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Structure and tectonic evolution of the Fuegian Andes (southernmost South America) in the framework of the Scotia Arc development

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ABSTRACT

The major structural and tectonic features of the Fuegian Andes provide an outstanding onshore geological framework that aids in the understanding of the tectonic evolution of the Scotia Arc, mainly known from offshore studies. The orogenic history of the Fuegian Andes (Late Cretaceous–Miocene) is thus compared and integrated with the tectonic history of the Scotia Sea. Late Cretaceous–Paleocene structures in the Fuegian Andes suggest a N-directed contraction consistent with an oroclinal bending of the southernmost South America–Antarctic Peninsula continental bridge. This N-directed contraction in the Fuegian Andes continued during the spreading of the West Scotia Ridge, between 40–50 and 10 Ma ago. The onset of major strike-slip faulting in Tierra del Fuego is considered here to be not older than the late Miocene, consistent with the recent history of the North Scotia Ridge; thus forming part of a tectonic regime superposed to the prior contraction in the Fuegian Andes.

1. Introduction

The Scotia Arc is a major morpho-tectonic feature comprising important subaereal mountain belts, like the southernmost Andes and the Antarctic Peninsula. Most of its extension, however, is composed of long submarine ridges and banks with local emergent islands surrounding the Scotia Sea (Fig. 1). The arc is formed by the North Scotia Ridge to the north, by the South Scotia Ridge to the south, by the Shackleton Fracture Zone and Antarctic Plate to the west, and by the South Sandwich Trench to the east (Fig. 1). The Scotia Sea contains several spreading ridges that, since the Oligocene, led to the opening of Drake Passage (Barker, 2001; Eagles et al., 2005; Livermore et al., 2005; Galindo-Zaldívar et al., 2006; Bohoyo et al., 2007).

Tierra del Fuego represents one of the largest segments of the Scotia Arc where onshore geological studies have provided a valuable means for understanding its tectonic history. The archipelago of Tierra del Fuego is located at the northwestern corner of the Scotia Arc and comprises the southernmost segment of the Andean Cordillera known as Fuegian Andes (Fig. 1). The Fuegian Andes have a very complex tectonic history, the last part of it linked to the Scotia Arc evolution, which has characterized geological features that are significantly different from the rest of the southern Andes.

The aim of this contribution is to integrate the tectonic history of the Fuegian Andes, based on more than 20 years of research in Argentine Tierra del Fuego, with the evolution of the Scotia Arc. We put forward the most recent results on tectonic research from this portion of the Andes and discuss contrasting models of orogenic evolution, placing an important constraint on the tectonic puzzle of the Scotia Arc.

2. Regional setting

The Fuegian Andes are a mountain belt extending with a WNW–ESE regional trend from the Magellan Strait to Staten Island (Fig. 2). The highest peaks, above 2400 m, are located at the culmination formed by the Darwin Cordillera. The axis of the Fuegian Andes runs along this culmination and through the southern part of the main island (Isla Grande) of Tierra del Fuego; the northern slope is characterized by low foothills, whereas the southern portion is transected by many channels and fjords which form a myriad of smaller islands.

This portion of the Andes connects eastwards with submerged continental blocks that form part of the North Scotia Ridge, extending up to South Georgia (Fig. 1). To the south, the Drake Passage separates it from the northern part of the Antarctic Peninsula and other partially submerged continental blocks that form the South Scotia Ridge. The

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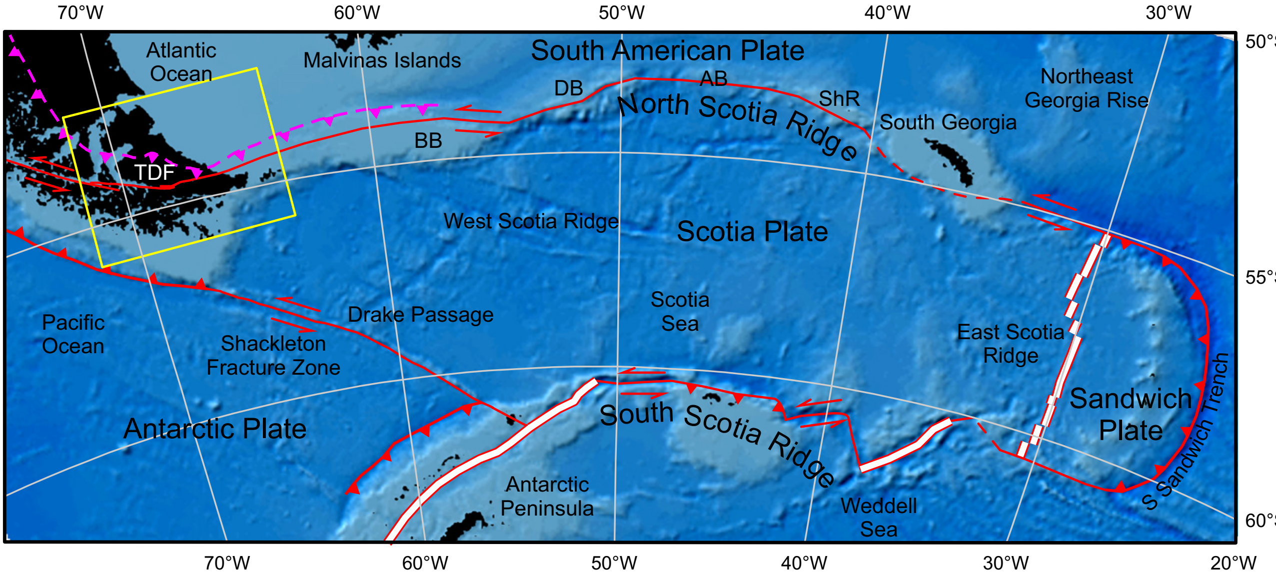

Fig. 1. Regional situation and main physiographic and tectonic features of the Scotia Arc. Red solid lines are present tectonic plate boundaries (cf. Bohoyo et al., 2007; Dalziel et al., 2013a): arrows indicate movement in transform segments, barbed lines indicate convergent margins with triangles on the upper plate. White bold lines are active spreading ridges. Barbed dashed pink line represents the Andean deformation front in southern South America. Bathymetry from Smith and Sandwell (1997); light blue colors define continental blocks. TDF: Tierra del Fuego, BB: Burdwood Bank, DB: Davis Bank, AB: Aurora Bank; ShR: Shag Rocks.

North Scotia Ridge comprises the active transform boundary between the Scotia and South American plates, which is constituted by a diffuse, and very complex fault zone cutting through continental blocks such as Tierra del Fuego, Burdwood Bank, Davis Bank, Shag Rocks and South Georgia (e.g. Klepeis, 1994b; Barker, 2001; Lodolo et al., 2003; Smalley et al., 2003; Dalziel et al., 2013a) (Fig. 1). The South Scotia Ridge also comprises the transform boundary between the Scotia and Antarctica plates developing restraining and releasing structures that cut across

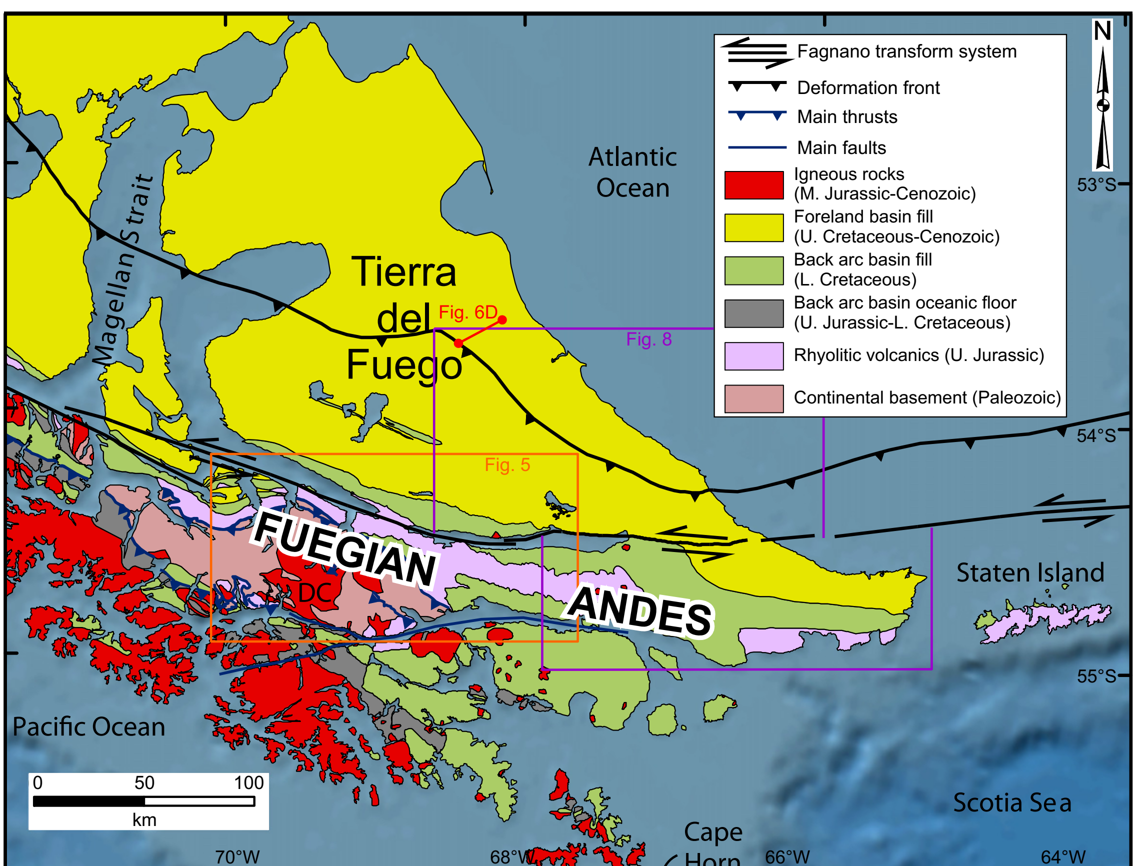

Fig. 2. Main geologic features of Tierra del Fuego, based on SERNAGEOMIN (2003), Olivero and Malumián (2008) and Klepeis et al. (2010). Background bathymetry from Smith and Sandwell (1997). DC: Darwin Cordillera.

continental blocks (Galindo-Zaldívar et al., 2002; Bohoyo et al., 2007). Together with the Shackleton Fracture Zone the North and South Scotia Ridges accommodate most of the present day deformation in the region (Fig. 1).

3. Tectonic evolution of the Fuegian Andes

3.1. Late Cretaceous closure of the Rocas Verdes basin and initial buildup of the Fuegian Andes

The formation of the Fuegian Andes started during closure of the Rocas Verdes back arc basin in the Late Cretaceous (Dalziel, 1981; Klepeis et al., 2010). Prior to this event, Late Jurassic continental stretching led to a volcano-tectonic rift associated with widespread acidic volcanism in the SW margin of Gondwana (Wilson, 1991; Calderón et al., 2007). Acidic volcanic and volcaniclastic rocks now preserved along the Fuegian Andes (Lemaire or Tobifera Formation), which unconformably rest on the Paleozoic continental basement, represent the early fill of that volcano-tectonic rift (Hanson and Wilson, 1991; Calderón et al., 2007) (Fig. 3A). From the Late Jurassic to Early Cretaceous, continued stretching caused the creation of oceanic floor in the Rocas Verdes basin (Mukasa and Dalziel, 1996; Calderón et al., 2007), which was filled mostly by Early Cretaceous marginal marine to arc-derived flysch sequences, such as the Yahgan, Beauvoir, Zapata, Erezcano, and Hardy formations, among others (Olivero and Martinioni, 2001; Fildani and Hessler, 2005) (Fig. 3A).

During Aptian–Albian times (cf. Olivero and Martinioni, 2001; Barbeau et al., 2009a), therefore, the Rocas Verdes basin was already a back arc basin extending from the Southern Patagonian Andes to South Georgia, considering the latter in a position just eastwards of the Fuegian Andes (Dalziel et al., 1975, 2013a; Carter et al., 2014). At this time, the Antarctic Peninsula and southern South America were still connected forming a continuous continental belt, according to paleogeographic reconstructions (Barker, 2001; Dalziel et al., 2013a). During the beginning of the Late Cretaceous, the Rocas Verdes basin closed in response to increased spreading rates in the South Atlantic ridge and the consequent rapid westward shift of South America relative to Africa (Dalziel, 1986).

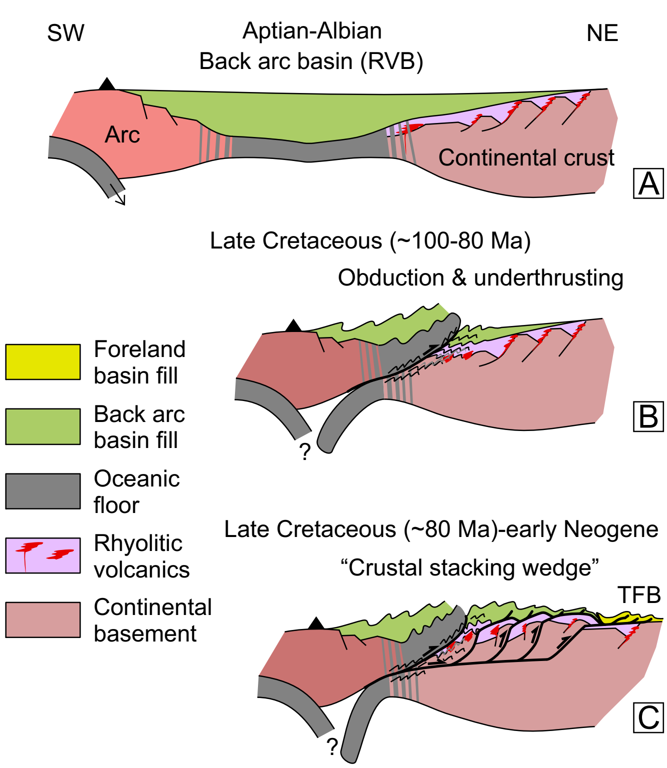

Fig. 3. Schematic cross-sections depicting the closure of the Rocas Verdes back arc basin (RVB) and formation of the Fuegian Andes orogenic wedge.

Basin closure started with obduction of the oceanic floor and underthrusting of the South American cratonic margin (Nelson et al., 1980; Klepeis et al., 2010). This process culminated with collision of the N–NE continental margin with the magmatic arc that rimmed the back arc basin at its Pacific side (Nelson et al., 1980; Dalziel and Brown, 1989; Cunningham, 1995; Klepeis et al., 2010) (Fig. 3B). This stage of early orogenic development is constrained by granitic rocks belonging to the Beagle Suite (Hervé et al., 1984; Mukasa and Dalziel, 1996), which post-date the obduction-related structures (Klepeis et al., 2010). These granitoids have zircon U/Pb crystallization ages spanning between ~86 and ~74 Ma (Klepeis et al., 2010).

The most notable structures related to this initial buildup of the Fuegian Andes are exposed in Darwin Cordillera (Fig. 2), where high-grade (upper amphibolite facies) metamorphic rocks (Nelson et al., 1980; Kohn et al., 1993) reflect the prograde metamorphism of mid-crustal rocks during the initial closure and obduction of the Rocas Verdes basin (Nelson et al., 1980; Klepeis et al., 2010). These rocks, which include the back arc Paleozoic continental basement, Middle–Upper Jurassic intrusives (granite and orthogneiss), Upper Jurassic volcanics of the Lemaire (Tobifera) Formation, and mafic dikes intruded during formation of the back arc oceanic floor, are affected by N- and NE-vergent (present day orientation) folds and ductile thrusts that formed the lower part of a mid-crustal shear zone associated with obduction and southward underthrusting of the continental margin (Nelson et al., 1980; Klepeis et al., 2010). In Argentine Tierra del Fuego and South Georgia, the Jurassic volcanics and Early Cretaceous back arc basin sedimentary fill are deformed under low-grade metamorphism (greenschist or lower facies) and also reflect and early stage of deformation possibly caused by significant, foreland directed simple shear during the obduction–underthrusting stage (Bruhn, 1979; Dalziel and Palmer, 1979; Tanner and Macdonald, 1982; Storey, 1983; Torres Carbonell and Dimieri, 2013) (Fig. 4A–D).

Both in the higher grade metamorphic rocks of Cordillera Darwin and in the greenschists of Argentine Tierra del Fuego and South Georgia, a main tectonic foliation dipping S and SW is recognized. It is mainly formed by flattened crystals, oriented phyllosilicates, and pressure-solution seams, and varies from continuous to disjunctive depending on the metamorphic degree. When present, stretching lineations dip mostly to the S and SW. Close to higher strain zones, such as ductile thrusts, a second crenulation foliation may be found, verging either to the N–NE (for thrusts) or S–SW (for backthrusts) (Dalziel and Palmer, 1979; Tanner and Macdonald, 1982; Klepeis et al., 2010; Torres Carbonell and Dimieri, 2013).

3.2. Latest Cretaceous to Neogene contraction in the Fuegian Andes

After collision and closure of the back arc basin, continued contraction produced large scale thrusting of the continental margin, forming a duplex that stacked the Paleozoic continental basement and the Lemaire Formation (Klepeis et al., 2010; Torres Carbonell and Dimieri, 2013). The duplex's floor thrust detached the upper part of the continental crust, and was probably connected to the shear zone that accommodated the underthrusting of the South American cratonic margin during the Rocas Verdes basin closure (Klepeis et al., 2010) (Fig. 3C). The roof thrust was located near the contact between the Lemaire Formation and the Cretaceous back arc basin sedimentary fill, which was identified as a shear zone with top-to-NE slip in several places along the Fuegian Andes (Klepeis, 1994a; Torres Carbonell and Dimieri, 2013) (Figs. 4E–F and 5).

This mechanism of orogenic growth due to crustal stacking explains the transference of significant shortening to the Fuegian thrust-fold belt

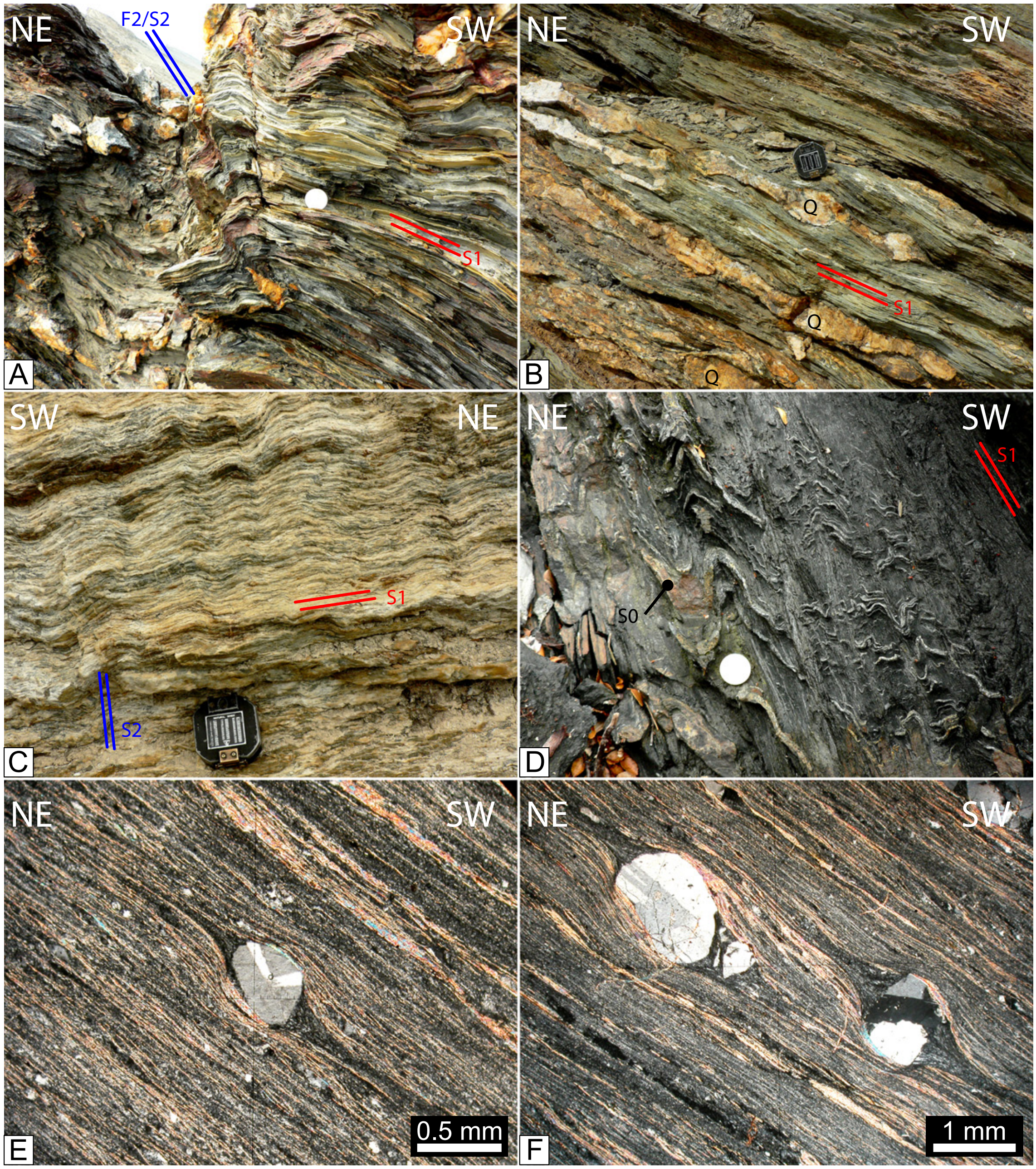

Fig. 4. Outcrop examples of the structures associated to deformation during closure of the Rocas Verdes basin and growth of the Fuegian Andes. All sites located in Fig. 5. A. Metapelites (phyllites) of the continental basement revealing a SW-dipping tectonic foliation (S1) formed by pressure-solution and flattened porphyroclasts, which has been affected by a subsequent generation of NE-vergent folds and associated crenulation foliation (F2/S2). B. The same phyllites with foliation-parallel, boudinaged, quartz veins (Q). Delta structures in the boudin necks reveal subsequent top-to-NE shearing of the boudinaged vein. C. Crenulated tectonic foliation in Upper Jurassic metavolcanic rocks (Lemaire Formation). D. First-generation folds and associated pressure-solution foliation in stratified (S0) metapelites of the Lemaire Formation. E–F. Mylonite located near the contact between the Lemaire and Yahgan Formations with sigma and s-c structures that indicate top-to-NE shearing.

(TFB) since the Late Cretaceous to the early Neogene (Torres Carbonell and Dimieri, 2013). According to this model, the duplex's roof thrust formed the main detachment of the TFB, which exhibits a staircase thrust geometry shallowing towards the foreland (Rojas and Mpodozis, 2006; Torres Carbonell et al., 2011) (Fig. 3C).

Early deformation in the internal TFB affected the oldest sedimentary fill of the Austral (Magallanes) foreland basin, which mostly includes fine-grained sedimentary rocks that span in age from the Campanian to the Danian (Olivero et al., 2009; McAtamney et al., 2011; Martinioni et al., 2013). These rocks were progressively deformed in low to very-low grade metamorphic conditions, through a sequence of layer-parallel shortening, folding and thrusting that led to construction of the initial thin-skinned thrust wedge in front of the crustal stack. This happened not later than the Danian, and at relatively shallow depths in the upper crust (Torres Carbonell and Dimieri, 2013; Torres Carbonell et al., 2013a) (Figs. 6A–C and 7).

A notable feature of this initial thrust wedge is that it reveals superposed tectonic pressure-solution foliations that record at least two contractional stages during the Late Cretaceous–Danian deformation (Torres Carbonell et al., 2013a). The pattern of orientations of these

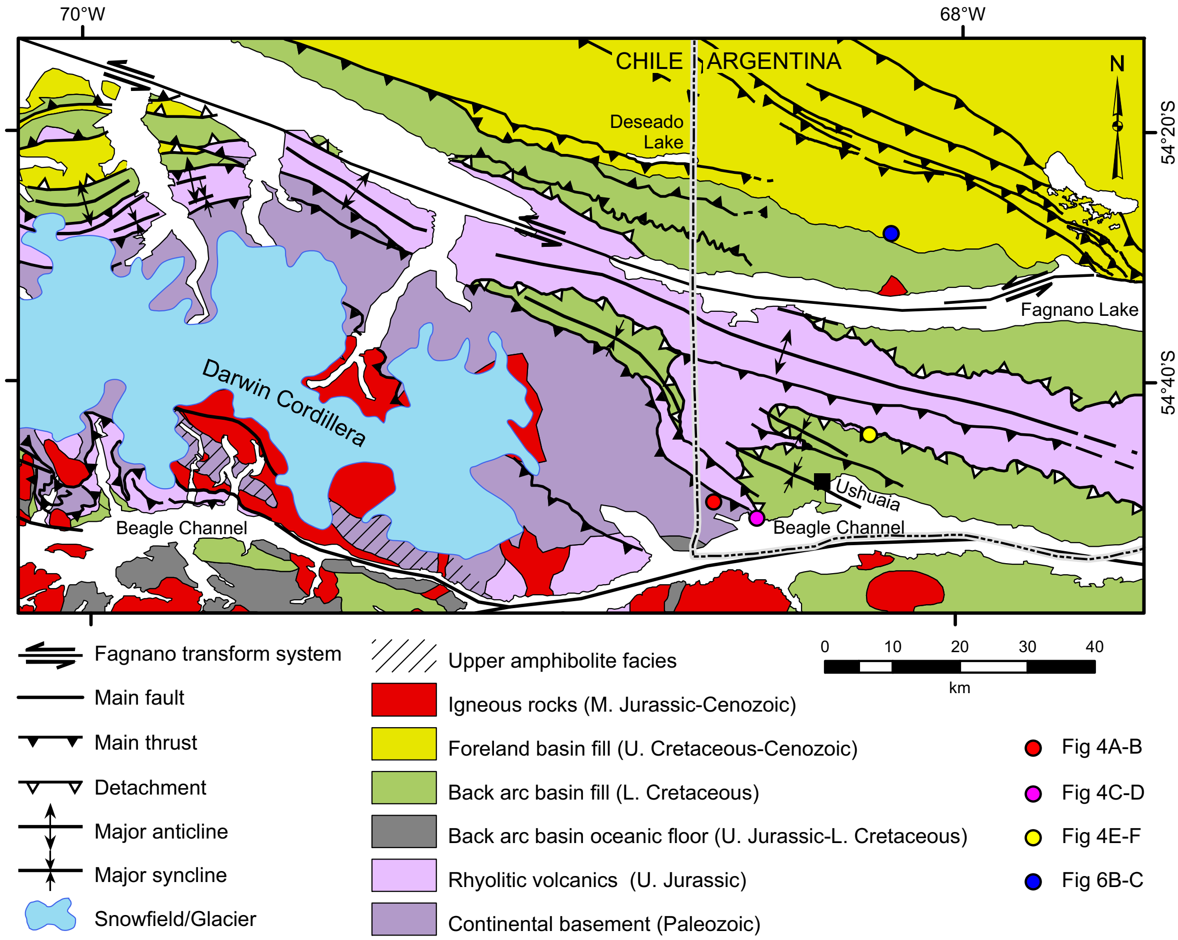

Fig. 5. Main geologic and structural features of the most studied region of the Fuegian Andes. Location in Fig. 2. Geology of Chile modified from Nelson et al. (1980), SERNAGEOMIN (2003), Klepeis et al. (2010), and geology of Argentina modified from Olivero and Malumián (2008) and Torres Carbonell and Dimieri (2013).

foliations along the Fuegian Andes mountain front reveals, in addition, the early formation of a concave-to-the-north map-view curve in the TFB, called Peninsula Mitre recess (Fig. 8). Current structural data indicate a very probable N–S oriented regional maximum compressive direction for this structural feature (Torres Carbonell et al., 2013a).

The age of the early TFB is constrained by the unconformity below Selandian–Thanetian (~62 Ma) conglomerates of the Austral basin, which bear detrital zircons and an overall composition indicating an episode of uplift and exhumation of the central belt during or before the Danian (Martinioni et al., 1999; Olivero et al., 2003; Barbeau et al., 2009b). This is consistent with the lack of penetrative tectonic foliations in beds younger than the Danian, which suggests that the foliations in Late Cretaceous to Danian strata were formed during the same episode that caused uplift of the central belt (Torres Carbonell et al., 2013a). Uplift in the central belt is well constrained by Ar^{40}/Ar^{39} geochronology and closing-temperature relationships of metamorphic rocks from Cordillera Darwin, which reveal a first rapid cooling episode between 90 and 70 Ma (Kohn et al., 1995).

After the initial construction of the thrust wedge, deformation continued from the Ypresian to the early Miocene (~56 to ~20–16 Ma), and was coeval with sedimentation in the foreland basin (Malumián and Olivero, 2006; Olivero and Malumián, 2008). At least six contractional stages involving deformation of syntectonic successions deposited above and in front of the TFB accommodated circa 45 km shortening in easternmost Tierra del Fuego (Torres Carbonell et al., 2008a, 2009, 2011; Torres Carbonell and Dimieri, 2013) (Fig. 9). Deformation in the external TFB was mostly located above a detachment in Paleocene horizons, and was distributed during two episodes of forward propagation of the thrust wedge when it attained a shape compatible with critical Coulomb wedge behavior; separated by an episode of internal wedge growth, comparable to a subcritical Coulomb wedge behavior (Torres Carbonell et al., 2011) (Fig. 9).

The last stage of deformation in the TFB is recorded by syntectonic angular and progressive unconformities in lower to middle? Miocene beds. These features are well revealed in seismic sections (Ghiglione et al., 2010; Torres Carbonell et al., 2013b) (Fig. 6D) and also interpreted from surface outcrops at the Atlantic coast of Tierra del Fuego (Ghiglione, 2002; Ponce et al., 2008; Torres Carbonell et al., 2008a). This means that, according to the interpreted mechanism of shortening transference to the foreland (Torres Carbonell and Dimieri, 2013), the crustal stack continued to grow until the early Miocene (Fig. 7).

3.3. Peninsula Mitre recess: insights into regional paleostress and shortening orientations

The formation of the Peninsula Mitre recess was enhanced during the Paleogene–early Neogene stages of TFB propagation. It was proposed that the remarkable basement promontory (the Rio Chico Arch) that formed the NE margin of the Rocas Verdes basin caused a buttressing effect on the TFB propagation (Torres Carbonell et al., 2013b) (Fig. 8). This major feature, formed during the Late Jurassic rifting stage (Biddle et al., 1986; Yrigoyen, 1989), has a subsurface architecture that is well constrained at its flanks from seismic sections and well data (Robbiano et al., 1996; Galeazzi, 1998). It has a N–S strike, and its southern border

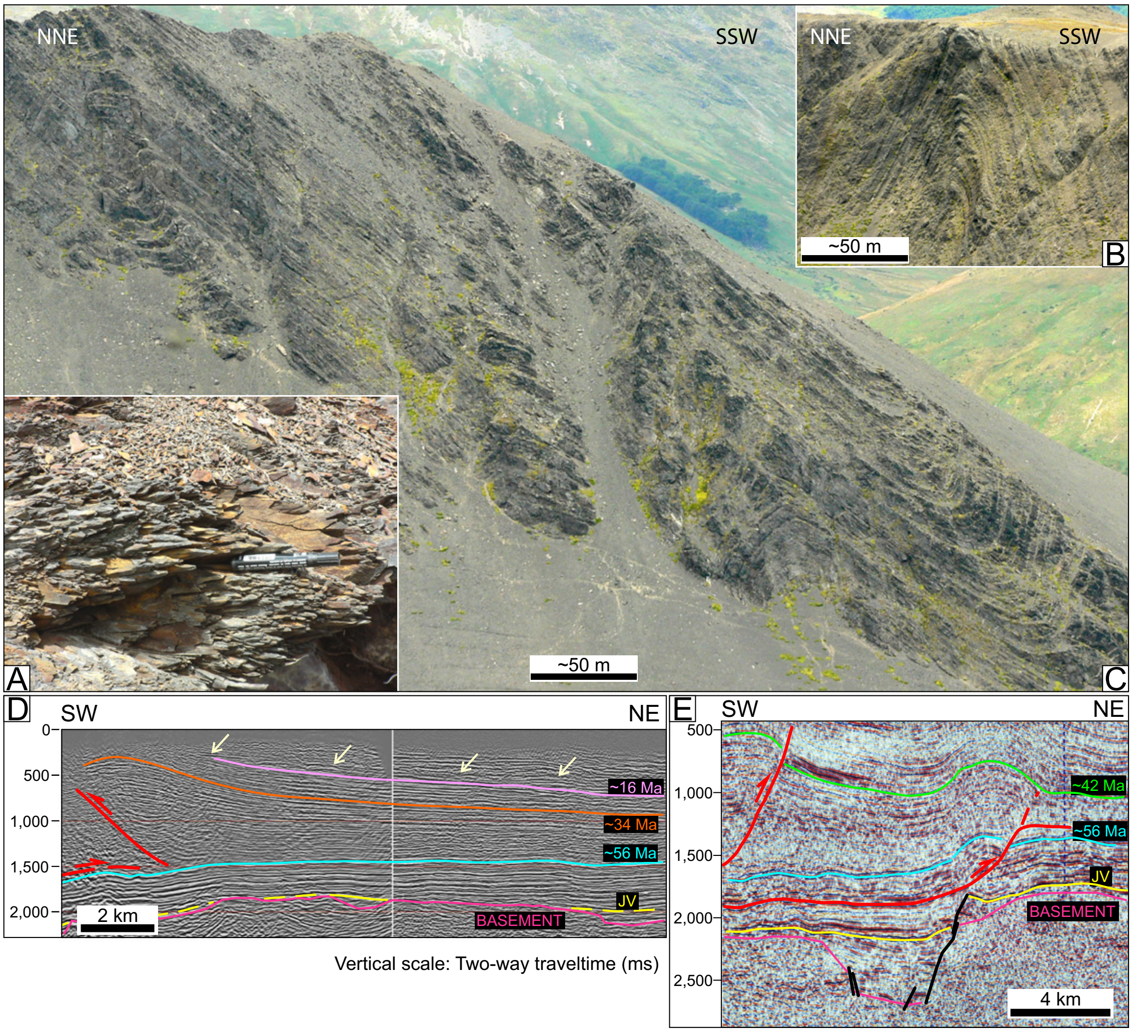

Fig. 6. Examples of deformation styles of the foreland basin fill in the Fuegian thrust-fold belt. A–C. Structures formed in the initial, Late Cretaceous–Danian thrust wedge (located in Fig. 5): intersection pencil structures in Campanian–Maastrichtian slates (A), NNE-vergent, asymmetric folds in Turonian slates (B–C). D–E. Seismic reflection sections of the thrust-fold belt front (located in Figs. 2 and 8), showing (D) the progressive unconformity above early Neogene strata that marks fossilization of the thrust front (arrows), and (E) the influence of basement topography (normal fault) on the location of the leading thrust. JV: Jurassic rhyolitic volcanics. Both sections modified from Torres Carbonell et al. (2013b).

(roughly following the ~3 km structural contour) approximately coincides with the TFB front in the western part of Tierra del Fuego (Fig. 8). In this latter location, the irregular basement topography is punctuated by Late Jurassic–Early Cretaceous normal faults that produce the deepening of the basement top surface toward the SW. These fault steps influence the location of the leading edge structures of the TFB (Torres Carbonell et al., 2013b) (Fig. 6E).

In addition, the strain in the frontal part of the TFB significantly increases from western Tierra del Fuego to the Atlantic coast, where the apex of the Peninsula Mitre recess is located (Fig. 8). This latter location, which reveals very complex structures and a higher local shortening (Torres Carbonell et al., 2013b) coincides with the longitudinal position of the southernmost edge of the Rio Chico Arch. These features support the inference of a buttressing effect exerted by the Rio Chico Arch on the advancing TFB during the Paleogene–early Neogene, as the main cause of the Peninsula Mitre recess (Torres Carbonell et al., 2013b).

In order to explain the map-view curve, especially its eastern flank, it is necessary to reassess the paleostress data obtained to date in Tierra del Fuego. Unfortunately, the only data of this nature comes from outcrops located at the western part of the Peninsula Mitre recess. Fault slip analyses given by Diraison et al. (2000) indicate SW–NE maximum horizontal shortening direction for that portion of the TFB, with a rotation to N–S directions in the easternmost measurement sites (Fig. 10), which coincide with the apex of the Peninsula Mitre recess where structural trends are E–W (Torres Carbonell et al., 2008a). Although these data do not consider the possibility of different faulting phases (all faults measured are assumed to correspond to a single deformation phase), and the method does not give information on the shape of the paleostress tensor (R factor), they consistently indicate a shortening which is near-perpendicular to the structural trends in each site.

A similar result can be obtained from the analysis of orientations of clastic dikes intruded in the Desdemona Formation (Chattian–Aquitanian?) (Malumián and Olivero, 2006) at the apex of the Peninsula Mitre recess, in the leading edge of the TFB (Punta Gruesa area, Fig. 10). These dikes were interpreted as syntectonic by Ghiglione (2002). The Desdemona Formation comprises the youngest progressive unconformity exposed in the Atlantic coast (Ghiglione, 2002; Ponce et al., 2008; Torres Carbonell et al., 2013b). The clastic dikes intruding the Desdemona Formation are subvertical and oriented between N150° and N180°, with a mode of N175° (Ghiglione, 2002). The paleostresses interpreted by Ghiglione (2002) indicate a horizontal N–S oriented maximum principal stress (σ1), a vertical intermediate principal stress (σ2), and a horizontal E–W minimum principal stress (σ3). Since the paleostress analysis is

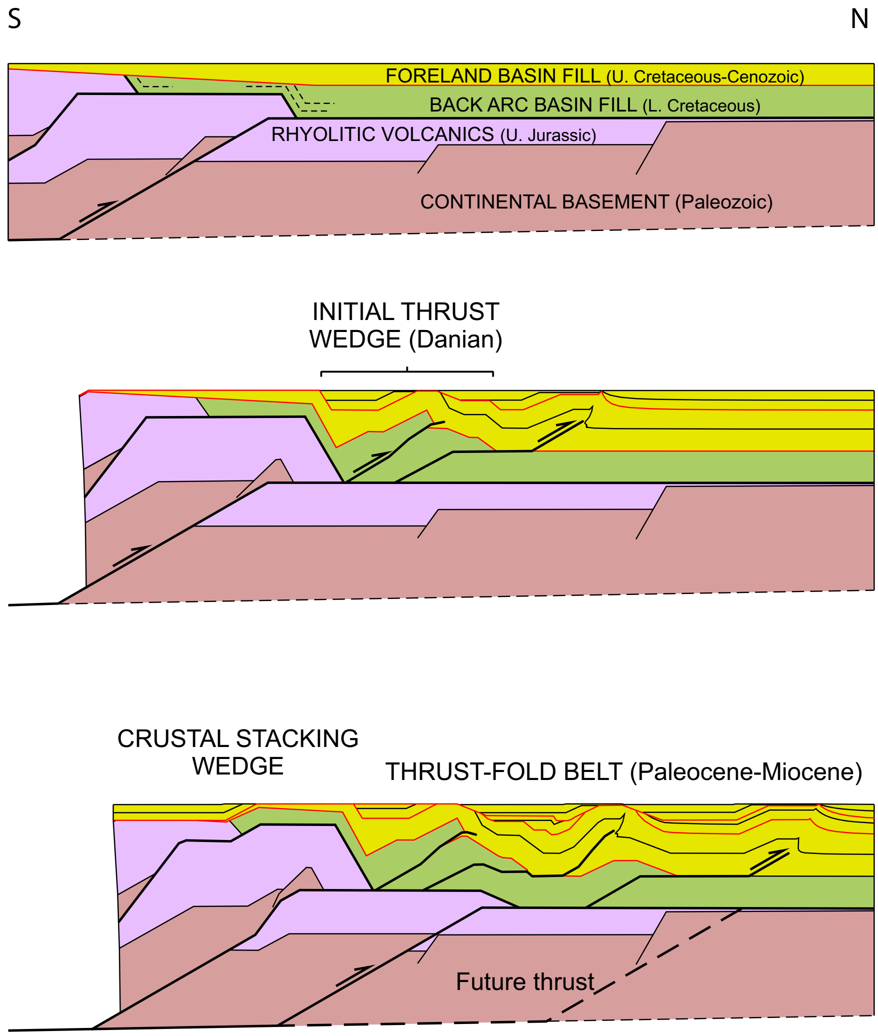

Fig. 7. Schematic, area-balanced model (developed with Pliegues 2D software from E. Cristallini) depicting the proposed evolution of a crustal stack that transfers shortening to the thin-skinned thrust-fold belt.

qualitative, the ratio between the principal axes of the paleostress tensor was not calculated; however, the differential stress should be small enough to form extensional rather than shear fractures (Twiss and Moores, 2007). Regardless of contrasting interpretations discussed later in this paper, a horizontal maximum compressive direction oriented NNW–SSE is obtained from the analysis of Ghiglione (2002) (Fig. 10).

3.4. Late Neogene strike-slip faulting

Following the end of contractional deformation, the Fuegian Andes were involved in the inception of a strike-slip faulting regime associated with the development of the Fagnano (Magallanes) transform system in Tierra del Fuego, which is a seismogenic fault zone that runs along the western part of the North Scotia Ridge (Lodolo et al., 2003) (Figs. 1 and 2). This system produced a left-lateral offset of c. 50 km to the foreland TFB (Torres Carbonell et al., 2008b) (Fig. 8). Although a dip-slip (mainly normal) component of displacement has been documented for some segments of the fault zone, the vertical separations are below 3 km, which is an amount significantly lower than the tens of kilometers reported for the left-lateral separation (Klepeis, 1994b; Torres Carbonell et al., 2008b). Extrapolation of that offset considering geodetic slip rates of 6.6 ± 1.3 mm a^{-1} to 4.4 ± 0.6 mm a^{-1} in Tierra del Fuego (Smalley et al., 2003; Mendoza et al., 2011) suggests an age of ~7 to ~11 Ma (late Miocene) for inception of strike-slip faulting.

The structures associated to the Fagnano transform system are aligned along a ~10 km wide, roughly E–W striking deformation zone. The fault zone is denoted by photo-lineaments, as well as scarps and en-echelon surface ruptures (Lodolo et al., 2003; Costa et al., 2006; Torres Carbonell et al., 2011). The effect of this fault zone on Tertiary and older rocks is rarely exposed due to the widespread Quaternary cover in Tierra del Fuego. Some outcrops such as in the Atlantic coast (Torres Carbonell et al., 2011), at Lago Deseado, and at the western end of Lago Fagnano (Klepeis, 1994b) reveal several strike-slip and oblique faults, many of which are consistent with the left-lateral kinematics of the Fagnano transform system. In all these cases, strike-slip faults post-date the contractional structures of the TFB (Klepeis, 1994b; Torres Carbonell et al., 2008b, 2011).

4. Discussion: coeval tectonic evolution in the Scotia Arc region

4.1. Late Cretaceous–Paleocene

An attempt to correlate the tectonic history of the Fuegian Andes with the coeval tectonic evolution of the Scotia Arc is possible, but this exercise has to deal with increasing uncertainties for older times. We

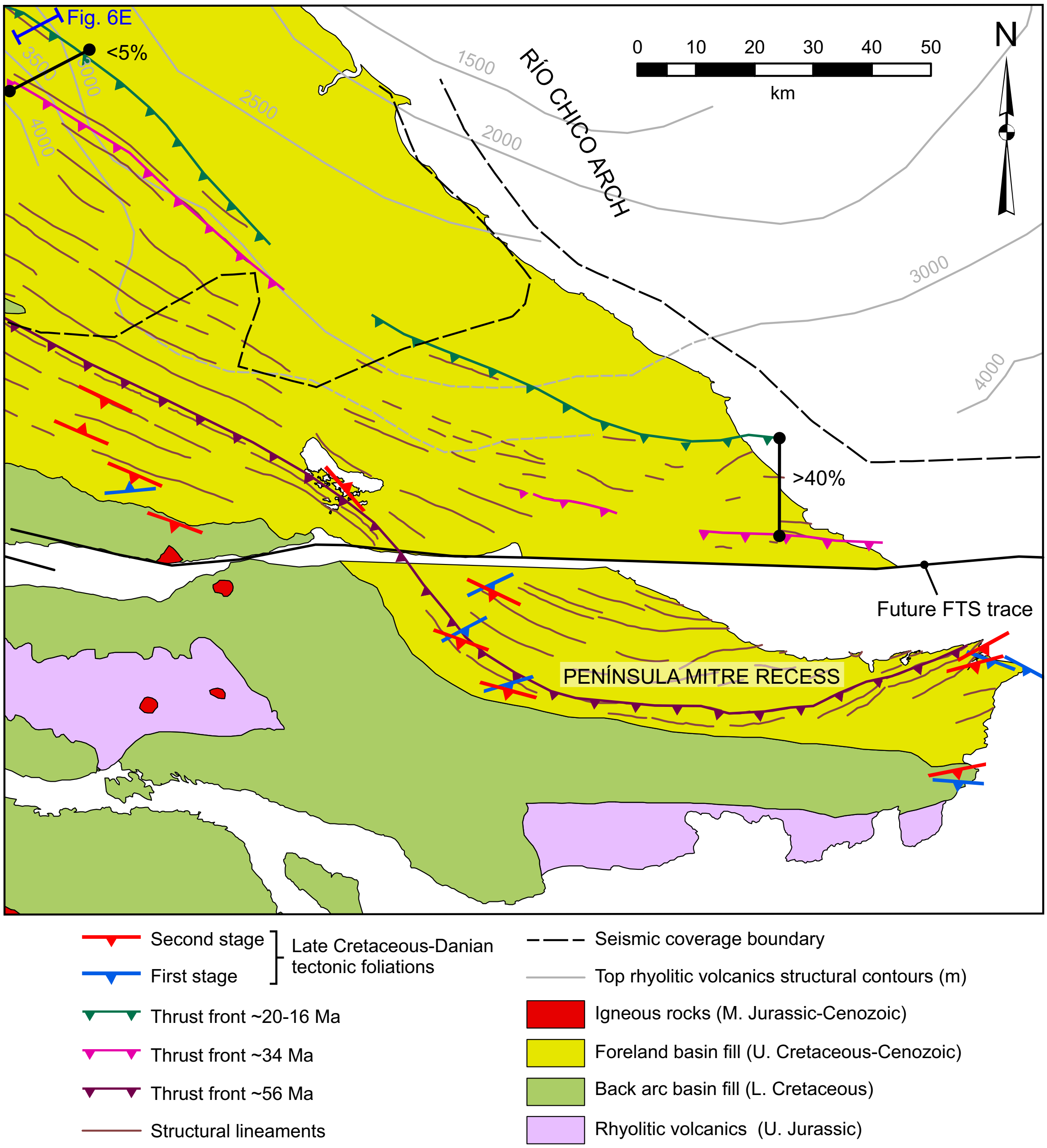

Fig. 8. Structural elements of the Fuegian thrust-fold belt positioned before inception of the Fagnano transform system (FTS). Note northward migration of thrust fronts mimicking the curvature of the basement topography that configures the Rio Chico Arch. The structural contours of the basement are speculative beyond the seismic data coverage. Percentages of shortening (from Torres Carbonell et al., 2013b) were calculated in two cross-sections across the thrust-fold belt front.

will start with the evolution of the Fuegian Andes after initial closure of the Rocas Verdes basin (i.e. after ~80 Ma). The paleotectonics during closure of this back arc basin were recently reviewed by Dalziel et al. (2013a). Up to the early Eocene, the Fuegian Andes orogenic wedge evolved within the northern part of the continental bridge that linked southernmost South America (sSAM) with the Antarctic Peninsula (AP). The age of continental rifting, thinning, and extension on this continental bridge has been established at ~50 Ma (Livermore et al., 2005), with localized creation of oceanic floor at ~44 to ~41 Ma (Eagles et al., 2006; Maldonado et al., 2014–in this volume).

As addressed above, the Late Cretaceous–Paleocene orogenic growth in the Fuegian Andes involved a northward migration of the crustal stack formed by the upper part of the underthrusted continental basement and the sedimentary fill of the Rocas Verdes and coeval foreland basin system (cf. Torres Carbonell and Dimieri, 2013) (Figs. 3 and 7). The northward migration of the orogenic wedge is interpreted on the basis of the curvature acquired by Late Cretaceous penetrative tectonic fabrics in the early TFB, which suggest an initial interaction with the Rio Chico promontory (Torres Carbonell et al., 2013a) (Fig. 8). This proposed northward migration of the orogenic wedge is consistent with the existing reconstructions for the sSAM–AP continental bridge. According to Barker and Lonsdale (1991) and Grunow et al. (1991), in the Late Cretaceous the convergent margin in the Fuegian Andes front changed laterally (southward) to a passive margin linked to extension in the Weddell Sea, along the eastern AP. During these times, the pole of the South American and Antarctic plates motion was located close

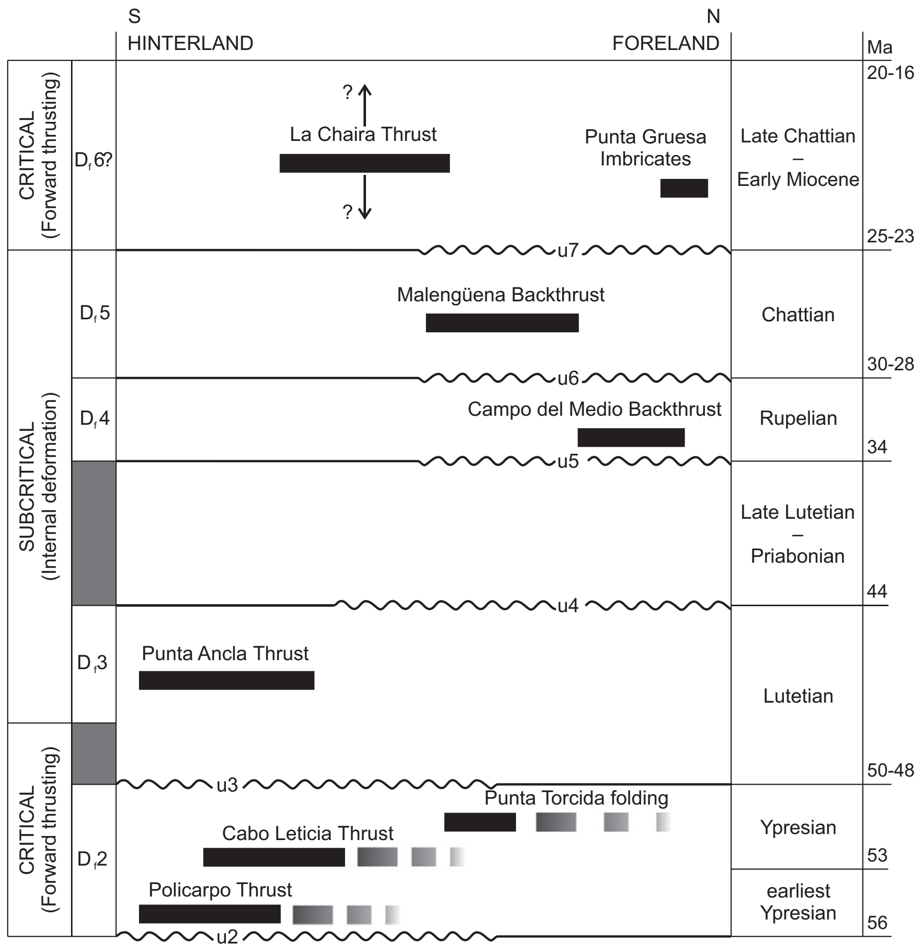

Fig. 9. Foreland contractional stages (D_f2–D_f6) of the eastern Fuegian thrust-fold belt, showing the relative position of deformation within the thrust wedge for each stage, the interpreted behavior (critical–subcritical), and relationship with coeval unconformities in the foreland basin fill (u1–u7). Modified from Torres Carbonell et al. (2011).

to the sSAM–AP connection. This may have been the cause of clockwise rotation of Antarctica with respect to SAM, which in turn provoked the bending of the continental bridge and its development into a cuspate, convex-to-the-east orocline (Barker, 2001).

This tectonic context forced the NW arm of the sSAM–AP connection to rotate counterclockwise (Fig. 11). This portion of the sSAM–AP belt contained the initial Fuegian Andes orogen, formed during the closure and inversion of the Rocas Verdes basin (Klepeis et al., 2010) (Fig. 3B). The undeformed part of the Rocas Verdes sedimentary fill and the newly formed foreland basin were located north of this initial orogen, draping the SW corner of the South American continent (Fig. 11). We speculate that during the Late Cretaceous–Paleocene oroclinal bending, this initial orogen acted as a rigid block (the Fuegian Andes backstop) that pushed the sedimentary succession in the foreland, driving the orogenic wedge toward the north. Thus, only the backstop rotated counterclockwise, whilst the buttressing exerted by the Rio Chico Arch caused the curvature attained by the evolving foreland thrust wedge.

4.2. Eocene–middle Miocene

The evolution of the sSAM–AP connection since initiation of continental stretching between 50 and 40 Ma involved the movement of the southern portion of the present-day Fuegian archipelago toward the north. This sSAM block, which had been recently separated from the AP, constitutes the Fuegian backstop mentioned above, i.e. the initial orogenic wedge formed from the Late Cretaceous to the early Paleogene (Fig. 11). Possible drift trajectories for the Fuegian backstop since the Eocene and more accurately constrained from the Oligocene to the Miocene are obtained from the analysis of sea floor magnetic anomalies in the West Scotia Sea made by Barker (2001) and Eagles et al. (2005). Although with discrepancies, in both cases a northward dominant component of drift is proposed for the southern portion of Tierra del Fuego from ~40 to ~11 Ma according to Barker (2001), and between ~20 and ~6 Ma following Eagles et al. (2005) (Fig. 12).

An Eocene–Miocene northward drift of the Fuegian backstop is strikingly consistent with the coeval thrust front migration in the Fuegian thrust-fold belt addressed before (Fig. 8). This backstop compressed the Paleogene–early Neogene foreland basin against the crustal buttress of South America forming the external thrust-fold belt and enhancing the Peninsula Mitre recess. The Miocene clastic dikes exposed at the apex of this recess (Section 3.3, Fig. 10) give some insight on the paleostresses acting during its late formation. Assuming that the dikes are syntectonic (comparable to tectonic joints cf. Engelder, 1985) Ghiglione (2002) interpreted their formation related to transpression associated to a strike-slip regime that should explain the E–W oriented fold axes and thrusts in Punta Gruesa (Torres Carbonell et al., 2008a). A more conservative view on these data may consider that $\sigma1$ corresponds to a horizontal tectonic compression associated to the TFB growth, and $\sigma2$ is the vertical stress associated with overburden, of a

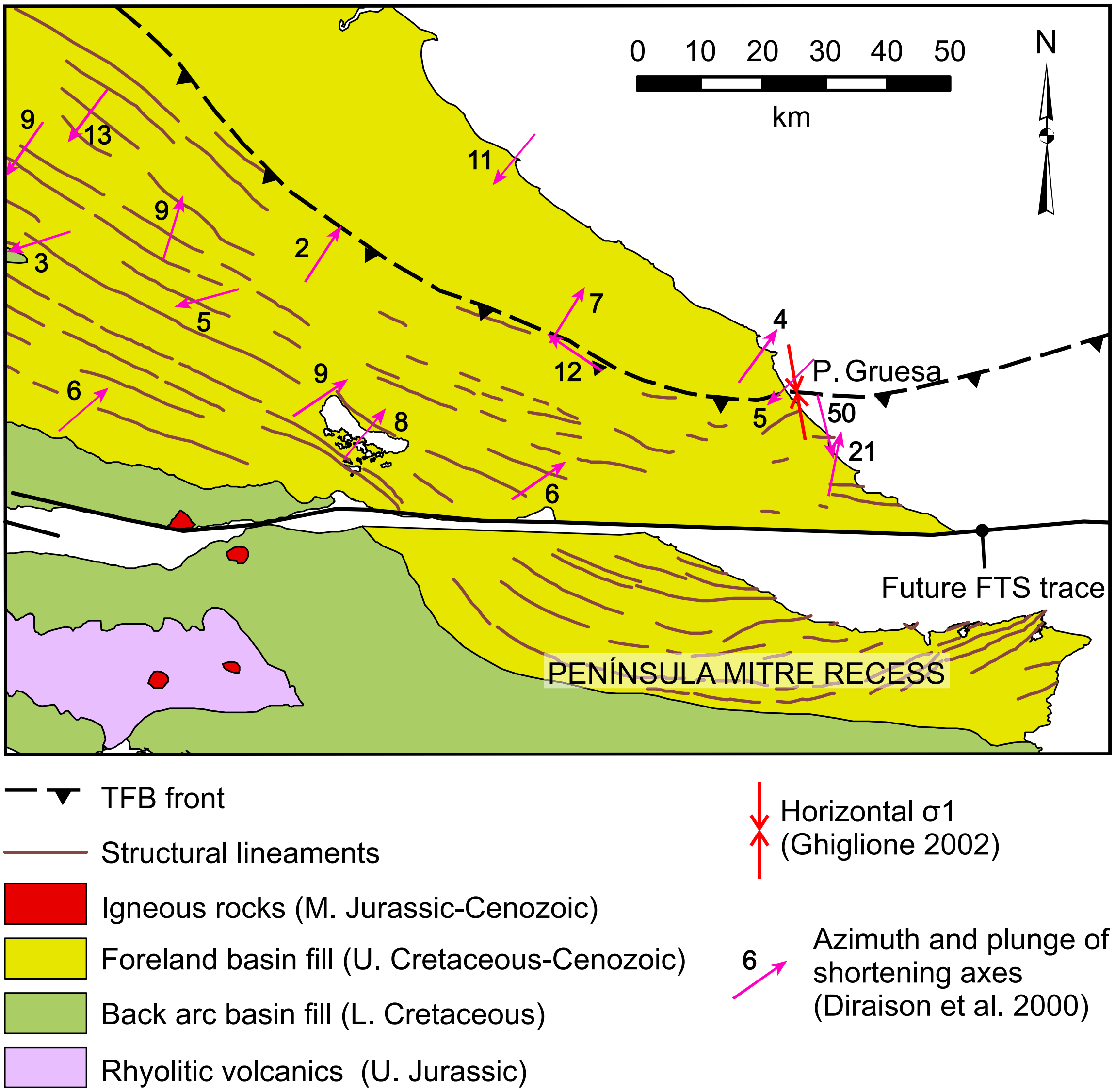

Fig. 10. Structural data from the Fuegian thrust-fold belt. The map shows positions previous to motion on the Fagnano transform system (FTS) (see Fig. 8). Strain and paleostress data from Diraison et al. (2000) (faults) and Ghiglione (2002) (syntectonic clastic dikes) are depicted.

greater but unknown magnitude than the horizontal σ3. Joints formed under this type of interaction between tectonic and burial stresses are very common in foreland thrust-fold belts affecting sedimentary basins (Engelder, 1985).

Considering the apparent change in shortening direction observed from the western flank of the recess toward its apex, and ruling out a SW–NE regional shortening direction for the formation of SW–NE trending folds, thrusts and penetrative tectonic foliations in the eastern flank of the Peninsula Mitre recess (Figs. 8 and 10), we argue that a regional S–N contraction combined with buttressing against the curved Rio Chico promontory is adequate for the pattern of thrust front migration shown in Fig. 8. This would imply a convergence of the horizontal shortening trajectories toward that curved promontory, a situation that may have started at the very beginning of TFB evolution during the Late Cretaceous–Danian.

The causative relationship between a continued northward migration of the Fuegian backstop since the Late Cretaceous and up to the Miocene, and coeval contraction in the Fuegian Andes, contradicts the Paleogene stretching proposed for Tierra del Fuego as a precursor to Drake Passage opening (cf. Ghiglione et al., 2008). This interpretation was mainly based on the hypothesis that the Ypresian Punta Noguera Formation (Olivero and Malumián, 2008; Torres Carbonell et al., 2009) represents a synrift succession, affected by several normal faults. As discussed elsewhere (Torres Carbonell et al., 2011), this hypothesis remains unsupported by structural evidence, since the proposed synrift faults are not described, i.e. no fault orientation and slip data is given by Ghiglione et al. (2008). Furthermore, the age of these faults is unconstrained, since they cut and produce the same apparent separation to both the Punta Noguera Formation and younger units (Lutetian Rio Bueno Formation) (Torres Carbonell et al., 2011). Thus, it is even possible that these faults pertain to the younger late Miocene–Recent tectonic stage (see following section).

Thus, we consider that simultaneously with the Eocene opening of the Scotia Sea and the associated activity in the West Scotia Ridge, the Fuegian Andes evolved (as addressed in this paper) through a history of contractional deformation instead of stretching, including both uplift in the central belt (e.g. Kohn et al., 1995; Gombosi et al., 2009) and thrust emplacement in the TFB (see Fig. 9). Contraction ceased during the Miocene,

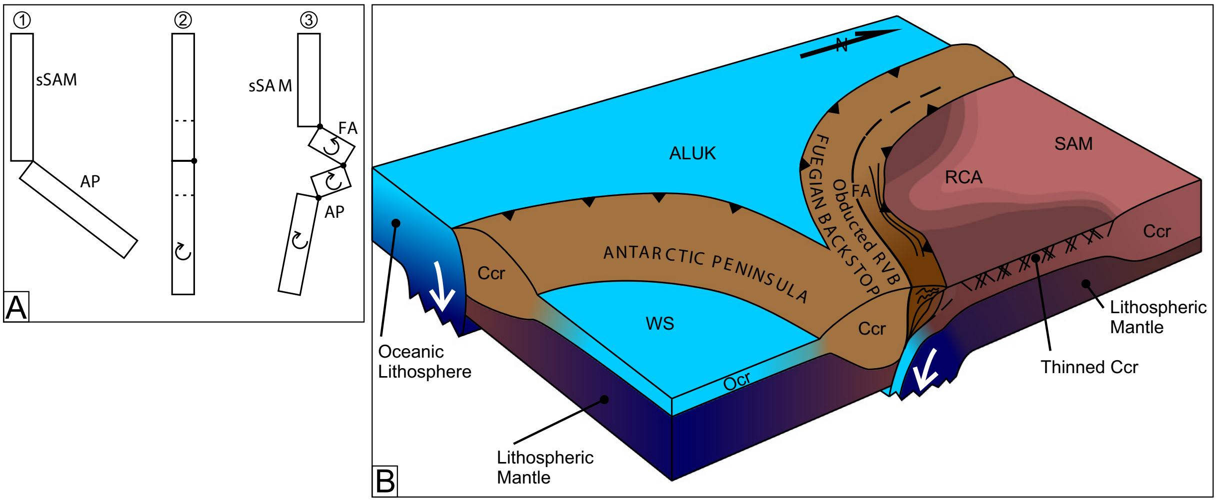

Fig. 11. Schematic development of the Late Cretaceous–Paleocene oroclinal bending proposed for the southernmost South America (sSAM)–Antarctic Peninsula (AP) continental bridge. A. Kinematics of bending. Steps 1–2: clockwise rotation of AP around a pole near the sSAM–AP connection; step 3: further rotation leads to orocline development involving the connection, with continued clockwise motion in AP and start of counterclockwise rotation in the initial Fuegian Andes (FA). B. Block diagram depicting the major tectonic features of the model. ALUK: Aluk plate, FA: Fuegian Andes (initial orogenic wedge), RCA: Rio Chico Arch, SAM: South American Plate, RVB: Rocas Verdes basin, Ccr: Continental crust, Ocr: Oceanic crust, WS: Weddell Sea.

when the West Scotia Ridge decreased its spreading velocity before ceasing definitively at 6.4 Ma (C3A) (Maldonado et al., 2000; Eagles et al., 2005).

4.3. Late Miocene–Recent

The decrease and subsequent cessation of seafloor spreading in the West Scotia Ridge between ~16 and ~6 Ma was followed by an increase in activity of the East Scotia Ridge (Barker, 2001; Larter et al., 2003; Eagles et al., 2005). Almost at the same time (~11 Ma) the South Georgia microcontinent collided with the Northeast Georgia Rise (Kristoffersen and LaBrecque, 1991; Dalziel et al., 2013b). This collision locked the eastward migration of the North Scotia Ridge and South Georgia that had been occurring since the late Oligocene due to spreading in the West Scotia Ridge (Barker, 2001; Eagles et al., 2005; Dalziel et al., 2013b).

This coincidence between late Miocene cessation of sea-floor spreading in the West Scotia Ridge, locking of eastward migration in the North Scotia Ridge, and inception of sea floor spreading in the East Scotia Ridge is a very probable cause for the formation of the present transform boundary between the Scotia and South America plates and consequently, the development of strike-slip faulting along the Fagnano transform system (Barker, 2001) (Fig. 13). It is noteworthy that a similar age (~8 Ma) has been considered for the beginning of the present left-lateral kinematics of the South Scotia Ridge (Bohoyo et al., 2007).

Different interpretations propose that significant strike-slip faulting in Tierra del Fuego controlled the Oligocene–Miocene evolution of the TFB in a transpressive regime, implying that the active Fagnano transform system is more than 25 Ma old (Diraison et al., 2000; Ghiglione and Ramos, 2005; Menichetti et al., 2008). Support for this line of work largely comes from poorly exposed structures. However, some quantitative data provided by authors in this line of work comes from fault analyses in several sectors of the Fuegian Andes (Diraison et al., 2000; Menichetti et al., 2008). These analyses are based either on the Right Dihedra method for determining bulk strain (Angelier and Melcher, 1977; Pfiffner and Burkhard, 1987; Marrett and Allmendinger, 1990) or the inversion method of Angelier and Gouguel (1979) for determination of paleostress axes. Most of the faults shown by these authors are left-lateral strike-slip faults.

The bulk strain analysis made by Diraison et al. (2000) for faults from Tierra del Fuego shows a regional SW–NE horizontal shortening axis (e.g. Fig. 10), and a subvertical intermediate axis of the strain ellipsoid. However, no specific information on the ages of faults is given, and all the measured faults are considered as pertaining to a single deformation phase. For instance, Diraison et al. (2000) indicate that the faults that they analyzed "necessarily formed during the stage of Late Cretaceous to Tertiary compression in the southernmost Andes" (p. 100).

In our opinion, this time span is large enough for more than one faulting phase to develop, especially considering the possibility of contrasting tectonic regimes (contractional deformation followed by strike-slip deformation) addressed here. In other words, the strike-slip faults shown by Diraison et al. (2000) and Menichetti et al. (2008) could have formed after contractional deformation ceased. Indeed, relative ages determined by crosscuting relationships in the best exposed, major strike-slip faults, indicate either recent activity (e.g. Punta Isleta fault system of Torres Carbonell et al., 2011) or that they postdate contractional structures (folds and thrusts) older than the late Oligocene (e.g. Lago Deseado strike-slip faults from Klepeis, 1994b; Fueguina fault from Torres Carbonell et al., 2008a).

An additional aspect that must be considered from the strain analysis made by Diraison et al. (2000) is the shape of the strain ellipsoids determined for the fault population of Tierra del Fuego, which are mostly of plane-strain type. Since Diraison et al. (2000) consider that in the Fuegian Andes "wrenching is the major component of deformation and thrusting is the minor component" (p. 104), strain ellipsoids of plane-strain type would imply deformation constrained to the horizontal shortening and stretching axes. This is obviously not the case for the well documented ductile and brittle thrust and fold structures from the internal TFB and central belt of the Fuegian Andes, from which a horizontal plane-strain cannot be argued (Bruhn, 1979; Dalziel and Palmer, 1979; Klepeis, 1994a; Torres Carbonell et al., 2013a). The external TFB, on the other hand, is assumed to be dominated by plane-strain during formation of thrust and fold structures; but with the shortening and stretching axes in the vertical plane, which validates construction of balanced cross-sections in the area (Alvarez-Marrón et al., 1993; Rojas and Mpodozis, 2006; Torres Carbonell et al., 2008a, 2011, 2013b). Therefore, we consider that the types of strain ellipsoids obtained for the fault population analyzed by Diraison et al. (2000) indicate either one of the following cases: a) wrenching is not dominant against thrusting-folding, and the plane strain ellipsoids derived from these faults reflect a minor component of orogen-parallel extension; or b) these faults pertain to a wrench-dominated tectonic regime that is distinct and separated in time from the one that gave birth to contraction in the Fuegian Andes. In any case, the change between the type of structures developed from

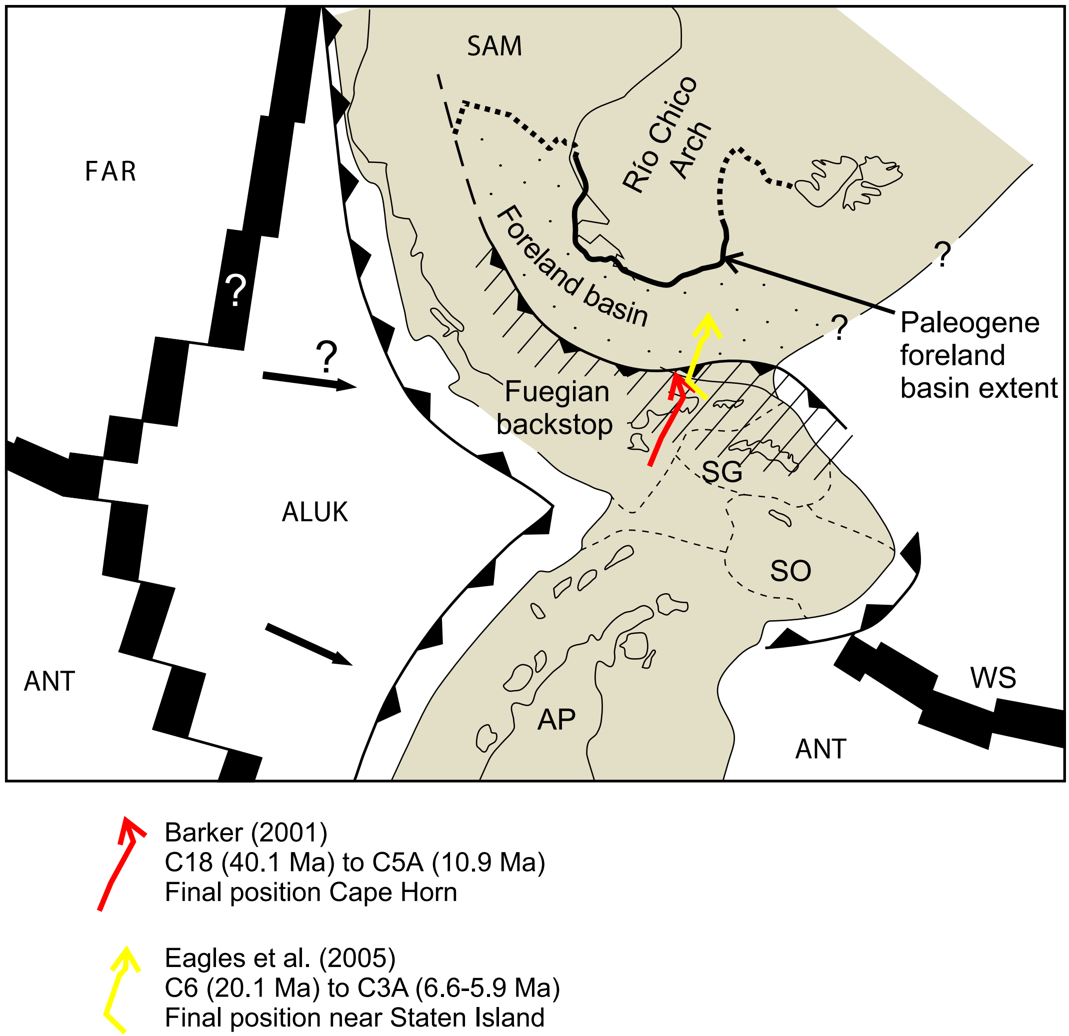

Fig. 12. Paleomap of southernmost South America–Antarctic Peninsula during the interval 50–40 Ma ago. The continental bridge is brown-colored. The dashed area represents the initial Fuegian orogenic belt. Only major blocks in the continental bridge are shown. Unshaded areas are oceanic crust, arrows indicate sense of motion of Aluk plate (ALUK) (uncertain in its northern portion), black bars are spreading ridges and barbed lines indicate subduction or underthrusting zones. SG: South Georgia, WS: Weddell Sea, SO: South Orkney, AP: Antarctic Peninsula, FAR: Farallon plate, ANT: Antarctic plate, SAM: South American plate. Based on reconstructions by Larter and Barker (1991), McCarron and Larter (1998), Barker (2001), Livermore et al. (2005), and Somoza and Ghidella (2005). Drift trajectories for positions in the Fuegian backstop are shown, taken from Barker (2001) and Eagles et al. (2005). Barker's trajectory refers to movement of Cape Horn with respect to a fixed South America (see Fig. 6 of Barker, 2001). The trajectory that ends near Staten Island refers to movement of the "Magallanes plate" of Eagles et al. (2005) with respect to fixed South America (see Fig. 11a from these authors).

the older thrusts and folds to the younger strike-slip faults, as recognized at the regional scale, cannot be neglected.

The interpretation of a late Miocene onset of significant strike-slip faulting in Tierra del Fuego (cf. Torres Carbonell et al., 2008b), therefore, is not only consistent with the geotectonic context of the Scotia Sea but also consistent with the few strain and paleostress analyses published from Tierra del Fuego. The addressed tectonic history of the Scotia Sea also helps to understand the evolution of the Fuegian Andes as an earlier history of contraction giving birth to the orogen itself, and a later, subsequent superposed strike-slip faulting regime related to the more recent evolution of the North Scotia Ridge (Fig. 13).

5. Conclusions

Integration of onshore geological data from the Fuegian Andes with the tectonic history of the Scotia Sea, mostly derived from offshore data, shows a remarkable compatibility between the evolution of both since about 40–50 Ma ago, and linkages can be further extended to their prior history.

A Late Cretaceous–Paleogene counterclockwise rotation of the Fuegian backstop related to the postulated bending of the sSAM–AP bridge during these times, explains the north-directed contraction interpreted for the formation of the Fuegian Andes after the initial closure of the Rocas Verdes basin. We propose that this north-directed contraction in the Fuegian Andes continued between the Eocene and early Miocene, probably driven by the migration of the broken, northern portion of the sSAM–AP peninsula continental bridge, i.e. the previously formed Fuegian backstop containing the initial Fuegian Andes orogenic wedge. Accordingly, we discard Eocene extension in Tierra del Fuego and point toward pure convergence between the Fuegian backstop and SAM, which caused the northward progression of the Fuegian TFB. Finally, our analysis of kinematic data from Tierra del Fuego has led us to conclude a late Miocene (~10 Ma) age for onset of the Fagnano transform system, consistent with the evolution of the North Scotia Ridge, and superposed to the Late Cretaceous–early Neogene previous contractional tectonic regime.

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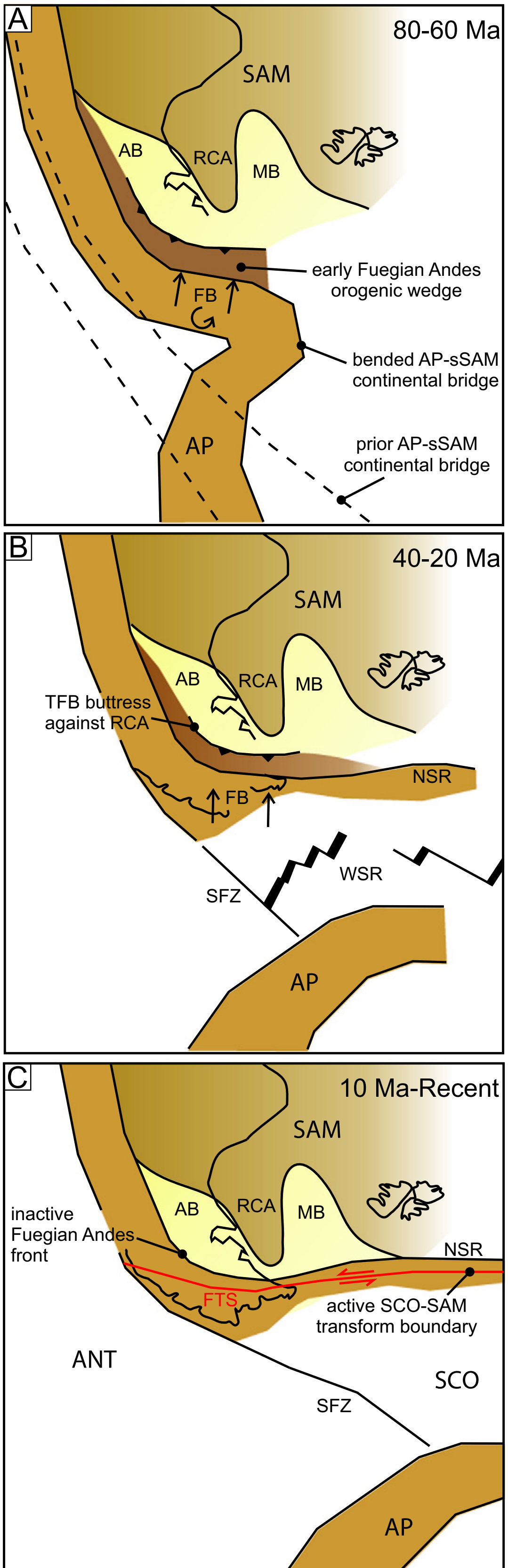

Fig. 13. Schematic reconstructions of the main tectonic stages addressed in this article. References for reconstructions are same as in Fig. 12. Brown color: continental crust, yellow: foreland basin, white: oceanic domains. A. Late Cretaceous–Paleocene bending of the southernmost South America (sSAM)–Antarctic Peninsula (AP) continental bridge, causing northward migration of the Fuegian backstop (FB) against the southern cratonic margin of the South American plate (SAM), featured by the Rio Chico Arch promontory (RCA) that separates the Austral and Malvinas basins (AB and MB). B. Eocene–middle Miocene separation of the Fuegian backstop and North Scotia Ridge (NSR) from the Antarctic Peninsula, during development of the West Scotia Ridge (WSR). The Fuegian thrust-fold belt (TFB) is "sandwiched" between the north-migrating Fuegian backstop and the Rio Chico Arch. SFZ: Shackleton fracture zone. C. Late Miocene–Recent development of the left-lateral transform boundary between the South American and Scotia (SCO) plates, forming the Fagnano transform system (FTS) in Tierra del Fuego superposed to the inactive, prior Fuegian Andes structures.

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