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Cenozoic contractional tectonics in the Fuegian Andes, southernmost South America: a model for the transference of orogenic shortening to the foreland

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ABSTRACT

The Fuegian thrust-fold belt has been subjected to significant shortening during the Cenozoic. Although contemporaneous shortening and uplift was also recognized in the Fuegian Andes central belt (hinterland), previous studies stated that most of that deformation developed out-of-sequence with the thrust-fold belt and hence did not contribute to its shortening. Therefore, no suitable geometric and kinematic model has been proposed for the mechanism that links deformation in both domains. Here we address the style and timing of the younger (Late Cretaceous-Paleogene) structures of the central belt and the structural evolution of the thrust-fold belt, based on published and own data. We reinterpret the style of the central belt structures, proposing a new model in which basement thrusting in the central belt caused all the shortening in the foreland cover. We postulate that the basement was involved in a regional-scale duplex whose roof thrust was the décollement of the thin-skinned thrust-fold belt. Therefore, the total slip transferred through the roof thrust accounted for the shortening in the cover rocks. The basement duplex incorporated the underthrust crust from the footwall of the orogenic wedge through forward propagation, in sequence with the thrust-fold belt, from the Late Cretaceous to the Miocene.

KEYWORDS **Central belt. Thrust-fold belt. Shortening transference. Crustal duplex. Cenozoic. Fuegian Andes.**

INTRODUCTION

Early structural work in the Fuegian Andes (Fig. 1) documented a Late Cretaceous shortening stage, considered the main phase of deformation, which caused several penetrative strain fabrics and intense metamorphism (Nelson *et al.*, 1980; Bruhn, 1979; Dalziel and Palmer, 1979). In the last decades, a growing body of evidence obtained in the foothills of the Fuegian Andes revealed that a significant shortening was accommodated in the Fuegian (Magallanes) thrust-fold belt during the Cenozoic, as well. This shortening has been reported by estimates from balanced cross-sections both in western (Chile) and eastern (Argentina) Tierra del Fuego (Fig. 1) (Álvarez-Marrón *et al.*, 1993; Rojas and Mpodozis, 2006; Torres Carbonell *et al.*, 2011). They show shortening values of several tens of kilometers along the thin-skinned thrust-fold belt, with a well-constrained Paleogene thrust-sequence established in eastern Tierra del Fuego (Torres Carbonell *et al*., 2011).

Paleogene shortening and uplift was also recognized in the central belt (hinterland) of the Fuegian Andes (Kohn *et al*., 1995; Gombosi *et al*., 2009), although previous workers interpreted that this deformation developed out-of-sequence with the structures of the thrust-fold belt and hence did not contributed to its shortening (Klepeis, 1994a; Rojas and Mpodozis, 2006). Accordingly, only one major stack of basement thrust sheets was interpreted to be responsible for the transference of displacement to the foreland (Klepeis, 1994a; Kley *et al*., 1999; Kraemer, 2003; Rojas and Mpodozis, 2006). However, a detailed restoration of some published cross-sections reveals inconsistencies between the kinematics and amount of shortening reported for the cover and basement thrust sheets.

Moreover, it has been proposed that most of the Paleogene shortening and uplift of the central belt was constrained to a localized portion of the orogenic belt, surrounding Cordillera Darwin (a topographic culmination of the southernmost Andes) (Fig. 1), and that orogenic deformation was less important toward the SE tip of the Fuegian Andes (Kraemer, 2003). These statements, therefore, impede a priori to relate the major Paleogene deformation of the central belt to the structures recognized along the thrust-fold belt, especially with those recognized laterally away from Cordillera Darwin at eastern Tierra del Fuego. Hence, the structural relationship between the central belt and the thrust-fold belt along the Fuegian Andes remains a matter of discussion.

In this paper, we will address the style and timing of the younger (Late Cretaceous- Paleogene) structures of the central belt of the Fuegian Andes, and the tectonostratigraphic and structural data obtained in the eastern Fuegian thrust-fold belt where several Paleogene contractional stages caused well-assessed amounts of shortening. The comparison of the geometry and kinematics of both domains of the orogen, and a reinterpretation upon discussion of previous models, suggest that the deformation of the complete orogenic belt must be balanced so that any given shortening in the foreland must have been originated and transmitted from the hinterland. We propose that the emplacement of deeper thrust sheets in the internal parts of the orogen caused the shortening recorded in the thrust-fold belt, as it has been widely recorded or interpreted in many orogenic belts, such as the Pyrenees (Muñoz, 1992; Teixell, 1998), the Alps and Himalayas (Coward and Butler, 1985; Butler, 1986), and the Canadian Cordillera (Price, 1981; Brown *et al*., 1992). In all these cases, collision or terrane accretion plus an amount of subduction or underthrusting of the foreland crust has been involved during the orogenesis

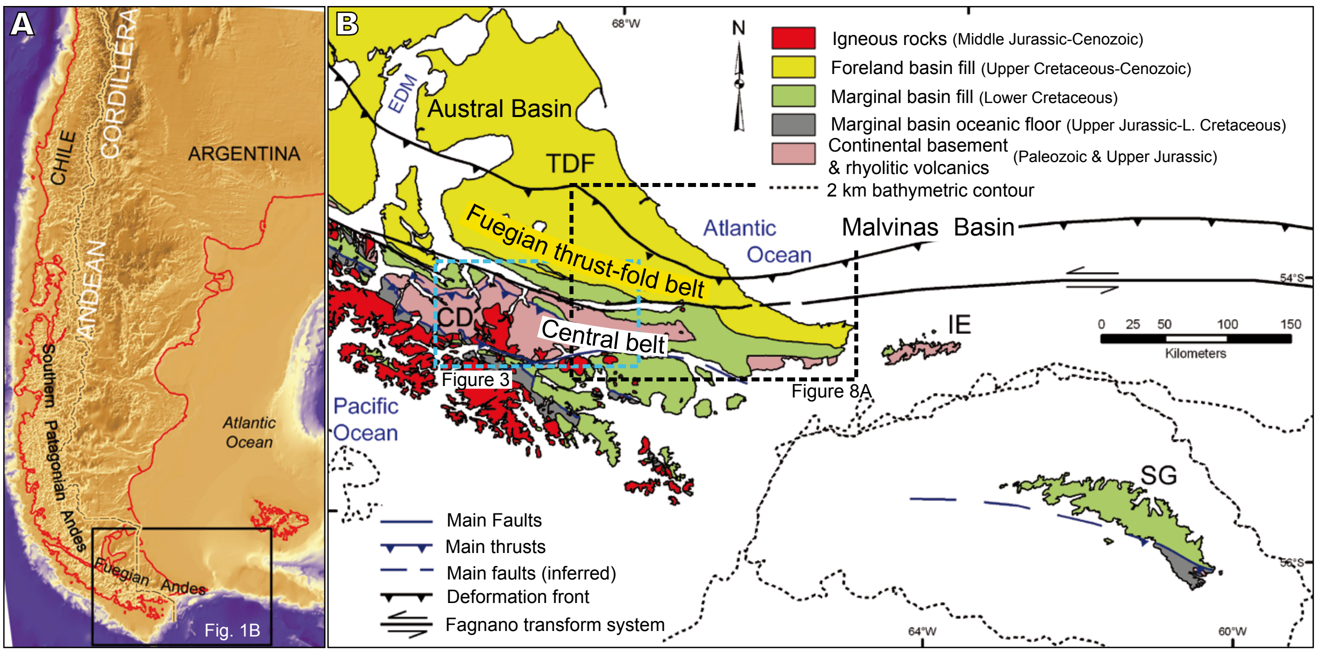

FIGURE 1 | A) Regional situation of the study area. Digital Elevation Model from the GEBCO One Minute Grid, version 2.0 (http://www.gebco.net). B) Tectonostratigraphic units and structural features of Tierra del Fuego (TDF), described in this paper; references are cited in the text. The South Georgia (SG) continental block (delimited by its 2km bathymetric contour) is situated in its interpreted early Cenozoic position (Tanner, 1982), in order to show the complete orogenic belt geography during most of its evolution (see text). CD: Cordillera Darwin, IE: Isla de los Estados, EDM: Estrecho de Magallanes.

(see Pfiffner, 2006, for more examples); these processes were also considered in the Fuegian Andes (Dalziel, 1981; Cunningham, 1995; Klepeis *et al.*, 2010).

Our hypothesis challenges previous models that stated that the Paleogene uplift of the central belt of the Fuegian Andes occurred because of out-of-sequence thrusting (Klepeis, 1994a; Rojas and Mpodozis, 2006), and rejects the proposed localization of orogenic uplift nearby Cordillera Darwin (Kraemer, 2003) suggesting that the geometric and kinematic features of the mountain system are maintained along its length. The model raised here has important influences on the stratigraphic and structural analysis of the related, hydrocarbon producing, foreland basin system.

GEOLOGIC SETTING

The Fuegian Andes form the southern extremity of the Andean Cordillera in South America (Fig. 1A). The evolution of this portion of the Andes involved the closure and inversion of an Early Cretaceous back-arc marine basin formed above the stretched SW margin of South America (Gondwana) (Dalziel, 1981; Klepeis *et al.*, 2010). This basin, known as Rocas Verdes Marginal Basin (RVMB), was floored by oceanic rocks and bounded to the west and SW by a subduction-related magmatic arc (Fig. 2A) (Dalziel, 1981; Calderón *et al.*, 2007). The basin constituted a longitudinal depression many hundred kilometers long, running from the southern Patagonian Andes to South Georgia (in its Cretaceous position) (Fig. 1) (Dalziel, 1981). The RVMB was filled with marginal-marine to deep-marine clastic and volcaniclastic successions (Storey and Macdonald, 1984; Olivero and Martinioni, 2001; Fildani and Hessler, 2005).

The history of closure of the RVMB, as recorded in the Fuegian Andes and South Georgia, started in the *mid*-Cretaceous leading to shortening and intense deformation of its continental basement, oceanic floor, and sedimentary fill, which were *sandwiched* between the magmatic arc and the cratonic margin (Fig. 2B, C) (Tanner and Macdonald, 1982; Klepeis *et al.*, 2010). The closure of the basin triggered the development of the mountain belt, with a foreland thrust-fold belt that progressively included the sedimentary fill of a related foreland basin system (Álvarez-Marrón *et al.*, 1993; Olivero and Malumián, 2008; Torres Carbonell *et al.*, 2011). A similar tectonic history was determined for the southern Patagonian exposures of the RVMB and foreland basin (Fildani and Hessler, 2005; Romans *et al.*, 2010). The development of the foreland basin and thrust-fold belt continued until Miocene times in Tierra del Fuego (Ghiglione, 2002; Torres Carbonell *et al.*, 2011), when the contractional tectonics ceased. Afterwards, deformation occurred due to strike-slip faulting related to the northern transform boundary of the Scotia Plate, which is still active in the present (Klepeis, 1994b; Barker, 2001; Torres Carbonell *et al.*, 2008a).

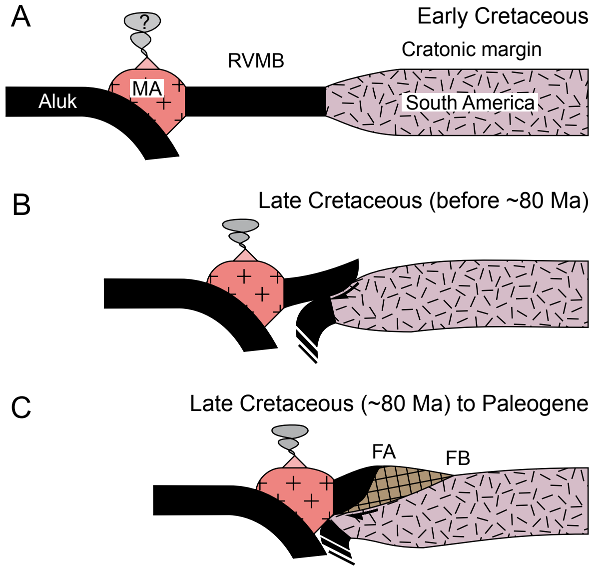

FIGURE 2 | Tectonic history of closure of the Rocas Verdes Marginal Basin (RVMB) (*cf.* Klepeis *et al.*, 2010, and references therein). A) The back-arc basin, floored by oceanic crust, was originally located between a magmatic arc (MA -with a debated volcanic activity), related to subduction of the Aluk (Phoenix) plate, and the cratonic margin of SW South America. B) During Late Cretaceous, the basin was destructed due to obduction of the oceanic floor and underthrusting of the cratonic margin. C) Afterwards, the magmatic arc, rooted in ensialic crust, collided with the cratonic margin causing thrust-related deformation and uplift of the Fuegian Andes (FA), enhancing growth of the orogenic wedge and development of the foreland basin (FB).

As a basis for our study we use five main tectono-stratigraphic units (Fig. 1), which are briefly described here. Further information on their geology is addressed in the cited references.

i) Paleozoic continental basement and Upper Jurassic rhyolitic volcanics. The continental basement (Forsythe, 1982; Hervé *et al.*, 2010) is now exposed as blocks of metamorphic rocks, uplifted and exhumed during the Late Cretaceous-Paleogene orogenesis (Tanner and Macdonald, 1982; Klepeis *et al.*, 2010). In Cordillera Darwin, it forms part of a unique high-grade metamorphic complex (Nelson *et al.*, 1980; Kohn *et al.*, 1993). In South Georgia and along exposures in southern Chile, the basement comprises metasedimentary rocks, schists, gneisses, and migmatites intruded by mixed granitic and mafic plutons (Kranck, 1932; Storey and Mair, 1982). In the subsurface of the Austral Basin, drilled Cambrian plutonic and metamorphic rocks have been assigned to the basement (Pankhurst *et al.*, 2003).

The term *rhyolitic volcanics* is here used to indicate an assemblage of Late Jurassic volcanic and volcaniclastic rocks deposited on top of the continental basement, in a submarine volcano-tectonic rift developed during the extensional phase that originated the RVMB. The volcanics filled the irregular surface of the rifted depocenters in the proto-marginal basin (Hanson and Wilson, 1991). These rocks, exposed along the southern Patagonian and Fuegian Andes, form part of a regional volcanic suite developed during Middle to Late Jurassic times (Uliana *et al*., 1985; Hanson and Wilson, 1991; Calderón *et al*., 2007). Stratigraphic names used elsewhere for this rock assemblage comprise the Tobífera and Lemaire formations.

ii) Upper Jurassic-Lower Cretaceous marginal basin oceanic floor. The oceanic floor of the RVMB formed between the Late Jurassic and Early Cretaceous during and after rifting of the basement and deposition of the rhyolitic volcanics (Dalziel, 1981; Mukasa and Dalziel 1996; Calderón *et al*., 2007). The oceanic floor is exposed as ophiolitic rocks along a discontinuous belt from the southern Patagonian Andes in Chile to the southern Fuegian islands, and in South Georgia. It is composed of mafic and mixed intrusives, pillow lavas, breccias and tuffs (Storey and Mair, 1982, Stern and deWit, 2003).

iii) Lower Cretaceous marginal basin fill. The RVMB sedimentary fill comprises Early Cretaceous marginal marine to flysch sequences. These sequences covered the entire RVMB forming, from North and Northeast to South and Southwest, a passive margin to deep-marine clastic wedge (Biddle *et al*., 1986; Olivero and Martinioni, 2001; Fildani and Hessler, 2005). The marginal basin fill is extensively exposed in the Fuegian Andes and South Georgia (Storey and Macdonald, 1984; Olivero and Martinioni, 2001; McAtamney *et al*., 2011). Lithostratigraphic units within the marginal basin fill include the Yahgan, Río Jackson, Beauvoir, Hito XIX, La Paciencia, Erezcano, and Zapata formations.

iv) Upper Cretaceous-Cenozoic foreland basin fill. The foreland basin was filled by Late Cretaceous to Miocene arc- and orogen-derived syntectonic successions, as recognized in eastern Tierra del Fuego (Olivero and Malumián, 2008; Torres Carbonell *et al*., 2009; Torres Carbonell, 2010), and elsewhere along the southernmost Andes (*e.g*. Malumián, 2002; Romans *et al*., 2010). Given their importance for the kinematic model developed in this paper, the syntectonic successions recognized in eastern Tierra del Fuego are further addressed in this paper. The foreland basin fill is also recognized in subsurface data from the Austral (Magallanes) and Malvinas basins, two main depocenters of the foreland basin system (Biddle *et al*., 1986; Galeazzi, 1998).

v) Middle Jurassic-Cenozoic igneous rocks. Several suites of intrusive and volcanic bodies compose the igneous rocks exposed in southern Tierra del Fuego and South Georgia, with ages that span from the Middle Jurassic to the Cenozoic (Halpern, 1973, Hervé *et al*., 1984, Mukasa and Dalziel, 1996). A number of magmatic suites are distinguished; those that are relevant to the description of structures in some parts of this work are: the Darwin suite (Middle to Upper Jurassic) and the Beagle suite (Upper Cretaceous) (Mukasa and Dalziel, 1996). The origin of the igneous rocks is related to an arc associated to subduction, with a discussed origin (Mukasa and Dalziel, 1996, Calderón *et al*., 2007; Klepeis *et al*., 2010).

The five tectonostratigraphic units described were differentially involved in deformation during closure of the RVMB and orogenesis. This history of deformation in the southern portion of the basin is addressed with more detail in the following sections. In summary, it involved the closure of the RVMB through obduction and underthrusting during the beginning of the Late Cretaceous (Fig. 2B), which caused penetrative deformation of the Paleozoic to Lower Cretaceous units coeval with peak metamorphism; followed by uplift plus thrust-related folding of the Paleozoic to Lower Cretaceous units and of the Upper Cretaceous-Cenozoic foreland basin fill until the early Neogene (Fig. 2C) (Bruhn, 1979; Tanner and Macdonald, 1982; Álvarez-Marrón *et al*., 1993; Klepeis *et al*., 2010; Torres Carbonell *et al*., 2011).

Some authors proposed that Late Cretaceous strike-slip faulting related to transpression affected the central belt of the Fuegian Andes and part of South Georgia (Cunningham, 1993, 1995; Curtis *et al*., 2010), although others state that most strike-slip faults in the Fuegian Andes post-date the main contractional structures (Klepeis, 1994b; Torres Carbonell *et al*., 2008a; Klepeis *et al*., 2010). We concur with the later opinion, according to which the end of the contractional tectonics during the Neogene was followed by the onset of the transform boundary between the Scotia and South American plates (Barker, 2001), crosscutting the Fuegian thrust-fold belt along the Fagnano Transform System in Tierra del Fuego (Fig. 1) (Klepeis, 1994b; Torres Carbonell *et al*., 2008a).

STRUCTURE OF THE CENTRAL BELT

Detailed studies on the structural geology of the central belt of the Fuegian Andes have been carried out in Cordillera Darwin and nearby areas (Fig. 1). On the other hand, structural studies in the Argentine portion are restricted to non-detailed surveys, attaining only few better-known areas. Therefore, much of what we know about the structure of the eastern central belt (Argentina) comes from the extrapolation of the knowledge gained in Cordillera Darwin. Upon this clarification, we will address here only the most important structural features of the central belt, based on published data (mainly from Cordillera Darwin) and our own observations.

In addition, we will consider the geology of South Georgia in our analysis of the central belt structure, since it forms part of a block originally attached to the continental border in the SE of Tierra del Fuego (Tanner, 1982), thus forming the easternmost hinterland of the Fuegian thrust-fold belt (Fig. 1A). It is widely accepted that the general geology of South Georgia shows a Cretaceous stratigraphy and structural evolution analogous to that of the Fuegian Andes (Dalziel, 1981; Tanner, 1982; Thomson *et al*., 1982; Tanner and Macdonald, 1982; Curtis *et al*., 2010). Accordingly, we will include South Georgia in our structural analysis of the central belt of the Fuegian orogenic belt.

Geometry of the main contractional structures

The structural geology of Cordillera Darwin and nearby regions (Figs. 1; 3) has been assessed by a number of authors (Nelson *et al*., 1980; Cunningham, 1995; Klepeis *et al*., 2010; among them). We will follow in general the descriptions provided by Klepeis *et al*. (2010), since they integrate most of the available data and show an actualized picture of the overall structure. In the Argentine part of the central belt, the regional structure has been addressed by Bruhn (1979) in the western area, while the easternmost portion, exposed at Isla de los Estados (Fig. 1), was described with some detail by Dalziel and Palmer (1979).

The mentioned published works are mainly focused on structures associated by these authors to the *main phase* of deformation of the Fuegian Andes (Late Cretaceous). Therefore, there is still poor knowledge of Cenozoic structures, although Cenozoic uplift was detected by thermochronologic studies (Kohn *et al*., 1995; Gombosi *et al*., 2009). Pre-andean structures (described by Nelson *et al*., 1980) are not essential to this work and thus not addressed here.

We will integrate and compare the data of these works with our own observations in order to give a necessary

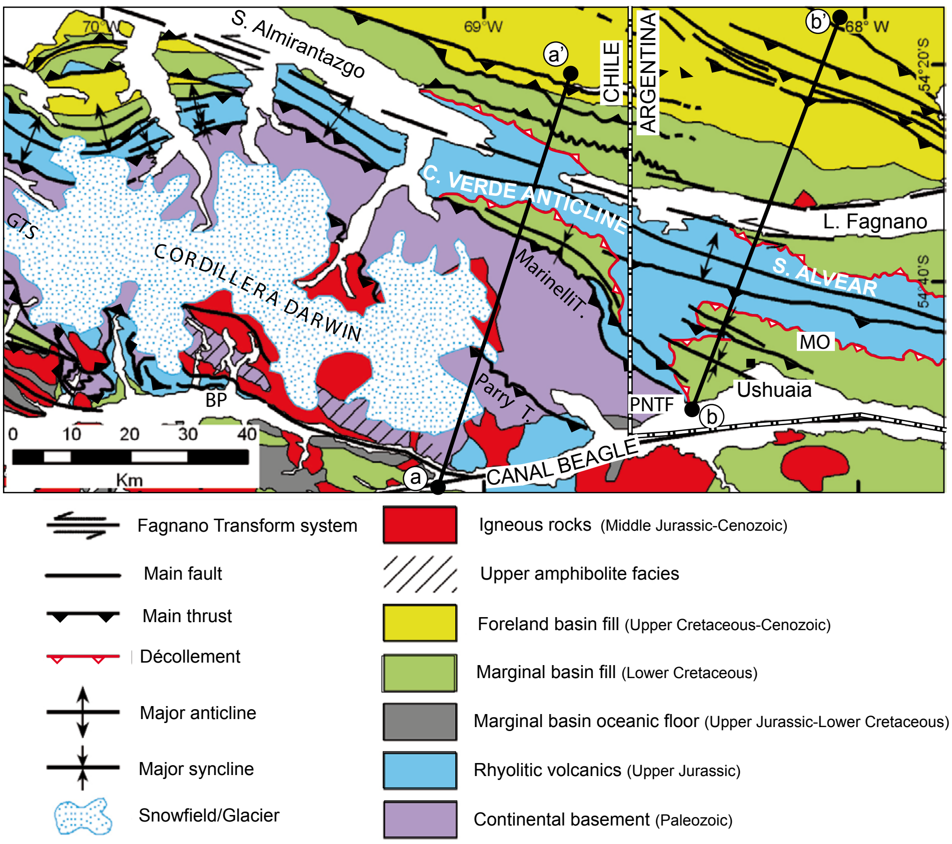

FIGURE 3 Geologic map of the central belt of the Fuegian Andes focused on the most accessible parts of its Argentine portion and on Cordillera Darwin. The geology of Chile is from Nelson *et al.* (1980), Klepeis (1994a) and Klepeis *et al.* (2010). The geology of Argentina is based on maps from Bruhn (1979), Olivero *et al.* (1997), Olivero and Malumián (2008) and our reconnaissance mapping. Location of cross-sections of Figure 5 is indicated by a-a' and b-b'. GTS: Garibaldi thrust sheet (blind), BP: Bahía Pía, PNTF: Parque Nacional Tierra del Fuego, MO: Monte Olivia.

structural framework of the central belt. To summarize and unify the extensive record of structures in a single scheme, we classify them here in three main groups, each revealing more than one set of structures. This classification is only put forward for organizational purposes. These groups comprise: (I) high-grade deformation structures, (II) thrust faults rooted in the continental basement, and (III) structures detached from the structural basement. Published data on the structure of South Georgia is given in a separate section.

Group I: High-grade deformation structures

In Cordillera Darwin, a core of highly strained rocks reaching upper amphibolite to greenschist facies metamorphism has been widely documented (Nelson *et al.*, 1980; Kohn *et al.*, 1993; Klepeis *et al.*, 2010) (Fig. 3). Detailed studies on the metamorphic facies were provided by Kohn *et al.* (1993), and will not be addressed here. These intensely deformed rocks include the Paleozoic continental basement (metapsamites, phyllites, schists) intruded by the Middle-Upper Jurassic Darwin suite (granite and orthogneisses), the Upper Jurassic rhyolitic volcanics, and mafic dikes intruded during formation of the marginal basin oceanic floor (Nelson *et al.*, 1980; Klepeis *et al.*, 2010).

At the southern border of Cordillera Darwin, the contractional structures recognized include N- and NE-vergent folds, with axial plane foliation, and mylonites reflecting thrusting with a top-to-NE shear sense (D1 of Nelson *et al.*, 1980), which are refolded at the zone of higher metamorphic grade (Bahía Pía, Fig. 3) (part of D2 sensu Nelson *et al.*, 1980; see Klepeis *et al.*, 2010). These structures are coeval to prograde (D1), and peak metamorphic conditions (D2) (Kohn *et al.*, 1993), endured during the ductile shearing associated to the obduction of the RVMB floor towards its craton margin (Nelson *et al.*, 1980; Klepeis *et al.*, 2010; see also Dalziel and Brown, 1989; Cunningham, 1995). Klepeis *et al.* (2010) envisaged that the higher-grade metamorphic rocks, associated to NE-directed ductile thrusting, comprise the lower portion of a mid-crustal shear zone reflecting the strains related to obduction and southward underthrusting of the continental margin. Peak metamorphic P-T conditions (8kbar, ≥600°C) indicate a maximum burial of 26-30km (Kohn *et al.*, 1993, 1995).

In Argentina, the continental basement is observed at the SW corner of the Parque Nacional Tierra del Fuego (PNTF) (Fig. 3). There, quartz-mica schists and phyllites with synkinematic garnet (snowball structures) were described by Olivero *et al.* (1997), although the correlation of these phyllites with the Paleozoic basement is still a matter of debate (see Bruhn, 1979; Olivero *et al.*, 1997). The main tectonic foliation (S1 in Fig. 4) dips to the SW, and is axial planar to small folds in quartz veins (F1) with variable plunges (Fig. 4A, D). Later deformation is reflected by meso- and microscopic folds (F2) and associated steep Southwest dipping crenulation foliation (S2) affecting S1; the F2 axes plunge gently to the Southeast (Fig. 4B-D). These two generations of structures also affect the Upper Jurassic rhyolitic volcanics exposed nearby (Fig. 3). Both generations have less metamorphic imprint, but a similar orientation than the two generations of structures at Bahía Pía, mentioned above (Klepeis *et al.*, 2010), and may be related to the same obduction-underthrusting stage.

Away from the PNTF area, both the Upper Jurassic rhyolitic volcanics and the Lower Cretaceous marginal basin fill are only affected by a generation of north- and Northeast vergent asymmetric folds with axial plane foliation dipping south and Southwest (Fig. 4E, F). These structures are associated with prehnite-pumpellyte to greenschist facies metamorphism (Bruhn, 1979) and are apparently not affected by a second set of penetrative structures except near fault zones as described in next section. The available data do not allow yet correlating these structures affecting the marginal basin fill and rhyolitic volcanics with either of the two fold generations recognized at the PNTF area. We cautiously suggest that the deformation such as that depicted in Figure 4E records relatively lower strains accommodated by these rocks during the obduction-underthrusting stage. Later deformation (structures of groups II and III), however, may have been responsible for part of the strain recorded, especially in the marginal basin fill.

Finally, at Isla de los Estados, Dalziel and Palmer (1979) described polyphase deformation with approximately E-W trends (folds and axial plane foliation, and crenulations) in the Upper Jurassic rhyolitic volcanics. They interpreted these structures to record progressive strains associated to horizontal contraction and folding causing significant tectonic thickening, during the *mid*-Cretaceous closure of the RVMB.

Group II: Thrusts rooted in the continental basement

The rocks of Cordillera Darwin with the above-mentioned group I structures are overprinted by two subsequent generations of contractional structures comprised within group II. The first generation (D2 of Nelson *et al.*, 1980) includes backfolds, with an axial plane crenulation foliation, and backthrusts, best revealed at South-Southwest Cordillera Darwin (Nelson *et al.*, 1980; Klepeis *et al.*, 2010). On the northern side of Cordillera Darwin these and the group I structures are subparallel (Nelson *et al.*, 1980).

The second generation of structures within group II (D3 of Nelson *et al.*, 1980) comprises backfolds and a crenulation

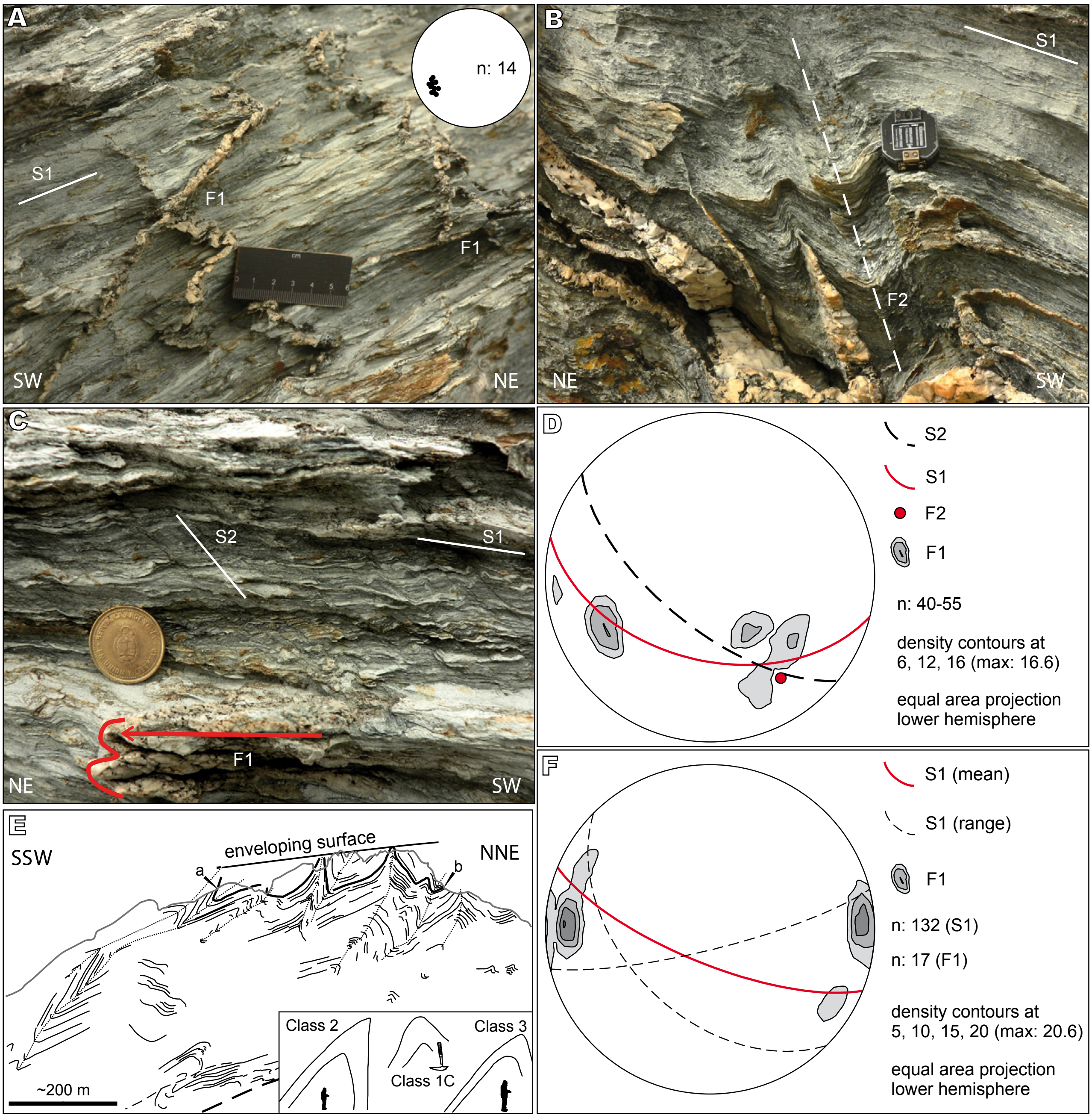

FIGURE 4 A-C) Photographs of structures recognized at the PNTF in the garnet-bearing phyllites supposedly part of the Paleozoic continental basement, as described in the text. S1: main tectonic foliation, S2: crenulation foliation, F1: first generation folds, F2: second generation folds. D) Stereographic projection of the same structures, including data from the Upper Jurassic rhyolitic volcanics; range of measurements indicated by *n*. Note the variable orientations of the F1 axes, a product of subsequent folding (F2) of that lineation. E) Depiction of the style of folding of the Lower Cretaceous marginal basin fill nearby Monte Olivia (location in Fig. 6C). Minimum (bed-length) shortening between points a and b is ~30%. Examples of fold classes are from structures in the rhyolitic volcanics and marginal basin fill. F) Stereographic projection of main foliation and fold axes in the rhyolitic volcanics and marginal basin fill nearby the location depicted in E.

foliation, which affect the previous structures at Western and Southwestern Cordillera Darwin; whereas it comprises NE vergent folds and a crenulation foliation affecting the group I high-grade structures at Bahía Pía (Nelson *et al.*, 1980; Klepeis *et al.*, 2010). Both generations of folds and backfolds of group II are coaxial (Klepeis *et al.*, 2010). The second generation of structures was coincident with retrogression of metamorphic assemblages (Kohn *et al.*, 1993).

These backthrusts and backfolds accommodated deformation in the hangingwalls of a system of ductile thrusts, which uplifted the high-grade structures of group I in the cordilleran core (Klepeis *et al*., 2010). These ductile thrusts, rooted in the continental basement, include the Parry thrust, which cuts the northern boundary of the high-grade metamorphic rocks of Bahía Pía; the blind Garibaldi thrust sheet at the Northwest of Cordillera Darwin; and the Marinelli thrust in the footwall of the Parry thrust (Figs. 3; 5) (Klepeis *et al*., 2010). The Marinelli thrust was mentioned as the leading "basement thrust" in earlier papers (Klepeis, 1994a; Kley *et al*., 1999).

Emplacement of these thrust sheets during uplift and exhumation was accompanied by retrogression of peak metamorphism (Kohn *et al*., 1993, 1995). Klepeis *et al*. (2010) schematically illustrated these structures as fault propagation folds, and argued that these are out-of-sequence structures disconnected to foreland deformation (*cf*. Klepeis, 1994a; Rojas and Mpodozis, 2006).

We interpret that this system of thrusts has continuity toward the east, into the Argentine portion of the central belt, were it is possible to follow the trace of the Marinelli thrust (Fig. 3) (Bruhn, 1979). This thrust system causes the repetition of the rhyolitic volcanics-marginal basin fill stratigraphic sequence nearby the city of Ushuaia, and is traced by mylonitic foliations in the rhyolitic volcanics along the central belt (Figs. 3; 5; 6E). These mylonitic foliations bear a Southwest plunging mineral stretching lineation with kinematic indicators that reveal

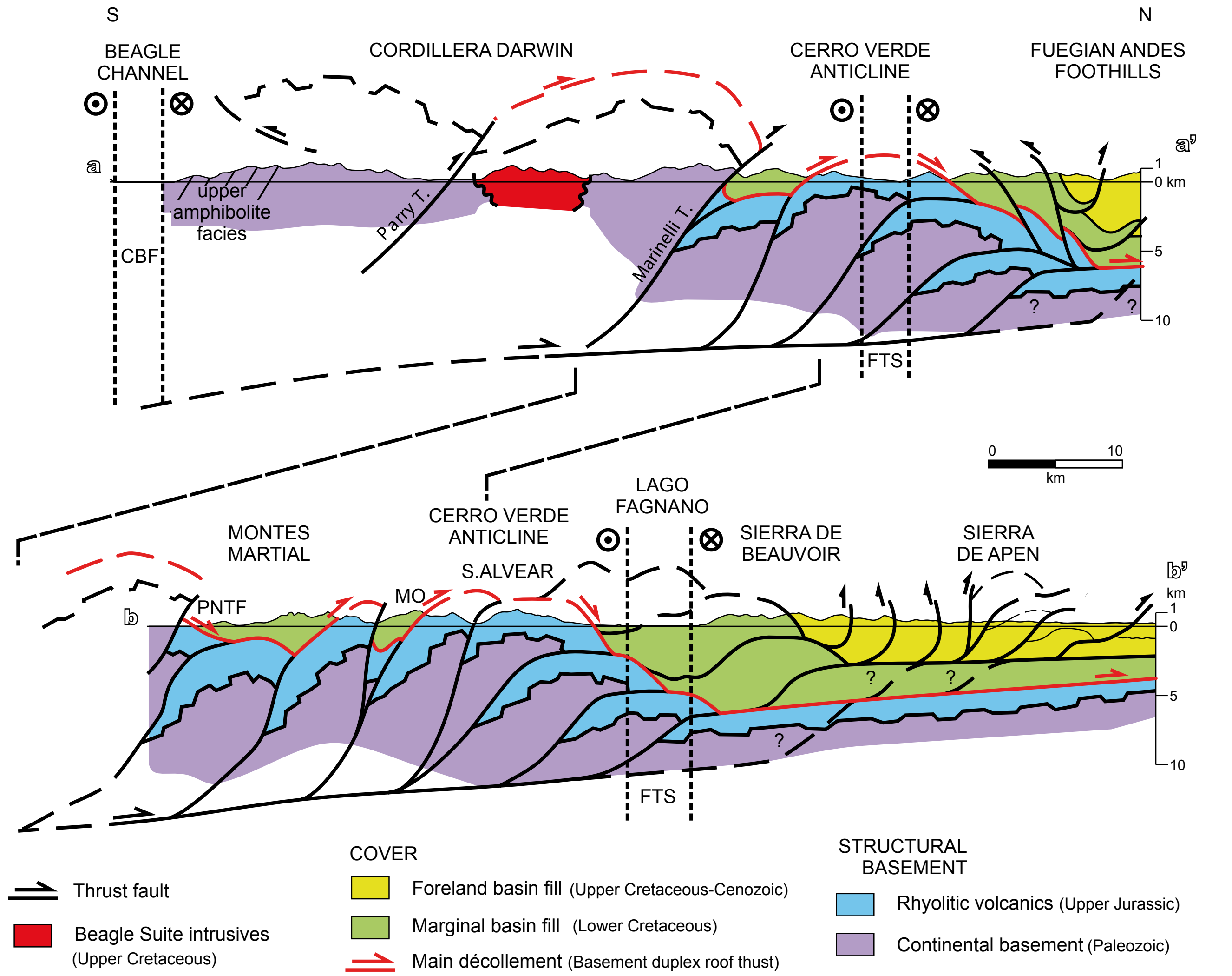

FIGURE 5 | Schematic cross-sections of the central belt, according to the interpretations addressed in this paper, centered at Cordillera Darwin (a-a') and at the western Argentine portion (b-b'). Location in Figure 3. Cross-section a-a' is constructed with surface data from Nelson *et al.* (1980), Klepeis (1994a), Rojas and Mpodozis (2006) and Klepeis *et al.* (2010). Cross-section b-b' is based on stratigraphic data summarized in Olivero and Malumián (2008) and own structural mapping. Effect of the Fagnano Transform System (FTS) and Canal Beagle Fault (CBF; see Cunningham, 1993; Klepeis *et al.*, 2010) are neglected in this schematic depiction. PNTF: Parque Nacional Tierra del Fuego, MO: Monte Olivia (projected).

top-to-Northeast displacements (Fig. 6E), consistent with observations made by Bruhn (1979).

Group III: Structures detached from the structural basement

The contact between the Upper Jurassic rhyolitic volcanics and the Lower Cretaceous marginal basin fill has been interpreted as a décollement level based on high shear strains reported from its vicinity (Klepeis, 1994a; Rojas and Mpodozis, 2006). These strains are manifested by penetrative foliations that overprint older structures and are more intense towards the décollement surface, becoming parallel to it (Klepeis, 1994a). Our own surveys in the Argentine side of the central belt reveal that this décollement is well preserved and has previously been recognized as a fault zone elsewhere (Kranck, 1932; Olivero *et al*., 1997; Bruhn, 1979). At the PNTF, we observed fault rocks from the area of the contact between the rhyolitic volcanics and the marginal basin fill (Lemaire and Yahgan formations, respectively). This fault, already reported by Olivero *et al*. (1997), is a Southeast dipping décollement where the Yahgan Formation overlies the Lemaire Formation (Figs. 3; 5; 6A); its attitude is caused by later folding of the fault surface. The fault zone is defined by a foliation that overprints earlier structures (group I) and parallels the fault (Fig. 6B). Eastward from the fault in the Yahgan Formation, this pervasive foliation becomes a crenulation formed in the earlier foliation (S1 of group I), that disappears 50-100m farther east; this reflects higher strains at the fault zone.

At the northern face of the Monte Olivia (Fig. 3), a fault zone dipping 45°-60°S, characterized by mylonites is recognized near the contact of green-schists and slates of the Yahgan Formation (south) with a quartz-porphyry of the Lemaire Formation (north) (Kranck, 1932; Olivero and Malumián, 2008; own unpublished data), thus constituting the same décollement recognized at the PNTF (Figs. 3; 5; 6C). Finally, at the northern side of the Sierra de Alvear (Fig. 3), the contact between the Lemaire Formation and the marginal basin fill dips to the north, and was depicted by Bruhn (1979) as fault (Fig. 5). This would indicate, consistently with the identified geometries at the PNTF and Monte Olivia, that the décollement has been folded by an anticlinorium between Monte Olivia and the northern flank of Sierra de Alvear. This anticlinorium is laterally continuous with the Cerro Verde anticline. The décollement is also deformed by a synclinorum between Monte Olivia and the PNTF (Figs. 3; 5).

The described décollement coincides with the sole thrust of the thrust-fold belt, which is interpreted to be approximately located at the base of the marginal basin fill (Klepeis, 1994a; Rojas and Mpodozis, 2006; Torres Carbonell *et al*., 2011). This implies that the structural basement of the Fuegian thrust-fold belt (*i.e*. the structural unit below its décollement) is composed of the Paleozoic continental basement and Upper Jurassic rhyolitic volcanics, which were attached during deformation. This may have occurred because of the irregular base of the rhyolitic volcanics that decreased its suitability as a décollement, since these deposits covered the paleotopography created by faulted hemigrabens (*cf*. Hanson and Wilson, 1991). By contrast, the shaly nature of the Upper Jurassic-Lower Cretaceous interface favors its role as a main décollement, as already recognized to the north of Cordillera Darwin (the Río Jackson detachment of Klepeis, 1994a).

We interpret that this décollement acted as the common roof thrust of the basement-rooted thrust faults described above (group II), which in addition caused the décollement's folding into anticlinoria and synclinoria (Figs. 3; 5). This interpretation implies that the emplacement of the thrust sheets of group II transmitted the shortening recorded in the thrust-fold belt, as further discussed in following sections.

In Argentina, the rocks of the central belt structurally above the décollement (marginal basin fill and early foreland basin fill –Lower Cretaceous-Santonian–) are mostly affected by north- and Northeast vergent folds as described above for the Lower Cretaceous rocks (Fig. 4E), and by class 1B (in competent beds), 1C and 2 (in less competent beds) folds in the Upper Cretaceous rocks (fold classification *cf*. Ramsay, 1967). A dominant axial plane foliation is observed in these rocks, varying from a continuous foliation formed by the alignment of micas and flattened quartz and feldspar in the Lower Cretaceous rocks, to disjunctive foliations formed by pressure solution in the Upper Cretaceous rocks (Bruhn, 1979; Torres Carbonell *et al*., 2013). Similar geometries are common in the rocks above the Río Jackson detachment in Chile (Klepeis, 1994a). As already mentioned, at least part of the deformation in the Lower Cretaceous marginal basin fill may have been produced during the obduction-underthrusting stage (structures of group I), *i.e*. prior to the development of the structures of groups II and III.

Structure of South Georgia

The generalized SW to NE cross-section of South Georgia reveals an uplifted block of the marginal basin floor, composed of welded oceanic and continental crust, faulted with Northeast vergence over folded marginal basin fill rocks (Fig. 1) (Tanner and Macdonald, 1982; Storey, 1983). The tectonic contact between the basin floor units and the basin fill is a notorious mylonitic zone (Storey, 1983). The marginal basin fill, with facies equivalent to those of the Fuegian Andes (Tanner, 1982; Thomson *et al*., 1982), is intensely folded and has been subjected to a minimum shortening

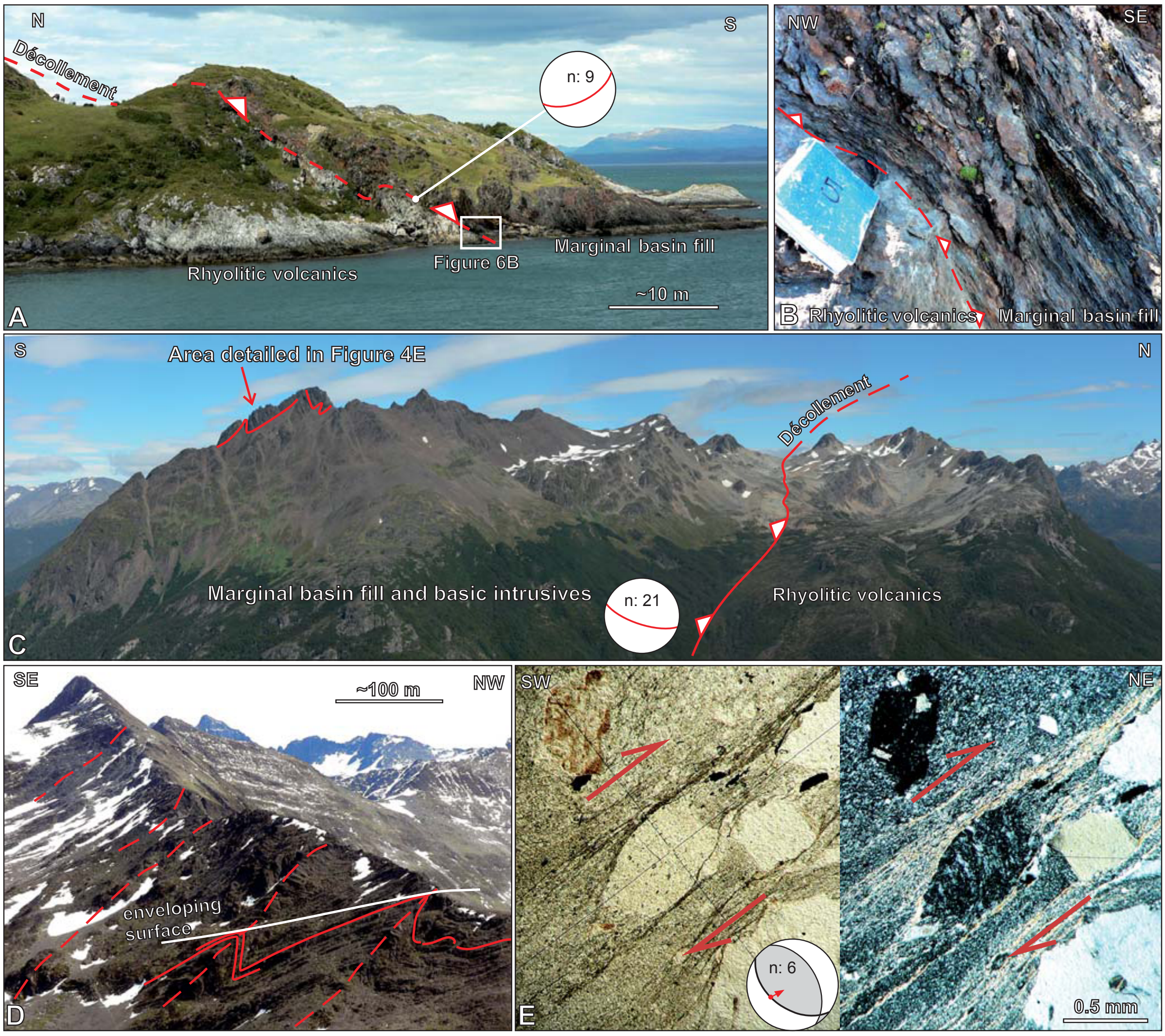

FIGURE 6 A) Fault contact (décollement) between the Lower Cretaceous marginal basin fill (Yahgan Formation) and the Upper Jurassic rhyolitic volcanics (Lemaire Formation) at the Parque Nacional Tierra del Fuego (PNTF). The stereographic projection indicates the average attitude of the fault. B) Detail of the décollement fault zone. The base of the marginal basin fill is highly strained, with a foliation parallel to the décollement and highly oblique to regional structural trends (*e.g.* Fig. 4); about 50m away (eastward) the strain decreases notably and the foliation becomes moderate and parallel to the NW-SE or W-E regional tectonic grain. C) Same décollement nearby Monte Olivia, photo taken from this mount in a direction parallel to the strike of the décollement. The stereographic projection is from measurements on the fault zone at the roadside. Note the folded strata in the marginal basin fill, depicted in Figure 4E. D) Folded strata in the oldest foreland basin fill (Upper Cretaceous), the enveloping surfaces of the anticlines in the fold trains dip consistently south and Southwest. E) Lithic porphyroclast with asymmetric strain shadows indicating top-to-NE displacements in a mylonite at the southern flank of Sierra de Alvear. Without (left) and with (right) crossed polars. Fault solution developed with *FaultKin* 1.2 software (by R. Allmendinger). Bold line indicates fault plane, arrow shows stretching lineation with sense of hanginwall movement; white and gray correspond to P and T quadrants, respectively.

and 55% (up to 30km) (Tanner and Macdonald, 1982). These rocks are metamorphosed to phrenite-pumpellite facies, with biotite-grade lower greenschist facies nearby the major mylonitic zone (Storey, 1983).

It has been suggested that the oceanic or continental crust flooring the marginal basin fill in South Georgia may have undergone a limited amount of subduction or underthrusting toward the south below the exposed basin floor, in association to the development of the mylonitic zone (Storey, 1983; Tanner and Macdonald, 1982). This process would have caused simple shear responsible for the deformation of the marginal basin fill (Tanner and Macdonald, 1982), reflecting a mechanism of basin closure very similar to the one interpreted from the structure of Cordillera Darwin (Nelson *et al.*, 1980; Klepeis *et al.*, 2010). Although uplift of the marginal basin floor may have certainly occurred along the mylonitic zone, recent kinematic analyses showed the possible interposition of left-lateral strike-slip displacements along the shear zone, which leads to interpret transpression during the marginal basin closure (Curtis *et al.*, 2010).

Time constraints on the uplift and exhumation of the central belt

The beginning of closure of the back arc basin and associated penetrative deformation has been constrained in the Fuegian Andes by the youngest age of the marginal basin fill. This age was provided by late Albian (~100Ma) inoceramids in the Yahgan and Beauvoir formations in southern and central Tierra del Fuego, respectively, consistently with previous Aptian-Albian fossil ages from the marginal basin fill (Olivero and Martinioni, 1996; Olivero *et al*., 2009; Martinioni, 2010).

Another time constraint arises from the Late Cretaceous Beagle suite granites in Cordillera Darwin, which intrude rocks deformed by group I structures (Klepeis *et al*., 2010). Ages for these intrusives were summarized by Kohn *et al.* (1995); the most recent estimates are based on zircon U/Pb crystallization ages spanning between ~86 and ~74Ma (Klepeis *et al*., 2010) (Fig. 7). The granites are cut by the structures of group II in Cordillera Darwin (Klepeis *et al*., 2010). Therefore, two discrete main contractional phases are determined for the central belt: obduction and underthrusting (group I structures) between 100 and 86Ma and emplacement of continental basement-rooted thrust sheets (group II) after ~80Ma (Fig. 7) (Klepeis *et al*., 2010). The recognition of Jurassic rhyolitic volcanics thrust over late Eocene strata in an intermontane basin in the eastern Fuegian Andes (Bahía Sloggett) (Olivero and Malumián, 2008) indicates that basement thrusting continued at least after the Eocene.

In addition, K-Ar and Rb-Sr geochronology (Halpern, 1973) and closing-temperature relationships of igneous and metamorphic rocks from Cordillera Darwin revealed an early cooling stage produced by uplift between the early metamorphism (100-85Ma) and c. 64Ma (Nelson, 1982). A subsequent stage of slow uplift-related cooling since ~60Ma was determined by Nelson (1982) on the basis of fission track geochronology and closing temperatures of apatite, zircon and titanite from the Darwin and Beagle suite granites, with an episode of rapid uplift between 43 and 38Ma (Fig. 7). Later, the addition of Ar^{40}/Ar^{39} ages from metamorphic rocks of Cordillera Darwin allowed recalibrating the first rapid cooling episode between 90-70Ma, followed by relatively slow cooling between 60 and 40Ma with a peak cooling at about 50Ma (Fig. 7) (Kohn *et al*., 1995). The latest results on thermochronology, based on zircon and apatite fission track and (U-Th-Sm)/He data from Upper Jurassic rhyolitic volcanics and a pluton intruding the Lower Cretaceous marginal basin fill in the Argentine Fuegian Andes, indicate an episode of rapid cooling between ~48 and ~36Ma (Fig. 7) (Gombosi *et al*., 2009).

Lastly, indirect evidence of rock uplift in the central belt arises from provenance studies in the adjacent Austral foreland basin. Detrital zircon U/Pb ages and petrographic analysis from the foreland basin fill sedimentary rocks reveal an initial supply of Upper Jurassic rhyolitic detritus at 80-70Ma (Fig. 7), evidencing orogenic unroofing (Olivero *et al*., 2003; Barbeau *et al*., 2009).

Regarding South Georgia, based on fossil and radiometric (K-Ar) ages Thomson *et al*. (1982) proposed an age as young as 82-91Ma for the main phase of deformation of the marginal basin fill, and subsequent continued uplift until 50Ma. A recent Rb-Sr biotite dating constrained the youngest age of the main deformation associated to the mylonite separating the basin floor from the basin fill unit (previous section) to ~83Ma (Curtis *et al*., 2010). These age constraints for the main phase, related to obduction of the marginal basin floor, are strikingly consistent with the ages determined in Cordillera Darwin for the first main contractional phase related to the closure of the marginal basin (Fig. 7) (Klepeis *et al*., 2010).

EASTERN FUEGIAN THRUST-FOLD BELT

Stratigraphy: uppermost Cretaceous-Cenozoic successions

During the Late Cretaceous, the Fuegian thrust-fold belt progressively incorporated the sedimentary successions of the foreland basin to the evolving thrust sheets (Fig. 8) (Álvarez-Marrón *et al*., 1993; Torres Carbonell *et al*., 2011). These successions are syntectonic, since their sedimentary evolution is intimately related to the development of structures in the thrust-fold belt (Torres Carbonell *et al*., 2008b, 2009, 2011). Among the evidence of syntectonic sedimentation, as further explained below, the most important is the occurrence of: i) conglomerates, detrital composition, and resedimented microfossils indicating significant erosion of previous successions; ii) angular unconformities evidencing deformation-uplift plus erosion before or during sedimentation; and iii) in some places, chaotic facies and/or growth structures and syntectonic clastic dikes in the limbs of anticlines (Ghiglione, 2002; Torres Carbonell *et al*., 2008b, 2009).

Systematic studies in eastern Tierra del Fuego allowed to define the chronostratigraphy of the uppermost Cretaceous-Cenozoic syntectonic successions (summarized in Martinioni *et al*., 1999; Olivero and Malumián, 2008; Malumián and Olivero, 2006; Torres Carbonell *et al*., 2009) (Table 1; Fig. 8). The main characteristics of the syntectonic successions recognized in the eastern Fuegian thrust-fold belt, including their lithostratigraphy, composition, thicknesses, and age constraints are summarized in Table 1. Synthetic stratigraphic columns are drawn in Figure 9. For further stratigraphic and sedimentologic information, the reader is referred to the cited papers.

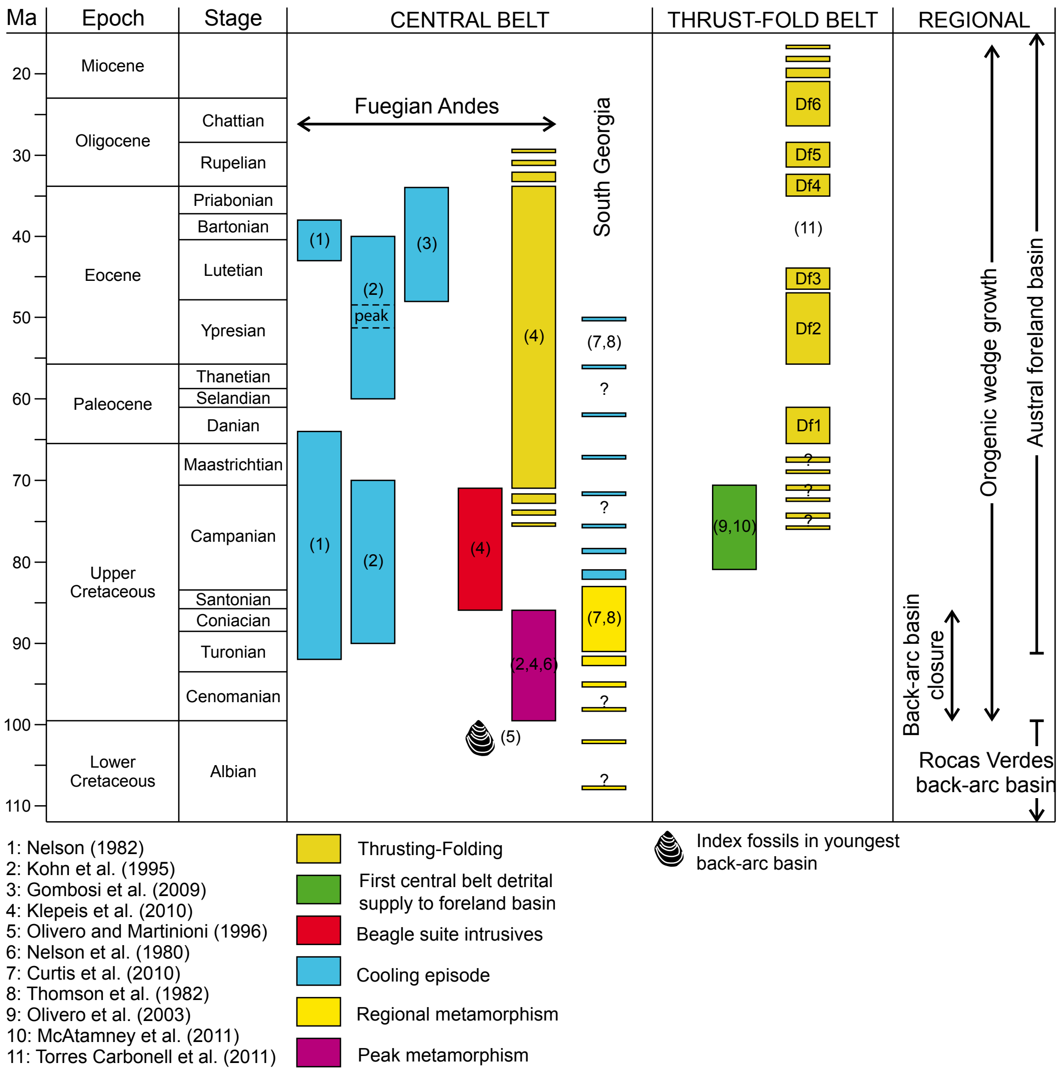

FIGURE 7 | Summary of episodes that constrain the timing of deformation in the central belt and thrust-fold belt of the Fuegian Andes and South Georgia.

Foreland contractional stages

Our previous work on the crosscutting relationships between each syntectonic succession and the structures of the thrust-fold belt, constrain the kinematic evolution of the frontal Fuegian Andes after the latest Cretaceous (Torres Carbonell *et al.*, 2009, 2011). Six foreland contractional stages (D_f) were identified in the eastern Fuegian thrust-fold belt (Torres Carbonell *et al.*, 2011).

To calculate shortening values and percentages for each contractional stage, we defined a minimum initial length for the studied part of the thrust-fold belt by combining and restoring cross-sections to the north and south of the Fagnano Transform System (Figs. 10; 11). This transform fault cut the Fuegian thrust-fold belt after the main contractional tectonics, probably during late Neogene times, producing a left-lateral offset of almost 50km (Fig. 8) (Torres Carbonell *et al.*, 2008a). Therefore, the northern and southern studied portions of the thrust-fold belt, now exposed in an almost continuous transect along the Atlantic coast, had an original lateral separation of ~50km. This leads to uncertainties in the estimations of shortening at a regional scale, (*i.e.* the shortening transferred to the foreland in the southern cross-section may be different to the coeval shortening in the northern cross-section, at least for some contractional stages), probably due to along-strike shortening gradients and/or to inherent errors in the construction of the cross-sections. We hence estimate qualitatively that errors may be of at least 10%.

D_f1: Late Cretaceous-Danian contractional stage

The Maastrichtian-Danian succession (Fig. 8), as well as older rocks, is affected by penetrative tectonic foliations with

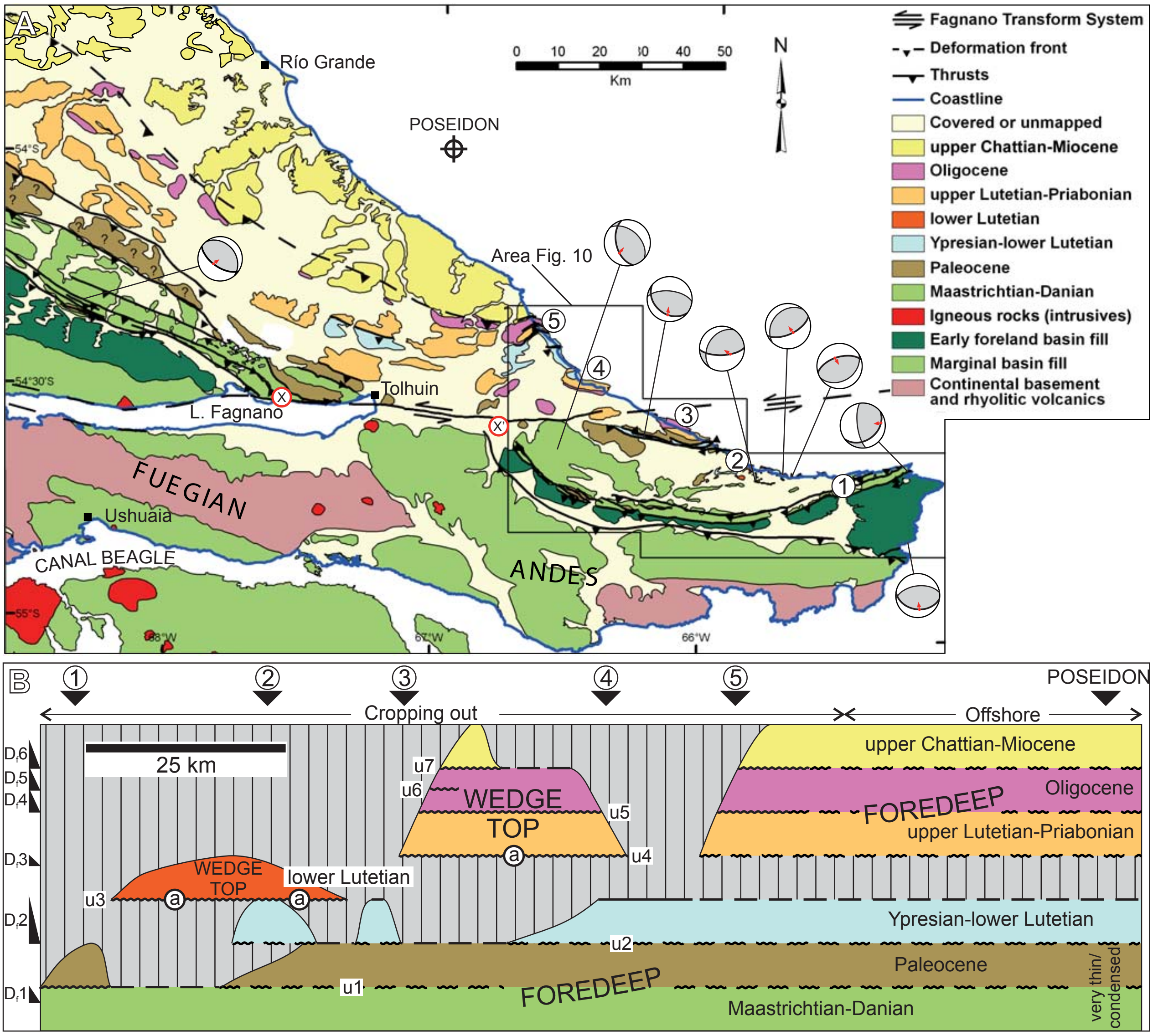

FIGURE 8 | A) Distribution of syntectonic successions and main geologic units in eastern Tierra del Fuego, and major related structures (location in Fig. 1B). Modified from Olivero and Malumián (2008). Locations marked with x and x' indicate reference points from which a left-lateral offset of almost 50km has been calculated along the Fagnano Transform System (Torres Carbonell *et al.*, 2008a). Fault solutions for thrusts are shown, indicating contraction approximately normal to the main structural trend in each location. Developed using *FaultKin* 1.2 software (by R. Allmendinger). Bold line indicates fault plane, arrow shows striae orientation with sense of hanginwall movement; white and gray correspond to P and T quadrants, respectively. Location of Figure 10 is shown. B) Chronostratigraphic chart of the syntectonic successions described in Table 1, according to locations indicated in A. Contractional stages D$_f$1 to D$_f$2 are also shown with their approximate time spans, as well as unconformities u1-u7. Circled *a* indicates angular unconformity. Stratigraphy of Poseidón well is from Malumián *et al.* (2008).

a varying degree of development. These structures include moderately to weakly developed pressure-solution disjunctive foliations and pencil structures subparallel to fold axial planes and axes, respectively (Fig. 12A, B) (Torres Carbonell *et al.*, 2013). These structures are not recognized in any younger unit, indicating a number (still not well-established) of contractional episodes during the Late Cretaceous to Danian (Torres Carbonell *et al.*, 2013), called here D$_f$1.

D$_f$1 is associated to a slightly angular to parallel unconformity (called u1), which separates the Maastrichtian-Danian succession from Paleocene conglomerates and sandstones (Figs. 8; 9) (Torres Carbonell *et al.*, 2011). The u1 coincides with an increased input of coarse detritus to the foreland basin, mostly deformed Upper Jurassic and Lower Cretaceous rock fragments eroded from the central belt, indicating uplift and exhumation (Olivero *et al.*, 2003; Martinioni *et al.*, 1999; Olivero, 2002; Barbeau *et al.*, 2009; Torres Carbonell, 2010). This central belt uplift is coeval with the end of the first rapid cooling stage of metamorphic rocks from Cordillera Darwin established by Nelson (1982) (Fig. 7).

TABLE 1 | Main characteristics of lithostratigraphic units that compose the syntectonic successions of the eastern Fuegian thrust-fold belt. Database summarized in Martinioni *et al.* (1999), Malumián and Olivero (2006), Olivero and Malumián (2008), Barbeau *et al.* (2009), Ponce (2009), Torres Carbonell *et al.* (2009), Martinioni (2010)

Syntectonic succession	Lithostratigraphic units included	Dominant lithology	Minimum thickness (m)	Boundaries	Depositional setting	Age constraints
Maastrichtian -Danian	Policarpo Fm.	Mudstones with fine sandstone interbeds	350-800	Base unknown Top u1	Turbidite systems Foredeep depocenter	Ammonites, foraminifera, dinocysts, detrital zircon depositional ages
Paleocene (Selandian? -Thanetian?)	Tres Amigos Fm. Cerro Apen Beds	Conglomerates and sandstones with minor siltstones	50-300	Base u1 Top inferred u2	Fan deltas, channeled turbidite systems Proximal? foredeep	Dinocysts, foraminifera
	Cabo Leticia Fm. La Barca Fm.	Fining upward conglomerates, breccias, sandstones and mudstones	370			
Ypresian -lower Lutetian	Punta Noguera Fm. Cerro Ruperto Fm. Punta Torcida Fm.	Interbedded sandstones -siltstones and mudstones	650-450	Base inferred u2 Top u3 and u4	Mostly channeled turbidite systems Proximal foredeep	Dinocysts, foraminifera, detrital zircon depositional ages
Lower Lutetian	Río Bueno Fm.	Limestones, marls, grainstones, calcareous sandstone	80	Base u3 Top unknown	Current-dominated carbonatic sedim., shallow water Wedge top margin	Foraminifera
Upper Lutetian -Priabonian	Leticia F. Cerro Colorado Fm. La Despedida G.	Sandstones and interbedded sandstone-mudstone	1100-1300	Base u4 Top u5	Transgressive from shallow water deposits to offshore channeled turbidite systems Wedge top depocenter	Foraminifera, calcareous nanoplankton, detrital zircon age peak
Oligocene	Tchat-chii Fm.	Conglomerates	70	Base u5 Includes u6 Top u7	Deep-water turbidites Wedge top and proximal foredeep	Foraminifera, calcareous nanoplankton, detrital zircon age peak
	María Cristina & Puesto Herminita Beds Puesto José Fm.	Mudstones with interbedded sandstones	200-1600			
Upper Chattian -Miocene	Desdémona Fm.	Mudstones	200	Base u7 Top unconformable	Debris flows, growth strata, depositional slope Proximal foredeep	Foraminifera
	Malengüena Fm.	Conglomerates and sandstones	200	Base u7 Top undefined	Channeled density flows Wedge top margin	

During D_f1, the Maastrichtian-Danian succession developed layer-parallel shortening (LPS) and minor folding, in front of more deformed areas of the thrust-fold belt (*e.g.* Figs. 6D; 12B) (Torres Carbonell *et al.*, 2013). A similar history of deformation (LPS then buckling) was proposed for rocks of the same age in the Chilean part of Tierra del Fuego (Winslow, 1983). Although precise shortening estimates related to the D_f1 deformation are difficult to calculate, regional shortening values of at least 10% to 25% may have been transferred to the foreland according to the penetrative structures recorded (*cf.* Ramsay and Huber, 1983).

D_f2: Ypresian-early Lutetian contractional stage

The Maastrichtian-Danian, Paleocene and Ypresian-lower Lutetian successions (Fig. 8) are incorporated into thrust sheets described in detail elsewhere (Torres Carbonell *et al.*, 2008a, 2011; Torres Carbonell, 2010). Since these structures do not affect younger rocks, they are constrained to the Ypresian-early Lutetian. These structures are assigned to the contractional stage D_f2.

The youngest age of D_f2 is marked by the angular unconformity u3, which separates the lower Lutetian

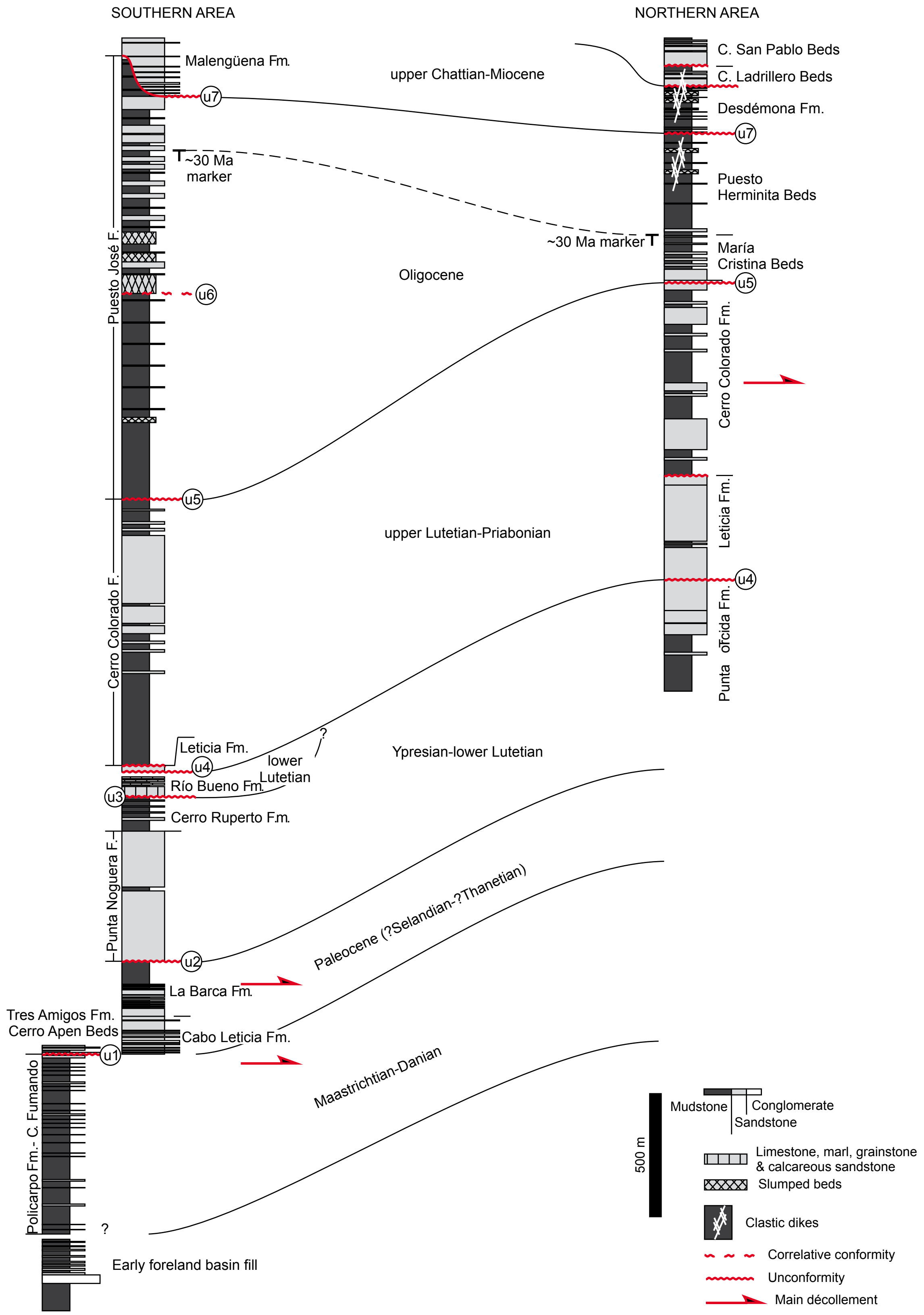

FIGURE 9 | Synthetic lithostratigraphic sections of the syntectonic successions described in Table 1, showing thicknesses, main lithologies, location of unconformities (u1-u7), names of lithostratigraphic units, and other significant features. For references, see Table 1.

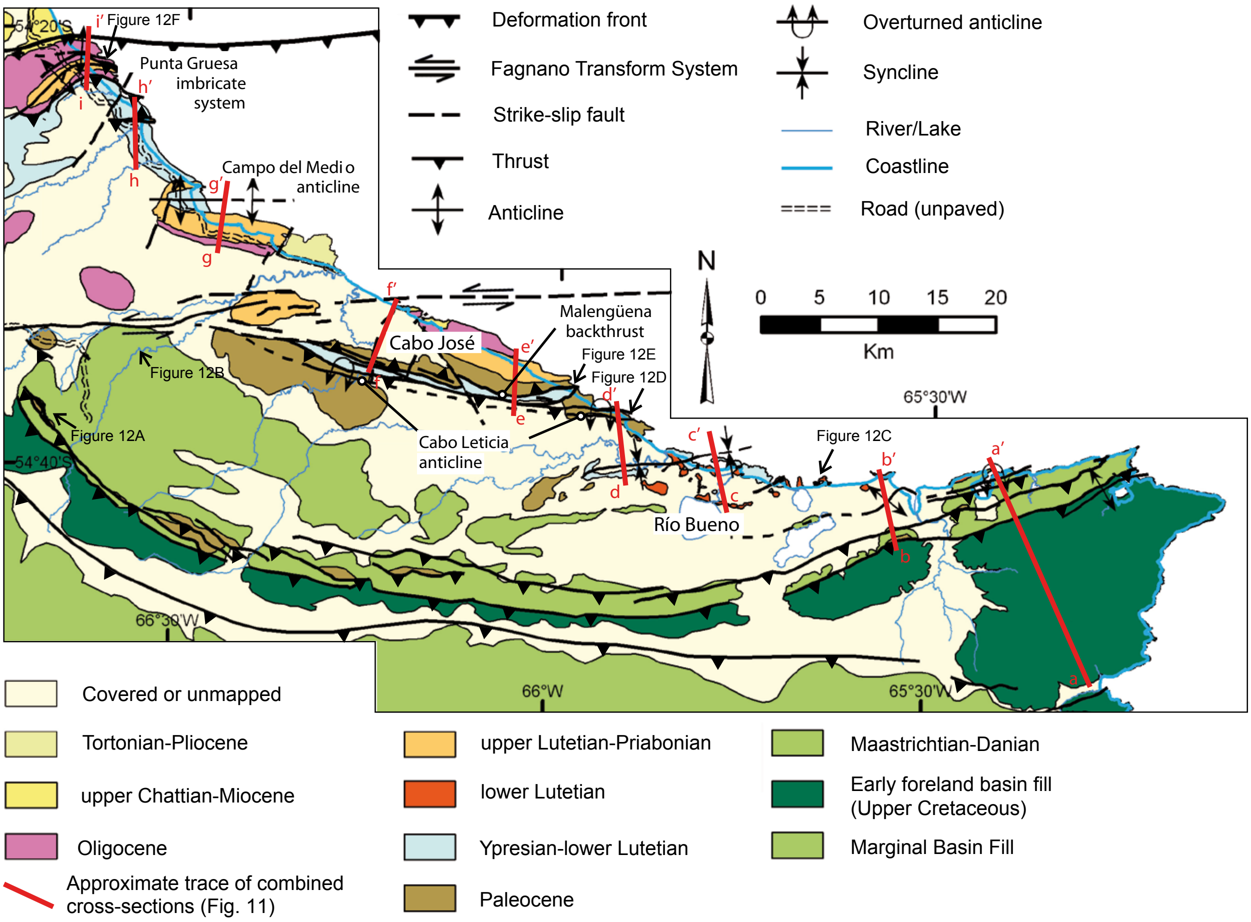

FIGURE 10 | Geologic map of the Fuegian thrust-fold belt in the eastern coast of Tierra del Fuego, where it is best exposed (location in Fig. 8), showing major structures, as well as the approximate location of the combined cross-section depicted in Figure 11.

succession (Río Bueno Formation), unaffected by D_f2, from the previous successions (Table 1; Figs. 8; 10; 12C). The youngest age of the Río Bueno Formation was constrained to 46.7Ma based on the most recent foraminifer calibrations (Olivero and Malumián, 2008; N. Malumián in Torres Carbonell *et al.*, 2009). The oldest age of stage D_f2 is less constrained; since it affected Paleocene (*e.g.* Fig. 12D) and Ypresian-lower Lutetian successions, it may not be older than the earliest Eocene (Torres Carbonell *et al.*, 2009, 2011).

During D_f2, the sole fault of the thrust-fold belt was ultimately connected to the base of the Cenozoic rocks of the foreland basin fill, and the thrust-fold belt leading edge was propagated to the foreland basin interior in sequence with emplacement of thrust-sheets formed by Maastrichtian-Danian to Ypresian-lower Lutetian rocks (Torres Carbonell *et al.*, 2011). The shortening produced during the D_f2 stage was of 20.1km (20.9%) (Fig. 11), and was coeval with the uplift that caused the marked erosive hiatus involved by u3 (Figs. 8B; 12C).

D_f3: Lutetian contractional stage

The lower Lutetian succession (Río Bueno Formation) (Fig. 8; Table 1) predates a stage of folding and thrusting called D_f3, which is thus younger than 46.7Ma (see previous section). The youngest possible age of the D_f3 stage is constrained by the major u4 unconformity, which separates Paleocene rocks from the upper Lutetian-Priabonian succession (Fig. 8B), and is associated to uplift in the thrust-fold belt during D_f3 (Torres Carbonell *et al.*, 2009).

The manifest angularity of u4, which involves a hiatus of as much as 12Ma in the study area, supports the post-D_f3 nature of the upper Lutetian-Priabonian succession (Torres Carbonell *et al.*, 2009). The same unconformity was recognized regionally in the foreland basin, involving different hiatuses depending on the location, indicating that it has been enhanced by tectonism (*i.e.* differential uplift across the basin) (Biddle *et al.*, 1986; Galeazzi, 1998; Malumián, 2002).

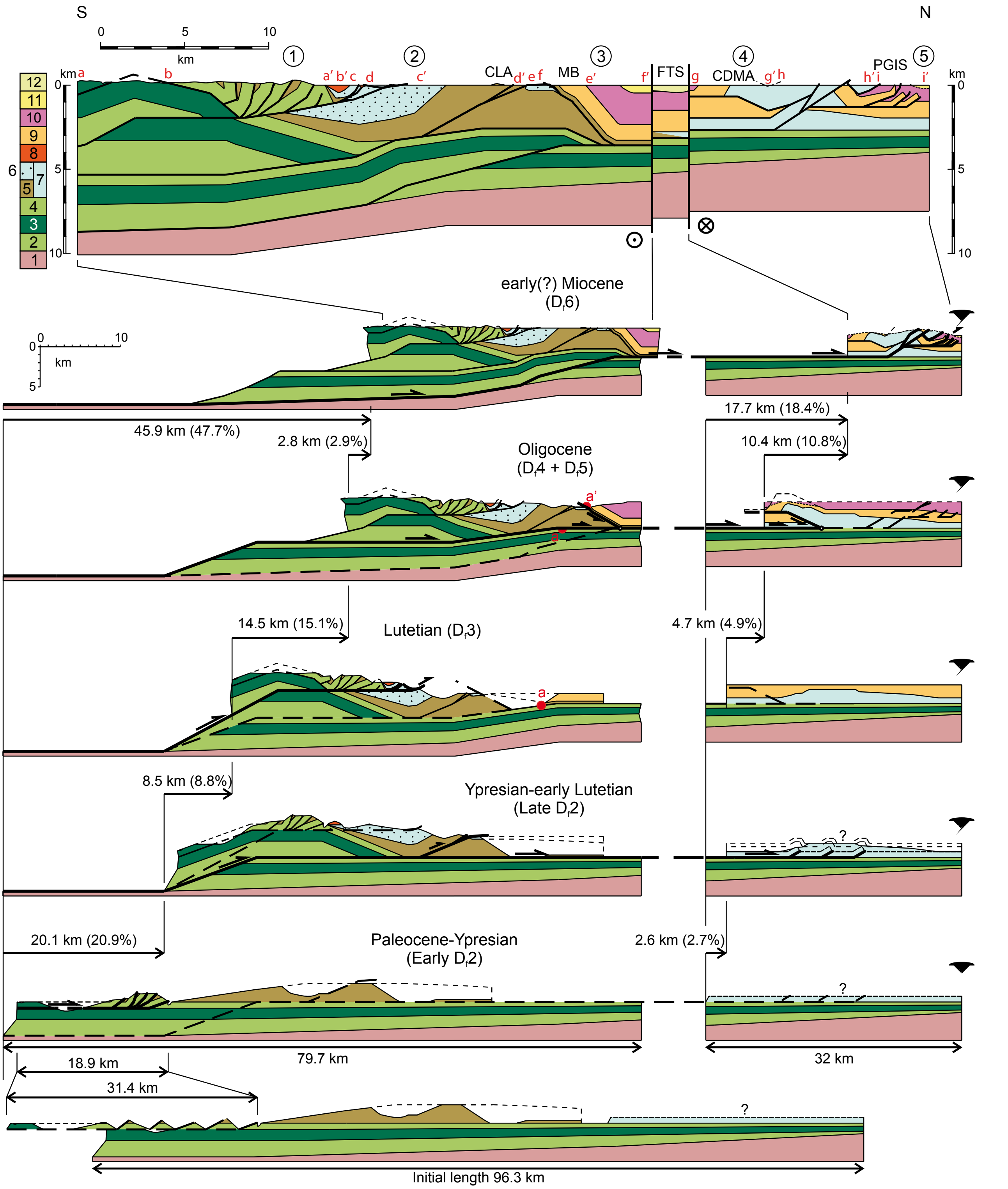

FIGURE 11 | Combination of restorable cross-sections in the Fuegian thrust-fold belt south and north of the Fagnano Transform System (FTS), showing their kinematic evolution during stages D_f2 to D_f6. Several detailed cross-sections across the major structures (located in Fig. 10) were used to construct this regional cross-section (endpoints marked by letters a-a' to i-i'). Stratigraphy (see text): 1) Paleozoic basement and Upper Jurassic rhyolitic volcanics, 2) Lower Cretaceous marginal basin fill, 3) Upper Cretaceous early foreland basin fill, 4) Maastrichtian-Danian, 5) Paleocene, 6) Ypresian-lower Lutetian, 7) Paleocene-lower Lutetian, 8) lower Lutetian, 9) upper Lutetian-Priabonian, 10) Oligocene, 11) upper Chattian-Miocene, 12) Tortonian-Pliocene(?) fill of FTS depocenters. CLA: Cabo Leticia anticline, MB: Malengüena backthrust, CDMA: Campo del Medio anticline, PGIS: Punta Gruesa imbricate system. The initial length is a minimum estimation for the combined cross-sections prior to the development of the FTS. Shortening percentages referenced to the initial length. See text for assumptions and further explanation. The rifted geometry of the basement (Mesozoic extension) is omitted for simplicity.

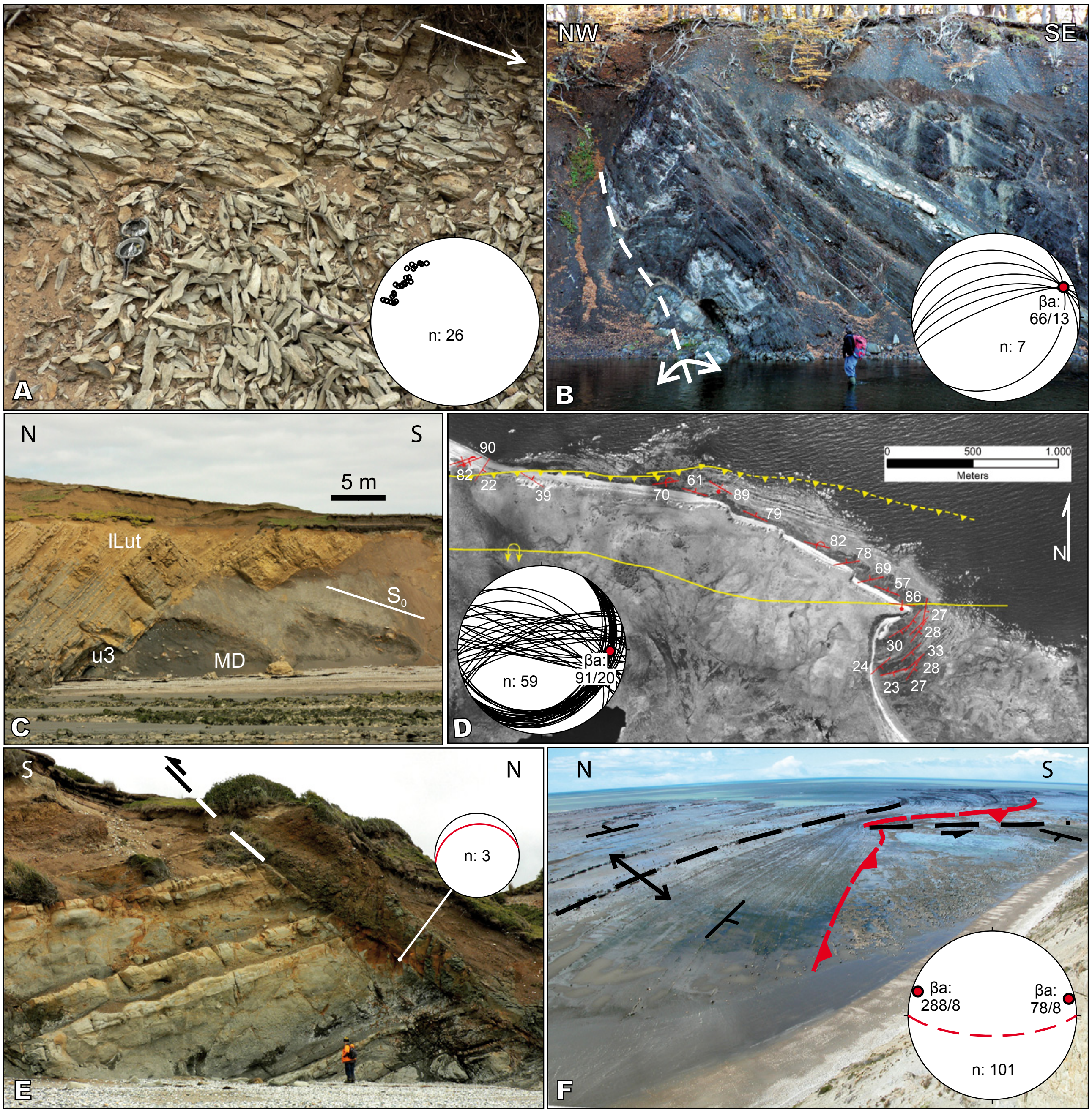

FIGURE 12 | Details of structures in the eastern Fuegian thrust-fold belt. All stereographic plots are lower hemisphere, equal area projections, with *n* number of measurements. A) Pencil structures in the Maastrichtian-Danian succession, developed during the contractional stage D_f1. B) Fold in Upper Cretaceous rocks, βa: beta axis. C) Detail of angular unconformity u3 separating the Maastrichtian-Danian (MD) and the lower Lutetian (lLut) successions. This unconformity constrains the youngest age of the D_f2 contractional stage. See Figure 10 for location. D) Aerial photograph showns structural detail of the thrust-related Cabo Leticia anticline, developed during the D_f2 stage. See Figure 10 for location. E) Malengüena backthrust detaching the upper Lutetian-Priabonian from underlying Ypresian rocks, developed during the D_f5 stage. Located in Figure 10. F) Surface traces of the thrust-related structures developed in Oligocene rocks in the Punta Gruesa imbricate system (Fig. 10), during the D_f6 stage. Beta axes of main folds are shown, together with the estimated orientation of the exposed thrust.

Additional evidence that strengthens this interpretation arises from the change in depositional setting across u4, from relatively deep-water Ypresian-lower Lutetian to shallow water upper Lutetian settings, indicating foreland uplift (Table 1) (Olivero and Malumián, 2008; Torres Carbonell and Olivero, 2012); and from the significant increase in detrital supply from the central belt (Middle-Upper Jurassic and Paleozoic detritus) in the upper Lutetian-Priabonian succession, indicating its exhumation (Olivero, 2002; Barbeau *et al.*, 2009; Torres Carbonell, 2010). This central belt uplift, coincident in part with the rapid cooling of rocks determined by Kohn *et al*. (1995) and Gombosi *et al*. (2009) (Fig. 7) is coeval with both the D_f2 and D_f3 stages.

In summary, the oldest age of the upper Lutetian-Priabonian succession, constrained at 43.7Ma by foraminifera and calcareous nanoplankton (Olivero and Malumián, 2008; Torres Carbonell *et al*., 2009) and by detrital zircons with a youngest significant U/Pb age peak at ~43Ma (Barbeau *et al*., 2009), places the end of stage D_f3 within the Lutetian. The D_f3 stage was characterized by the development of out-of-sequence structures (Torres Carbonell *et al*., 2011), and added 8.5km (8.8%) shortening to the eastern Fuegian thrust-fold belt (Fig. 11).

D_f4 and D_f5: Oligocene contractional stages

The upper Lutetian-Priabonian and Oligocene successions (Fig. 8) are involved in backthrusts within the thrust-fold belt (the Campo del Medio anticline and Malengüena backthrust sheet) (Figs. 10; 11; 12E) developed during two related contractional stages, called D_f4 and D_f5 (Torres Carbonell *et al*., 2011), which postdate the latest Priabonian. D_f4 was coeval with deposition of the lower part of the Oligocene succession, age-constrained by foraminifer and calcareous nanoplankton markers (Malumián and Olivero, 2006; Torres Carbonell *et al*., 2009) and by a significant peak of detrital zircon U/Pb ages at 26.27±0.63Ma (Barbeau *et al*., 2009).

Tectonostratigraphic evidence for this includes a marked wedging of the lower Puesto José Formation and María Cristina Beds (Table 1) against the D_f4 Campo del Medio anticline (Figs. 9; 10), well constrained by a marker foraminifer event of ~30Ma traced across the thrust-fold belt (Fig. 9) (Malumián and Olivero, 2006; Torres Carbonell *et al*., 2009). Thus, growth of the Campo del Medio anticline controlled the accommodation space for these formations (Torres Carbonell, 2010). Additional evidence for the oldest age of D_f4 comes from the apparent angularity of the u5 unconformity between the upper Lutetian-Priabonian and the Oligocene successions at central Tierra del Fuego, where it separates the La Despedida and Tchat-chii formations (Table 1) (Malumián and Olivero, 2006).

The second Oligocene stage (D_f5) is constrained at the *mid* Oligocene on the basis of syntectonic strata in the Puesto José Formation that bear the marker foraminifer event of ~30Ma (Fig. 9). These strata form part of the Malengüena backthrust sheet, cropping out at the Cabo José area (Figs. 10; 12E), and overly a correlative conformity surface called u6 and referred to the stage D_f5 (Torres Carbonell *et al*., 2009).

Both D_f4 and D_f5 evolved in a short time span, accommodating 14.5km (15.1%) shortening (Fig. 11). They coincided with a period of uplift and exhumation of the Fuegian Andes during the Eocene-Oligocene transition, evidenced by the dominance of rock fragments of deformed Upper Jurassic rhyolitic volcanics in the detrital composition at the base of the Oligocene succession (Olivero, 2002; Malumián and Olivero, 2006; Barbeau *et al*., 2009). The start of the Oligocene contractional stages in the thrust-fold belt coincides with the end of the Eocene rapid cooling determined by Gombosi *et al*. (2009) for rocks of the central belt (Fig. 7).

D_f6: latest Oligocene-Miocene contractional stage

At least one last contractional stage, called D_f6, was coeval with the upper Chattian-Miocene succession (Fig. 8). Two episodes, probably synchronous, occurred during this stage. One of these episodes involved thrusting and folding during deposition of the Malengüena Formation (Table 1), in the southern portion of the thrust-fold belt (Figs. 9; 10; 11), associated to refolding of the Malengüena backthrust sheet owed to emplacement of a deep-seated major thrust sheet that caused a shortening of at least 2.8km (2.9%) (Fig. 11) (Torres Carbonell *et al*., 2009, 2011).

The u7 unconformity, located below the Malengüena Formation (Fig. 9), constrains this episode's age most probably to the Miocene, as suggested by the foraminifera and the stratigraphic position of the Malengüena Formation (Torres Carbonell *et al*., 2009). The u7 unconformity reveals significant erosion of part of the underlying beds, which are younger than 30Ma (Torres Carbonell *et al*., 2009; Torres Carbonell, 2010). Evidence of erosion associated to u7 is accompanied by a dominance of sedimentary lithic detritus in the Malengüena Formation, which also bears resedimented foraminifera from the Cretaceous and Eocene, suggesting exhumation of previous thrust sheets (Torres Carbonell *et al*., 2009).

The other episode within D_f6 is recorded at the leading edge of the thrust-fold belt by a series of forward directed thrusts (Punta Gruesa imbricate system) (Figs. 10; 11). These thrusts deform rocks from the upper Lutetian-Priabonian to the uppermost Oligocene-Miocene successions (Figs. 11; 12F) (Torres Carbonell *et al*., 2008b, 2011). Age constrains for the thrusts come from coeval syntectonic strata in the upper Chattian (Puesto Herminita Beds) and at the upper Chattian-Miocene (Desdémona Formation) (Table 1): both units are intensely deformed by slump folds and intruded by syntectonic clastic dikes, and were accumulated in front of evolving thrust sheets (Ponce, 2009). The Desdémona Formation also reveals slumped packages with attitudes that decrease from 20°N to subhorizontal away from the imbricate system (Ghiglione, 2002; Ponce, 2009).

The exposed geometry of this syntectonic succession, though limited, strongly suggest that the Desdémona Formation comprises a growth succession in front of the evolving Punta Gruesa imbricate system (Torres Carbonell *et al*., 2008b; Ponce, 2009). Therefore, the D_f6 stage marking the end of contractional deformation in the eastern thrust-fold belt is constrained to the late Oligocene-early Miocene, with a youngest age of 17.3Ma according to dating of the Desdémona Formation (Malumián and Olivero, 2006). The associated shortening is of at least 10.4km (10.8%) (Fig. 11).

Shortening estimation

By combining the contractional stages described above we obtained a minimum amount of shortening for the eastern thrust-fold belt of almost 46km (±5km), nearly 48% of a restored length of ~93km (Fig. 11). This shortening was accommodated above an interpreted décollement at the base of the Cretaceous succession and progressively transmitted to shallower levels (Torres Carbonell *et al*., 2011), consistently with previous interpretations elsewhere in Tierra del Fuego (Klepeis, 1994a; Rojas and Mpodozis, 2006). Although an additional shortening in the hinterland of the studied portion of the thrust-fold belt must be considered (associated to the contractional stage D_f1) (Fig. 12A, B), it is not calculated here due to the unavailability of necessary structural data.

Structural timing of the central belt and thrust-fold belt compared

Time constraints from structures of the central belt and thrust-fold belt suggest a roughly synchronous evolution between both domains of the Fuegian Andes, with a trend indicating forward propagation of the deformation (Fig. 7). Nevertheless, precise correspondence between uplift episodes in the central belt and thrust sheet emplacement on the thrust-fold belt is not possible with the available data. This is particularly a problem of differing chronologic resolutions from both domains; *e.g*. the dating of syntectonic successions using microfossils allows a resolution within a few million years, and there are as many crosscutting relationships as syntectonic successions found.

On the contrary, in the central belt the main age constraint is obtained from crosscutting relationships with the Beagle suite intrusives, whose ages span about 13Ma. In addition, the thermochronologic models developed for the central belt are mostly applicable to the individual thrust sheet sampled; therefore, the lack of identification of individual structures in the central belt gives rise to a less accurate spatial definition of uplift rates. The same happens with the lack of data of this kind from buried basement thrust sheets (*e.g*. those forelandward).

GEOMETRIC AND KINEMATIC LINKS BETWEEN THE CENTRAL BELT AND THRUST-FOLD BELT

Assessment of previous models

Previous shortening estimates in the Fuegian Andes differ moderately from our results. Table 2 summarizes these estimates, all obtained in the western sector of the Fuegian thrust-fold belt (more than 130km west from our study area), or nearby the Chile-Argentina border of Tierra del Fuego. The studies by Álvarez-Marrón *et al*. (1993) and Rojas and Mpodozis (2006) were performed combining field and seismic data. We made a detailed analysis of the sections of Rojas and Mpodozis (2006) and restored them applying bed-length conservation. The results are shown in Table 2, and reveal a notably higher shortening of the sedimentary cover compared to the structural basement. This indicates that the slip transferred to the foreland due to the basement thrusting, according to these sections, is insufficient to account for the contraction recorded in the thrust-fold belt.

In order to compensate this shortening difference, previous models proposed a duplex or antiformal stack geometry in the basement (the Cerro Verde anticline; Figs. 3; 5) (Klepeis, 1994a; Kley *et al*., 1999; Kraemer, 2003). The balanced cross-section presented by Kley *et al*. (1999), for instance, depicts several basement horses stacked below and in front of the Cerro Verde anticline. The shortening obtained by line-length restoration of that cross-section is shown in Table 2.

On the other hand, Kraemer (2003) raised a regional interpretation that includes the central belt and thrust-fold belt of the Fuegian Andes. Our bed-length restoration of the Cenozoic cover rocks of the northernmost (frontal) 110km of the cross-section are separated in two stages (Paleogene and Miocene), as proposed by Kraemer (2003) (Table 2). The sum of both contractional stages rises to almost 58km (53%) of shortening in a restored length of 110km, an amount consistent with our results.

We find two main flaws in the addressed models, one kinematic and the other geometric. In the model introduced by Kley *et al*. (1999), since the basement duplex and the foreland thrusts are Paleocene or younger (*cf*. Klepeis, 1994a), they cannot be responsible for the penetrative deformation recorded in Lower and Upper Cretaceous rocks of the marginal and foreland basins fill, older than the Maastrichtian (older D_f1; *e.g*. Fig. 6D) (Winslow, 1983; Klepeis, 1994a; Torres Carbonell *et al*., 2013), whose shortening thus remains unexplained. Kraemer (2003), on the other hand, assigned almost all the deformation in the Cenozoic cover rocks to Neogene structures, while we have modeled a progressive evolution of the thrust-fold belt from the Late Cretaceous-

TABLE 2 Summary of published shortening estimates in the Fuegian Andes

Author/s	Shortening Basement*	Cover	Age of deformation
Álvarez-Marrón et al. (1993)	-	~30 km (60%)	Oligocene or older
Rojas and Mpodozis (2006)	Overall 50 km		Paleocene-Eocene
	14-18 km (20%)	27-30 km** (30-37%)	
Kley et al. (1999)	59 km (41%)	35 km (24%)	Paleocene or younger
Kraemer (2003)	Overall 50 km		Paleogene
	-	6-7 km (6%)	
	Overall 80 km		Miocene
	-	51 km (46%)	
This work	-	46 km (48%)	Paleocene to Miocene in 6 stages

*Units below the main décollement of the foreland thrust-fold belt
**Marker bed at the top of the Lower Cretaceous

Paleocene (D_f1) to the Miocene (D_f6), characterized by several and distinct contractional stages each producing a partial amount of shortening (Fig. 11). It is highly probable that this apparently diachronic kinematic evolution along the Fuegian thrust-fold belt arises from the lack of stratigraphic definition in the central and western Fuegian Andes foothills.

The second inconsistence arises from the geometry of the basement uplifts in the central belt, which was interpreted by Klepeis *et al.* (2010) as a system of fault-propagation folds, and by Kraemer (2003) as a system of fault-bend folds with no structural connection to the foreland (*i.e.* no production of cover shortening). The emplacement of these thrust sheets was postulated as out-of-sequence with the deformation recorded in the Fuegian thrust-fold belt (Klepeis, 1994a; Rojas and Mpodozis, 2006; Klepeis et al., 2010).

Therefore, by postulating that the exhumation of the central belt during the Paleogene was out-of-sequence, the capability to produce foreland shortening of the thrust structures formed during this contractional phase is inevitably neglected. According to that, the only structure left in order to balance the shortening in the cover rocks is the Cerro Verde anticline, north of Cordillera Darwin (Fig. 3; 5) (Klepeis, 1994a; Kley *et al.*, 1999; Kraemer, 2003; Klepeis *et al.*, 2010). This would imply that the Cerro Verde anticline, with an exposed width of less than 20km (Klepeis, 1994a) comprises an antiformal stack that accommodated 30 to 60km shortening, resulting in amounts of local contraction (above 60%) that may be considered unlikely. Hence, both from a kinematic and geometric point of view, the mentioned interpretations of the basement thrusting in the central belt are not suitable to account for all the cover shortening during the Late Cretaceous-Cenozoic evolution of the thrust-fold belt.

Model for the transference of orogenic shortening to the foreland

Geometry

We put forward a different explanation, aiming to integrate the evolution of the complete orogenic wedge in a single scheme. The new model proposed considers that the basement uplifts recognized in Cordillera Darwin consisted in thrust sheets that transferred discrete amounts of slip to a common upper detachment at the basement-cover interface. These thrust sheets formed a regional-scale duplex within the structural basement, whose roof thrust coincided with the décollement of the thin-skinned thrust-fold belt, recognized in the central belt exposures (Figs. 5; 6A-C). Therefore, the total amount of slip transferred to the roof thrust should account for the shortening measured in the cover rocks (Fig. 13).

The thrusting of this regional-scale duplex was not limited to the Cerro Verde anticline, but instead formed a domain of basement thrusting along the entire length of the central belt, and across the Fuegian Andes between the obducted RVMB floor and the thin-skinned thrust-fold belt (Fig. 14). The basement thrust proposed in the previous models as the boundary of the out-of-sequence basement uplifts (Klepeis, 1994a; Kley *et al.*, 1999; Klepeis *et al.*, 2010), may be well explained as a breaching thrust (*cf.* Butler *et al.*, 2007) that uplifted a portion of the duplex above the cover rocks, locally cutting the roof thrust (Fig. 5).

The proposed model of basement thrusting has been used elsewhere in the Andes, for example in the Cordillera Principal of Mendoza, Argentina (Dimieri, 1997; Turienzo, 2010). It has also been depicted in the core of many orogenic belts, where the upper crust is involved in thrust sheets that transferred shortening to their upper flats (*e.g.* foreland thrust or fold belts) (Price, 1981; Butler, 1986; Muñoz, 1992). Backthrusts, as those described by Klepeis (1994a), Rojas and Mpodozis (2006) and Klepeis *et al.* (2010) may develop to help accommodate the internal strain caused by flexure of the hangingwall ramp during the emplacement of the basement thrust sheets (Fig. 13) (*cf.* Erslev, 1993; Dimieri, 1997; Turienzo and Dimieri, 2005).

Kinematics

The basement thrust wedge evolved during the second main contractional phase after emplacement of the Beagle granite suite at around 80Ma, as recorded in Cordillera Darwin by Klepeis *et al*. (2010). The overlap of episodes of rapid uplift in the central belt and contraction in the thrust-fold belt during the second main contractional phase (Fig. 7) support the linked kinematics between both domains. The causative relationship between the basement thrusting and development of the Fuegian thrust-fold belt implies that the basement thrust sheets continued their emplacement until the early Miocene, which is the youngest age of the thrust-fold belt (Figs. 7; 11) (*cf*. Torres Carbonell *et al*., 2011).

Contrary to previous models, we consider that the basement thrusting developed in sequence with the propagating orogenic wedge, progressively attaching horses of the underthrust crust from the footwall of the evolving duplex. The sole thrust, therefore, may have branched from the major mid-crustal shear zone envisaged by Klepeis *et al*. (2010) in the interface between the obducted RVMB and the underthrust continental crust (Fig. 13). Accordingly, after underthrusting, the continental margin of South America responded to collision with the magmatic arc (Fig. 2C) by decoupling the upper continental crust, which was thus involved in the thrust wedge (Klepeis *et al*., 2010).

This mechanism has been proposed for many collisional orogens (*e.g*. Price, 1981; Butler, 1986; Muñoz, 1992; Pfiffner, 2006), where it produced a crustal stacking wedge (*e.g*. Mattauer, 1986). We think that in the Fuegian Andes the decoupling surface may be related to a prior discontinuity within the upper crust, such as an older extensional décollement formed during the Jurassic rifting of SW Gondwana (Fig. 15) (see similar model in Dewey *et al*., 1986).

Domain of basement thrusting in the eastern Fuegian Andes

The significant shortening that affected the eastern portion of the Fuegian thrust-fold belt (Fig. 11) implies that the basement thrust wedge had continuity toward that region of the orogenic belt. Exposures of the structural basement are recognized in Isla de los Estados (Fig. 14), where the Upper Jurassic rhyolitic volcanics are deformed in an overturned syncline that represents the front of a north- to Northwest vergent antiform (Dalziel and Palmer, 1979). This major structure may continue in the southern Península Mitre, with exposures of the rhyolitic volcanics (Fig. 14). In addition, an important set of these former Andean structures is now exposed at South Georgia, which, as addressed before, formed the easternmost hinterland of the Fuegian Andes (Fig. 1) (Dalziel, 1981; Tanner, 1982; Thomson *et al*., 1982; Tanner and Macdonald, 1982; Curtis *et al*., 2010).

Although the nature and structure of the basement below the marginal basin fill of South Georgia are

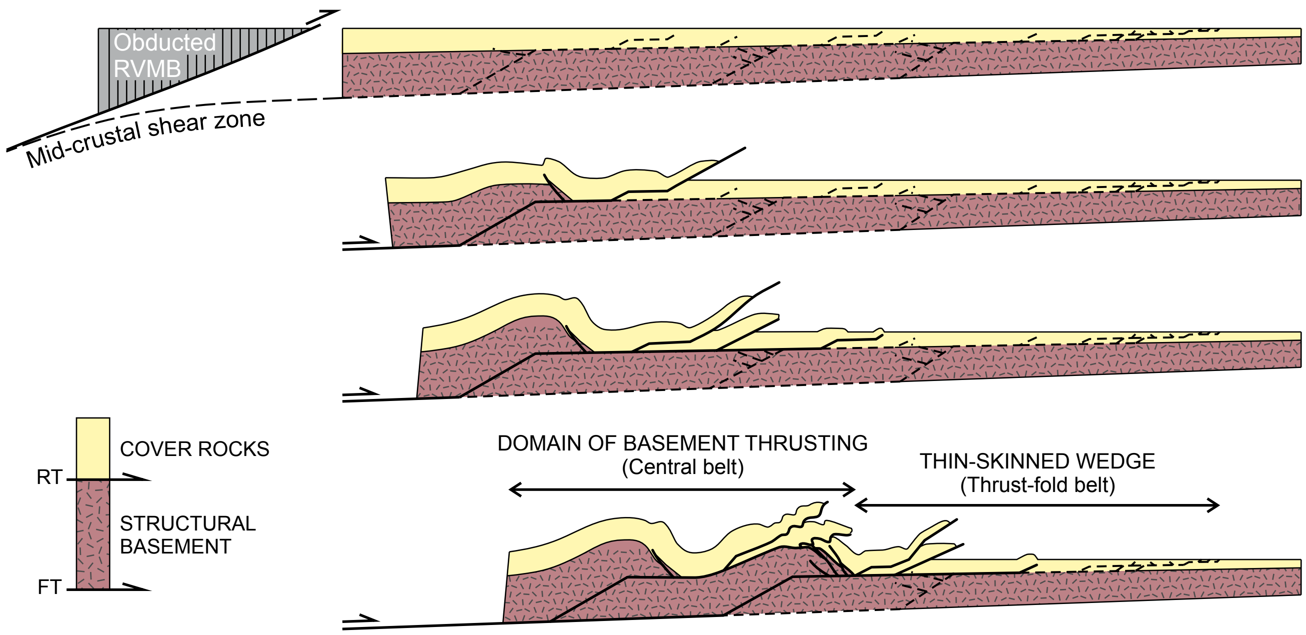

FIGURE 13 | Mechanism proposed in this paper to link deformation in the central belt with shortening in the thrust-fold belt of the Fuegian Andes. The emplacement of basement thrust sheets with a duplex style transfers slip to the cover forming the thin-skinned wedge. Sections are simplified and not to scale, but area-balanced (with software *Pliegues 2D* by E. Cristallini). Solid lines are thrusts, dashed lines are future thrusts for each stage. RVMB: Rocas Verdes Marginal Basin, RT: roof thrust, FT: floor thrust. Cover rocks comprise the marginal basin fill and foreland basin fill, the structural basement is formed by the continental basement of the RVMB and the rhyolitic volcanics (see text).

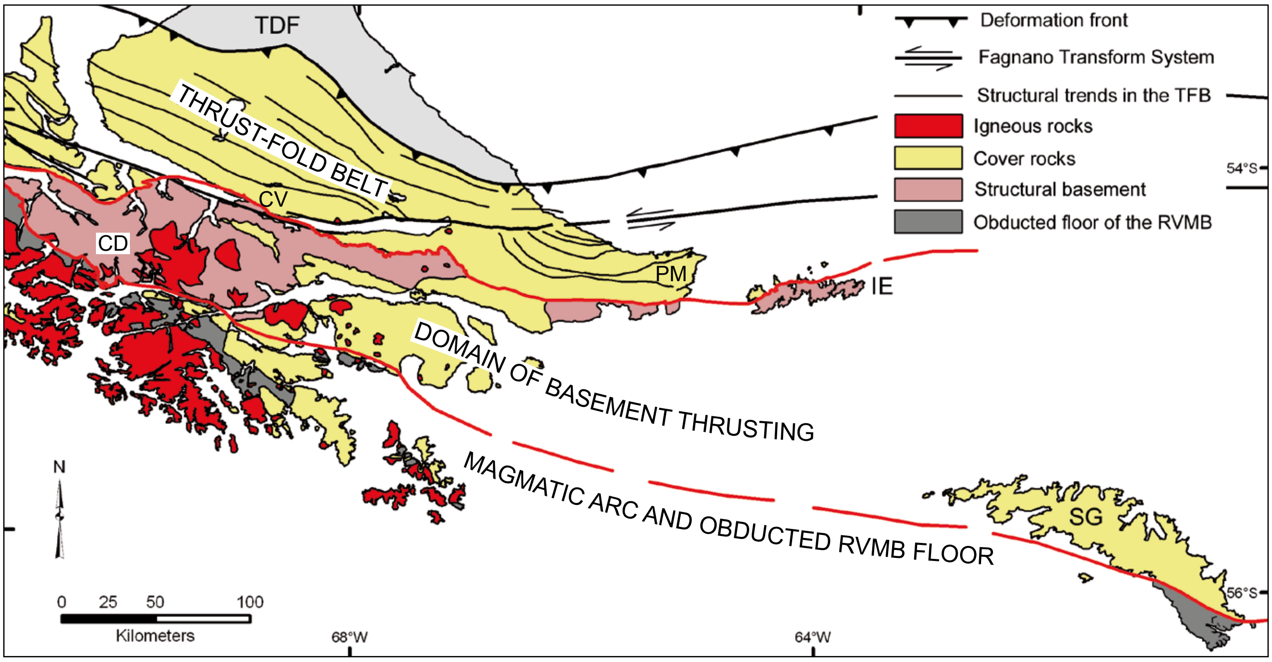

FIGURE 14 Main structural domains of Tierra del Fuego (TDF) and South Georgia (SG), delimited by thick red lines. TFB: Thrust-fold belt, CD: Cordillera Darwin, CV: Cerro Verde Anticline, PM: Península Mitre, IE: Isla de los Estados, RVMB: Rocas Verdes Marginal Basin. South Georgia in its early Cenozoic position, see Figure 1A. Restoration along the Neogene Fagnano Transform System (~50km left-lateral slip) was neglected for simplicity. For the references to colours in this figure, see the web version of this article

unknown, it is valid to assume that a lateral continuity of the thick-skinned thrust wedge existed between South Georgia and the Fuegian Andes, based on the paleogeographic reconstructions of South Georgia and its structural similarities with the Fuegian Andes (Fig. 1). Hence, the domain of basement thrusting between South Georgia and Isla de los Estados should have accounted for the shortening observed in the eastern Fuegian thrust-fold belt. Accordingly, the exposures at Isla de los Estados form the northernmost basement uplift of the thick-skinned wedge, in analogy to the Cerro Verde anticline. Both uplifts represent the leading edge of the domain of basement thrusting along the Fuegian Andes (Fig. 14).

CONCLUSIONS

Using published and own structural data, we compared the geometry and kinematics of the central belt and thurst-fold belt of the Fuegian Andes. The integration of time constraints from both domains suggests a roughly synchronous evolution, with a trend indicating forward propagation of the deformation and episodes of rapid uplift in the central belt approximately coeval with contractional stages in the foreland. We highlighted evidence for a significant shortening in the foreland of the entire orogenic belt during the Cenozoic with ~46km (±5km) shortening at the eastern termination of the thrust-fold belt. This contraction was necessarily transferred from the central belt of the orogen.

Previous models of basement shortening state a localized and out-of-sequence Paleogene uplift of the Fuegian Andes core, without shortening transference to the foreland. Alternatively, we propose that the basement uplifts in the central belt formed a regional-scale duplex whose roof thrust coincided with the décollement of the thin-skinned thrust-fold belt. In this model, the total amount of slip transferred to the roof thrust accounted for the shortening measured in the cover rocks.

The basement duplex progressively incorporated the underthrust crust from the footwall of the orogenic wedge through forward propagation (in sequence). Basement thrusting developed since ~80Ma, after the closure of the RVMB, and continued until the early Miocene according to the youngest thrust-fold belt structures. We highlight that the domain of basement thrusting had continuity in the hinterland of the eastern portion of the Fuegian Andes, which accommodated significant orogenic shortening.

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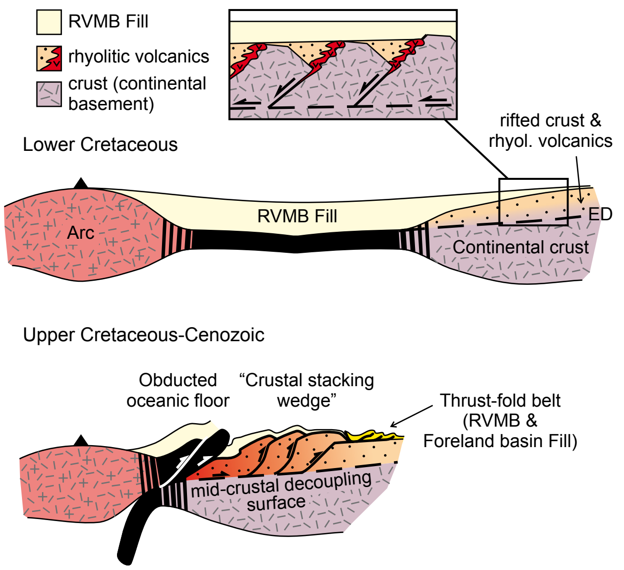

FIGURE 15 Cartoon depicting the possible inheritance of a Mesozoic extensional detachment (ED) in the continental basement, which acted as a weakness zone favoring decoupling of the upper crust and its involvement in the crustal stacking wedge (basement duplex) during orogenesis. RVMB: Rocas Verdes Marginal Basin.

gallo (CADIC-CONICET) prepared the thin sections analyzed. J. Kley, J. Bourgois, J. García-Sansegundo, A. Teixell and J. Álvarez-Marrón are thanked for constructive comments that significantly improved this work. We acknowledge financial support from CONICET, ANPCYT, and UNS to L. Dimieri and P. Torres Carbonell, and ANPCYT-FONCYT PICTO 0114.

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