor thrusts located at Punta Gruesa are the last emergent faults (Fig. 9). The tectonic relations involving early Eocene to middle Miocene sequences in Punta Gruesa attest the Neogene fault activity in the region (Fig. 14). The Punta Gruesa thrust places lower Oligocene rocks over younger Oligocene–Miocene rocks from the Castor anticline. The Castor thrust places Oligocene–Miocene rocks on top of slightly younger mid-Lower Miocene rocks from the Austral basin foredeep depocenter. The tectonic relations between the different units show active faulting until at least the Lower Miocene (Fig. 14).

3.2. Lower Miocene foredeep

The mid-Lower Miocene rocks exposed along the Atlantic cliffs north of Punta Gruesa consist of very thick deep-water deposits covered by prograding deltaic successions wedging markedly northward (Ghiglione et al., 2002b). Sedimentation sources, from the south, southwest and west came from the previously uplifted Southern Andes toward the Atlantic Ocean (Galeazzi, 1998). The Miocene deposition was linked to strike-slip deformation, liquefaction and clastic dike intrusion (Ghiglione, 2002). Seismically induced liquefaction features are commonly encountered within the Lower Miocene marine deposits developed

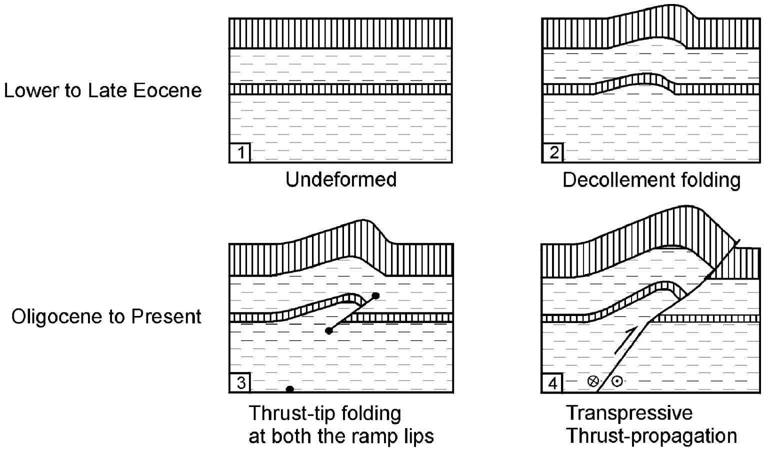

Fig. 13. Evolutionary model for thrust-related folds in Campo del Medio and Irigoyen anticlines. Modified from Ghiglione et al. (2002a).

from Punta Gruesa up to Viamonte Cape and probably beyond (Figs. 9 and 11c; Schmitt, 1991; Ghiglione, 2002). A seismically triggered origin for this sandstone intrusion has been proved using structural (Schmitt, 1991; Ghiglione, 2002) and sedimentological criteria (Ghiglione et al., 2002b). Principal strain deduced from the clastic dike orientations and their geometric relations with the structures between Punta Gruesa and San Pablo River, as well as in several other Miocene outcrops, define a left-lateral strike-slip system (Figs. 9 and 14; Schmitt, 1991; Ghiglione, 2002). The kinematics analysis of fault-slip data from this sequences also shows dominant strike-slip faulting with respect to thrusting (Figs. 9 and 14; Diraison, 1998; Diraison et al., 2000). This wrench kinematics is linked in space and time to the counterclockwise movement along the Magallanes–Fagnano fault system (Schmitt, 1991; Diraison et al., 2000; Ghiglione, 2002). Additional evidence for synorogenic deposition of the mid-Lower Eocene sequences is provided by a syntectonic angular unconformity observed 5 km north of Punta Gruesa (Figs. 4, 9 and 14). The presence of co-seismic sand intrusions and of a syntectonic intraformational unconformity, as well as the structural relations observed in the deformational front (Figs. 4 and 14), indicate the synorogenic deposition of the mid-Lower Miocene sequences.

The widespread distribution of Paleocene to Oligocene sedimentary deposits shows that the northern domain was a major depocenter during the Paleogene, with a maximum of sedimentary accommodation and sedimentation in the Lower to Middle Eocene (Figs. 2, 8 and 9). Tectonic load and subsidence shifted northward in the Neogene, and sedimentation was concentrated north of Punta Gruesa and in the Irigoyen pull-apart basin along the Magallanes–Fagnano fault zone (Figs. 3, 4 and 9).

4. Chronology of orogenic front propagation in Península Mitre

Fig. 4 summarizes regional patterns of thrust faulting, sedimentation, and erosion in the Fuegian fold-thrust belt of Península Mitre. The propagation of the deformation occurred in three main episodes: San Vicente thrusting, ca. 61–55 Ma, Río Bueno thrusting, ca. 49–34, and Punta Gruesa strike-slip event, ca. 24–16 Ma.

San Vicente thrusting constituted the onset of thrust propagation within foreland basin deposits following the basement uplift in the internal domain (Fig. 4). This thrust propagation event is marked by the angular unconformity between Danian and Paleocene deposits in the southern domain (Figs. 4 and 6). Additional evidence is provided by the presence of seismically triggered sand intrusions in the Malengueña anticline (Fig. 8), suggesting the proximity of the thrust-front, probably along the northeastern border of the southern domain.

The major orogenic front propagation took place during the Río Bueno thrusting through the central and northern domains, creating a progression of tec-

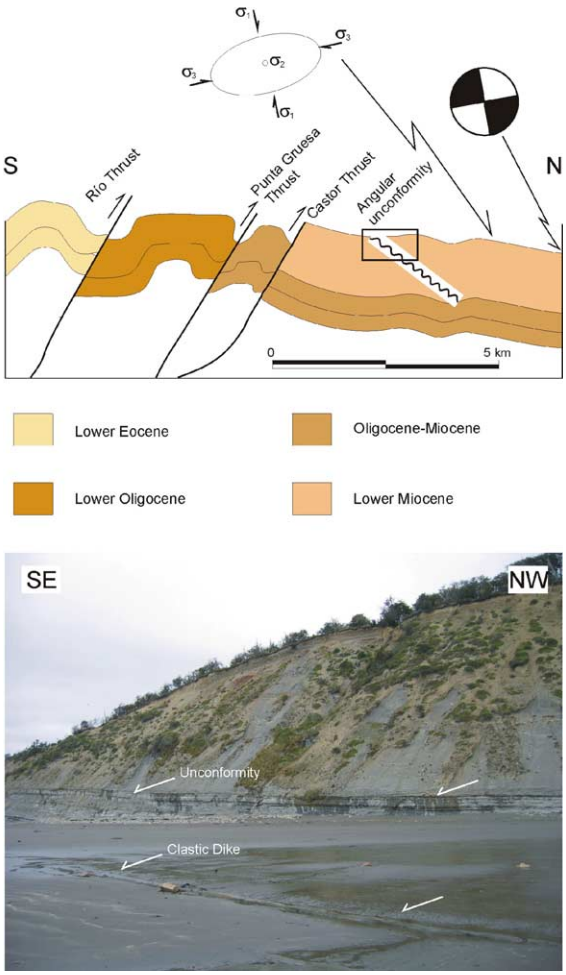

Fig. 14. Cross-section showing tectonic relations between Tertiary sequences at Punta Gruesa. Field photograph toward the south of the intraformational angular unconformity between Lower Miocene marine sequences (cliff is ~30 m). Stress ellipsoid is from Ghiglione (2002). Kinematic stereograms from fault fault-slip data are from Diraison (1998).

tonic-related unconformities (Fig. 4). The inception of Río Bueno thrusting is marked by syntectonic angular unconformities between the Lower and Middle Eocene rocks in the central domain (Figs. 4 and 7) and within the upper part of the Lower Eocene sequences in the northern domain (Figs. 4 and 9). This contractional episode continued up to the Late Eocene, as shown by syntectonic and progressive unconformities in middle and Late Eocene sequences (Figs. 4, 8 and 9). Rio Bueno thrusting produced the main phase of sedimentation recorded by the widespread distribution of Lower to Middle Eocene deposits.

Punta Gruesa strike-slip event is best defined in the orogenic front and in the contiguous foreland-basin foredeep (Fig. 4). The tectonic relations at Punta Gruesa provide clear evidence of post-mid-Lower Miocene faulting (Fig. 14). These data can be linked with the synorogenic deposition of the Lower Miocene sequences to suggest that faulting took place during the Lower Miocene. The strike-slip character of this deformation event is interpreted as related to the counterclockwise movement of the Magallanes–Fagnano fault system (Schmitt, 1991; Ghiglione, 2002).

The presence of several younger over older relations, and the tilting of all the pre-Miocene sequences indicate out of sequence thrusting and folding through the Oligocene and the Neogene (Figs. 3 and 4). Since the Middle Eocene the thrust-front migrated at most 5 km, from the Irigoyen Cape to Punta Gruesa (Figs. 4 and 9). This fact indicates the interruption of an evolutionary trend of continuous thrust-front advance since the Late Cretaceous. It is further consistent with the regional change from contractional to wrench deformation during the Oligocene. The kinematic analysis of fault-slip data from the Irigoyen thrust and in San Pablo River also shows dominant strike-slip faulting (Figs. 9 and 14; Diraison, 1998; Diraison et al., 2000). These data support the concept of the two-step evolution or faulted detachment fold for the propagation of folding in the northern sector (Figs. 9 and 13). The first stage (detachment folding) occurred during the Río Bueno thrusting, as mark by the presence of growth strata; the subsequent post-Eocene stage involving fault propagation occurred during the regional wrench kinematics (Figs. 9 and 14). Therefore, we interpret all the post-Early Oligocene folding and thrusting to be the result of strike-slip deformation.

5. Discussion: history of the Fuegian orogenic wedge in terms of the critical taper models

In order to explain the development of the Fuegian orogenic wedge, we adopted a symptomatic approach (DeCelles and Mitra, 1995) and the concept of propagation of deformational fronts (Gray and Mitra, 1999), with the assumption that the critical wedge theory (Chapple, 1978; Davis et al., 1983) governs the overall behavior of the orogen. Likewise, data on time–space distribution of faulting, erosion and sedimentation were used together with previously published data from the hinterland and foreland to qualitatively infer the state of the wedge (subcritical, critical or supercritical) through time.

Critical taper models share the same general concept that the fronts of orogenic wedges develop taper toward their undeformed forelands and propagate when the sum (θ) of their basal (β) and upper (α) slopes reaches a critical value (θ_c) (Chapple, 1978; Davis et al., 1983; Dahlen, 1984). When the wedge becomes subcritical ($\theta < \theta_c$), the active orogen contracts and the rear of the wedge undergoes internal deformation to recover the critical taper. When $\theta > \theta_c$, a critical (constant length) or supercritical (expanding length) wedge may deform by propagating toward the foreland, and deformation fronts can be expected to migrate forelandward (Gray and Mitra, 1999). All these phenomena may repeat cyclically throughout the growth of a single Coulomb wedge, as it cycles through periods of supercritical, critical and subcritical development (DeCelles and Mitra, 1995). The Fuegian Andes endured at least 3 cycles between subcritical, critical and supercritical stages.

5.1. First cycle (Late Cretaceous)

The Fuegian orogenic wedge underwent through critical to supercritical stages during the Late Cretaceous. The first cycle started with the closure of the Rocas Verdes marginal basin from ~100 to ~85 Ma (Halpern and Rex, 1972; Natland et al., 1974; Hervé et al., 1981). Subsequently, the uplift of the Rocas Verdes block during the lower Late Cretaceous (Dalziel et al., 1974; Nelson et al., 1980; Nelson, 1982; Ramos et al., 1986) was followed by a first episode of folding, thrusting, and rapid exhumation in Cordillera Darwin between 90 and 70 Ma with north vergent thrusting concentrated at lower structural levels (Fig. 4; Nelson et al., 1980; Nelson, 1982; Kohn et al., 1995). During its initial uplift, the Cordillera Darwin underwent extension distributed at relatively high structural levels (Kohn et al., 1995) probably triggered by gravitational instabilities typical of the supercritical stage. The uplift and thickening within the rear of the orogenic wedge was synchronous with fast subsidence and deposition of Andean-derived coarse clastic sediments in the early foreland basin (Winslow, 1982; Biddle et al., 1986; Olivero et al., 2003). The beginning of the Late Cretaceous deformational event is marked by an Albian–Cenomanian unconformity recognized in the subsurface (Biddle et al., 1986). Geochronological data from detrital zircons show that the age of the first clastic infill in the northern sector of the basin is not older than Turonian (92 ± 1 Ma) (Fildani et al., 2003), i.e. younger than previously reported (Katz, 1973; Natland et al., 1974; Wilson, 1991). This finding is in agreement with the ages of analogous coarse deposits reported as Coniacian–Campanian in the western part of Tierra del Fuego (Winslow, 1983; Alvarez-Marrón et al., 1993) and Campanian–Maastrichtian in the eastern part (Olivero et al., 2003). Therefore, the initial foreland stage of the Austral basin was synchronous with the uplift in the inner domain and not older, as previously inferred (Klepeis and Austin, 1997). The synorogenic deposition of the Coniacian–Maastrichtian sequences from Tierra del Fuego is suggested by the large-scale occurrence of seismically-induced clastic intrusions (Winslow, 1983; Schmitt, 1991; Diraison et al., 2000; this work). Towards the end of this compressional cycle, erosion caught up to the rate of uplift, and a regional Late Maastrichtian–Early Paleocene unconformity developed on top of the wedge (Caminos et al., 1981; Biddle et al., 1986; Alvarez-Marrón et al., 1993). The external wedge then stalled because its upper slope was no longer steep enough for critical taper and remained in a subcritical stage.

The onset of this compressional regime appears to be driven by an increase in the global production of oceanic crust and an accelerated opening of the South Atlantic Ocean, which increased the convergence rate between the South American plate and the Pacific Ocean lithosphere (Ramos et al., 1986; Ramos, 1988). The uncertainties in the Late Cretaceous reconstructions are so large that no definitive statement can be made about the relative motion of the Nazca and South American plates in the southern Andes (Pilger, 1983, 1984; Pardo-Casas and Molnar, 1987). However, we suggest that the structural features described for the Late Cretaceous in the Fuegian Andes (Cunningham, 1993, 1994, 1995; Klepeis, 1994a) are those of a transpressive orogen (e.g. Goscombe et al., 2003), and suggest the existence of oblique convergence. This fact can explain the strain partitioning along an orogen-parallel lithospheric wrench fault described by Cunningham (1993, 1995) in the Beagle Channel (BFZ in Figs 1 and 15A). Displacement along these trench-parallel faults is a direct confirmation of strain partitioning (Chemenda et al., 2000). The Beagle Channel, cratonward from the volcanic arc, was the axis of the Rocas Verdes marginal basin during the Early Cretaceous (Olivero and Martinioni, 2001) and was the weakness zone where the partitioning took place, generating an important transpressive zone (Fig. 15A). The frictional stress and resulting friction force necessary to induce the strain partitioning (Chemenda et al., 2000) progressively contributed to increase the compression of the overriding plate and eliminated the extension from the previous marginal basin extensional regime.

5.2. Second cycle (Paleocene–Lower Eocene)

The wedge started another critical to supercritical stage after the initiation of a second episode of basement exhumation at 60 Ma and propagated forward onto foreland basin deposits during the late Paleocene (Fig. 15B). Models of K–Ar release spectra show a complex P–T-t history between 60 and 40 Ma (temperatures of 325 and 200 °C, respectively), including rapid cooling at ~50 Ma between two slow cooling episodes (Kohn et al., 1995). During the episode of slow cooling from ~60 to 50 Ma, the basal decollement ramped upward and northward onto the foreland craton (Fig. 4). The southernmost Austral basin and the northern Cordillera Darwin experienced basement-involved contractional deformation during this pulse of exhumation (Klepeis and Austin, 1997). In Tierra del Fuego, the onset of thin-skinned thrusting onto the foreland basin deposits started in the Latest Cretaceous–Paleocene in the northern sector of the Austral basin (Winslow, 1982; Biddle et al., 1986; Wilson, 1991), the Maastrichtian–Danian in western Tierra del Fuego (Sierra de Apen; Martinioni et al., 1999; Ghiglione et al., 2002a) and in the Late Paleocene in Península Mitre (this work). An analogous angular unconformity is also recognized regionally between the Campanian–Maastrichtian and Late Paleocene–

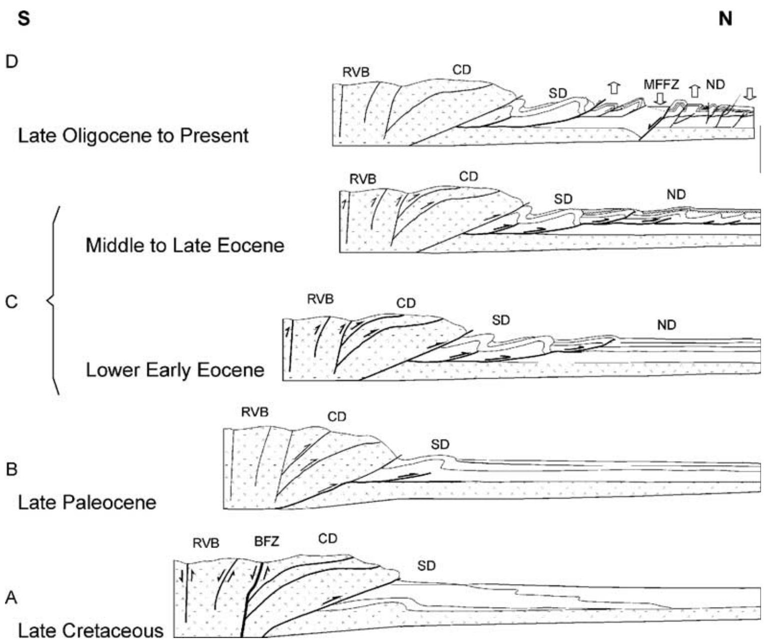

Fig. 15. Series of schematic, south–north cross-sections across the Fuegian Andes in five stages from Late Cretaceous to Present, illustrating the proposed history of orogenic wedge behavior. The asymmetric half-flower structure in the hinterland and its transpressional uplift is from Cunningham (1995). Abbreviations are BFZ: Beagle Channel fault zone; CD: Cordillera Darwin; MFFZ: Magallanes–Fagnano fault zone; ND: northern domain; RVB: Rocas Verdes basin; SD: southern domain. For explanation and further discussion, see text.

Eocene sediments (Caminos et al., 1981; Olivero and Malumian, 1999). Through the Early Eocene the wedge remained subcritical and deformation became confined to the inner part of the wedge, with continuous exhumation and cooling in Cordillera Darwin (Kohn et al., 1995). Sediments bypassed the orogenic wedge and accumulated within the realm of the adjacent foreland basin, as shown by widely distributed Paleocene to Early Eocene sequences (Biddle et al., 1986; Alvarez-Marrón et al., 1993).

5.3. Third cycle (Middle Eocene–Oligocene)

Following the rapid exhumation and cooling of Cordillera Darwin at ~50 Ma (Kohn et al., 1995), thrusting propagated rapidly forward from the inner part to the external part of the wedge (Fig. 15C). The major orogenic front propagation that accompanied the uplift of the hinterland started in the Lower Eocene and continued through the Middle and Late Eocene, as shown by the progression of syntectonic and progressive unconformities located in Península Mitre (Fig. 4). Equivalent angular unconformities are located at the base of Upper Eocene–Lower Oligocene fan delta conglomerates in the western sector of Tierra del Fuego (Biddle et al., 1986; Martinioni et al., 1999; Kraemer, 2003). The unconformities show that during this cycle of major thrust displacement, erosion caught up to the rate of uplift, and regional unconformities developed on top of the wedge (Fig. 15c). The external wedge then stalled because its upper slope was no longer steep enough for critical taper, and a drape of sediments (Lower Middle Eocene to Oligocene deposits) was deposited atop the wedge (Figs. 2, 8 and 9; Biddle et al., 1986; Olivero and Malumian, 1999; Ghiglione et al., 2002a) as taper was rebuilt by the continuous shortening and uplift of the rear of the wedge up to the Upper Middle Eocene (Nelson, 1982; Kohn et al., 1995).

There is clear evidence that since at least the Early Middle Eocene throughout the Oligocene the Nazca–Farallon plate has moved in a NE direction toward South America (Pilger, 1983, 1984; Pardo-Casas and Molnar, 1987). Particularly, the Middle Eocene was a period of rapid convergence (Pardo-Casas and Molnar, 1987), with a null east convergence component and a north component of 5 cm/y in the southern Andes (Somoza, in press). This period of rapid convergence and northward-directed subduction coincides precisely with the Río Bueno thrusting, synchronous with the rapid uplift of Cordillera Darwin at 50 Ma. It seems that the shift in the Farallon plate convergence direction and rapid convergence has produced an increasingly compressive component of relative motion along the plate boundary in the Fuegian Andes due to its E–W orientation (Ramos, 2005). The Eocene compression could also be connected with the approach and collision of the Farallón-Aluk plates spreading ridge against South America (Suarez et al., 2000; Ramos, 2005) that migrated from north to south reaching Tierra del Fuego by approximately 40–42 Ma (Cande and Leslie, 1986). However, although this collision produced an important episode of deformation in the Patagonian Andes in the Fuegian Andes the main compression started 8 Ma before the collision, during a period of fast convergence rate.

5.4. Neogene deformation

Propagation of the Fuegian wedge apparently stopped after the Río Bueno thrusting (Fig. 4). Although there is clear evidence of Neogene deformation in Tierra del Fuego (Diraison et al., 1997; 2000; Kraemer, 2003) we consider that it is wrench-related and not associated with the initial contractional history of the fold-thrust belt (Fig. 15D). A kinematic analysis of fault-slip data from Diraison et al. (2000) reveals that in the Fuegian foothills wrenching is the major component of deformation and thrusting is the minor component. The age of this strike-slip event is best defined north of Punta Gruesa (Fig. 9) from tectonic relations, fault-slip data, and sedimentological criteria (Fig. 14). In the Andes of western Tierra del Fuego, Late Tertiary contractions were overprinted by left-lateral transtensional deformation since the Oligocene (Klepeis, 1994b; Klepeis and Austin, 1997). The slow rates of basement exhumation to the rear of the wedge during the Neogene are due to post-tectonic uplift (Fig. 4; Nelson, 1982; Kohn et al., 1995) and suggest that Neogene strike-slip deformation was concentrated along the Magallanes–Fagnano fault zone and the adjacent foothills. The partition zone migrated northward from its position during the Late Cretaceous to the Magallanes–Fagnano fault zone (Cunningham, 1995).

6. Conclusions

The Fuegian Andes propagated continuously from the Late Cretaceous up to the Middle–Late Eocene. Cratonward migration of the fold-thrust belt and foreland basin depocenters appears to have been continuous during Paleogene times. The propagation of the deformational front occurred in two main episodes: San Vicente thrusting, ca. 61–55 Ma, and Río Bueno thrusting, ca. 49–34 Ma. The major northward jump of the fold-thrust belt occurred during Río Bueno thrusting in the Early–Middle Eocene, as indicated by a progression of tectonic unconformities. Río Bueno thrusting induced a phase of high sedimentation and maximum sedimentary accommodation in the Austral basin. Afterward, the deformational front remained in a stationary position, coinciding with a regional change from contractional to strike-slip deformation. Therefore, all post-Late Eocene thrusting and folding, including Punta Gruesa faulting (ca. 24–16 Ma) and the Miocene?–Pliocene Irigoyen basin are interpreted to be related to regional wrench kinematics.

The evolution of the Fuegian Andes cycled between subcritical, critical and supercritical stages. The earliest orogenic stage in the Late Cretaceous involved prograde metamorphism, uplift and development of topography within the rear of the orogenic wedge, in the Rocas Verdes block and the Cordillera Darwin. The structural features described for the Late Cretaceous in the Fuegian Andes are those of a transpressive orogen due to oblique convergence. Following the beginning of a second pulse of rapid exhumation in the hinterland at ~60 Ma, the basement basal decollement ramped upward and northward into weak Cretaceous and Paleocene shales. Afterward, critical taper was maintained by the offsetting effects of basement uplift in the rear of the wedge and forward imbrication at the front of the wedge. The fast orogenic front propagation and rapid basement uplift during the Early to Middle Eocene coincides precisely with a shift in the Farallon plate convergence direction toward the north and an increase in its convergence rate. This sustains the hypothesis that the increasingly compressive component of relative motion along the plate boundary in the Fuegian Andes during this period was due to its E–W orientation.

Acknowledgments

This work has been carried out by the financial support of the Agencia Nacional de Promoción Científica y Tecnológica with grant PICT 14144/03 awarded to V.A. Ramos and a Doctoral grant from Consejo Superior de Investigaciones Científicas (CONICET) awarded to M.C. Ghiglione. We want to express our gratitude to N. Malumián and E.B. Olivero for providing unpublished data and for fruitful discussion. We are thankful to Julie Brodeur and Matthew Robson for the correction of the manuscript. We are grateful to the Editor Jean-Pierre Burg and two anonymous reviewers for their suggestions, which have allowed a considerable improvement of the paper.

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