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The Fuegian thrust-fold belt: from arc-continent collision to thrust-related deformation in the southernmost Andes

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Abstract

New detailed structural data from the Fuegian Andes including new ages and cross-cutting relationships with intrusive rocks, as well as an appraisal of published structural data, support that this orogen evolved as a basement-involved thrust-fold belt after initial formation in an arc-continent collision scenario. New structural data from a deformed 84 Ma intrusive indicate that structures from the collisional event in the Argentine Fuegian Andes are of Campanian age, comprising only the youngest and less intense deformation of the orogenic wedge. In the internal thrust-fold belt, these structures are cut by intrusives with new ages of 74 Ma (Ar/Ar on hornblende). The superposition of thrusts on these early structures indicates a subsequent event in which a thrust-fold belt formed since the Maastrichtian-Danian. Additional new data confirm brittle-ductile thrusting in the central belt, with thrusts joining a common upper detachment in the base of the Lower Cretaceous rocks. These thrusts formed a first-order duplex system that transferred the shortening accommodated in the foreland until the Miocene.

Keywords: arc-continent collision, thrust-fold belt, Ar/Ar dating, deformation chronology, Fuegian Andes

1. Introduction

In the last 10 years a systematic research has been carried out in the Fuegian Andes attempting to unveil the structural relationships between a poorly known central belt (between Lago Fagnano and Canal Beagle, Fig. 1a), and the foreland thrust-fold belt located northwards. The connection between both domains was obscured not only by limited structural knowledge of the central belt, but also because the geometry of the foreland structures was only constrained by studies at its external portion, especially at the best exposed Atlantic coast (Álvarez-Marrón et al., 1993; Ghiglione, 2002; Ghiglione et al., 2010; Torres Carbonell et al., 2011, 2013a; Zanella et al., 2014). In addition, the internal part of the thrust-fold belt (Fig. 1a), involving mostly Cretaceous mudstones and slates with scarce stratigraphic control, was practically not addressed from a structural geology perspective, with the exception of a limited area in Chile (Klepeis, 1994; Rojas and Mpodozis, 2006).

Despite a greater amount of structural data from early works in the central belt of the Fuegian Andes, especially from Cordillera Darwin and surrounding areas (Fig. 1a), our analysis of that research shows us that the deformation of the foreland has been implicitly circumvented. Indeed, early investigations focused their attention on the spectacular deformation of high-grade metamorphic rocks exposed in Cordillera Darwin. These studies, as well as others along the central belt up to Isla de los Estados (Fig. 1a), determined that most of the shortening registered in the Fuegian Andes was of “mid” Cretaceous age (the “main phase” of early works), related to multiple folding and faulting generations and associated regional metamorphism (Bruhn, 1979; Dalziel and Palmer, 1979; Nelson et al., 1980; Cunningham, 1994, 1995; Kohn et al., 1995). An interesting aspect of these studies is that they led to a distinction of the structure of the Fuegian Andes with respect to the rest of the Andean Cordillera. Accordingly, the style of deformation was found to be more similar to the Alpine chain (Nelson et al., 1980), and it was clear that a collisional process closing a prior back-arc basin was responsible for this structural style, in contrast with the geodynamic context of the rest of the Andes of South America (Dalziel et al., 1974; Dalziel, 1986).

Following, and building on this early research, more recent works revealed that after the “main phase” of deformation, thrust-related uplift of the central belt progressed during the Late Cretaceous and the Paleogene (Klepeis, 1994; Kohn et al., 1995; Gombosi et al., 2009; Klepeis et al., 2010; Maloney et al., 2011). It was recognized that at least part of the exhumation in Cordillera Darwin and its surroundings was coeval with thrusting in the foreland (e.g. Bruhn, 1979; Dalziel and Palmer, 1979; Álvarez-Marrón et al., 1993; Barbeau et al., 2009a; Gombosi et al., 2009). However, an implicit separation between deformation in both domains came out from these works, since most of the central belt thrusting was considered out-of-sequence with the structures in the foreland thrust-fold belt (e.g. Klepeis, 1994). With the incorporation of new data from the foreland, which led to Eocene-Miocene shortening estimates of tens of kilometers (Torres Carbonell et al., 2011, 2017a), it became clear that models explaining the connection between both ends of the orogenic system were increasingly needed.

One early approach to explain Cenozoic shortening in the foreland with coeval development of structures in the central belt was proposed by Torres Carbonell and Dimieri (2013). As a working hypothesis, these authors presented a schematic cross-section of the Fuegian Andes, combining the central belt and the foreland into a thrust-fold belt with basement involvement, in which a first-order duplex in the central belt transferred all the shortening recorded in the foreland (Fig. 1b). In this sense, even if punctuated by successive deformation phases (or superposed generations of structures) as previously suggested (Bruhn, 1979; Dalziel and Palmer, 1979; Nelson et al., 1980; Cunningham, 1995; Klepeis et al., 2010), deformation in the Fuegian Andes comprised a protracted history from the Late Cretaceous to the Miocene.

In this work we analyze previously published structural information from the Fuegian Andes, and integrate it with new data that fill gaps in knowledge regarding the age and style of deformation of the Argentine part of the orogen. Our new data include detailed descriptions and cross-sections of two previously uncharted areas where the relationships and superposition of the main phases of deformation in the Fuegian Andes are well-revealed. We also include a detailed description of cross-cutting relationships between two intrusive suites and deformation of their host rocks, together with three new geochronological analyses of the youngest of these suites (of previously unknown age), providing key temporal constraints on the timing of these deformation phases in the Argentine Fuegian Andes. The critical appraisal of the published information together with our new data, support the proposed scheme of structural evolution of the orogen (Fig. 1b), with a first event comprising pre-Maastrichtian collision, ductile deformation and metamorphism, and a second event involving Maastrichtian-Danian to early Neogene faulting and uplift. The present study validates the interpretation of the Fuegian Andes as a basement-involved regional thrust-fold belt with a linked evolution between the central belt and the foreland.

2. Regional geologic setting

The origin of the Fuegian Andes involved the closure of a prior back-arc basin called Rocas Verdes Basin (Fig. 1b). This back-arc basin formed after Middle to Late Jurassic rifting of the southwestern margin of Gondwana, which preceded Early Cretaceous generation of oceanic floor between a volcanic arc and the continental margin. The basin was filled with marine successions during the Early Cretaceous (Dalziel et al., 1974; Dalziel, 1981; Stern and de Wit, 2003). Fragments of the oceanic floor are exposed as incomplete ophiolitic strips in the Tortuga, Sarmiento, and Capitán Aracena Complexes (Fig 1a), as well as intensely deformed and metamorphosed amphibolites at Cordillera Darwin (Cunningham, 1994; Stern and de Wit, 2003; Klepeis et al., 2010; Calderón et al., 2016). These ophiolitic rocks represent remnants of the Late Cretaceous collision between the magmatic arc and the continent during closure of the Rocas Verdes Basin (Nelson et al., 1980; Dalziel, 1986; Cunningham, 1994, 1995; Klepeis et al., 2010). Near Cordillera Darwin, the ophiolitic rocks are highly strained, involved in mylonitic zones that have been interpreted either as related to convergent strike-slip deformation (Cunningham, 1995), or as thrust sheets reflecting north-northeastward obduction of part of the oceanic floor during basin closure (Klepeis et al., 2010). The Canal Beagle (Fig. 1a) manifests itself as a conspicuous structural boundary separating strongly deformed and metamorphosed rocks in Cordillera Darwin from less deformed and mainly magmatic rocks towards the south.

Closure of the Rocas Verdes Basin and further development of the Fuegian Andes also led to formation of a Late Cretaceous-Neogene foreland basin system in front of the orogen, called Austral basin (Magallanes in Chile, Biddle et al., 1986, Fig. 1a, b). Protracted deformation and development of the thrust-fold belt, therefore, affected syntectonic successions deposited in this basin. The stratigraphy of these successions as well as their overprinting relationships with the structures of the thrust-fold belt has been helpful to constrain several stages of uplift, erosion, and orogenic expansion (Torres Carbonell and Olivero, 2019). A more detailed description of the stratigraphy and a summary of the tectonic stages of the Fuegian Andes are given in the following sections.

2.1. Stratigraphic framework

The stratigraphic framework of the Fuegian thrust-fold belt is synthetically described, focusing on lithologies and thicknesses involved in deformation, and chronologic information useful to constrain structural stages (Fig. 2). For the sake of brevity, we omit further detailed information that can be found in the cited references. Throughout the text, we use formal names defined in Argentina for units that are also recognized in Chile, as shown in Fig. 2. For simplicity, we omit in our framework the back-arc mafic floor, which does not crop out in Argentina, as well as some intrusives of unknown age.

2.1.1. Paleozoic basement

The basement is included in the Cordillera Darwin Metamorphic Complex, which portrays metamorphic grades from greenschist to upper amphibolite facies (Hervé et al., 2010a, 2010b). Within these metamorphic rocks, a distinction is made amongst the Mesozoic cover (Jurassic synrift deposits and Cretaceous sedimentites) and the “true basement” of the Rocas Verdes Basin (Figs. 2 and 3). The latter, composed mainly of phyllites, schists and metabasites, is characterized by pre-Permian detrital zircon ages

(Hervé et al., 2010b). A single zircon U/Pb crystallization age of 153.12 ± 0.93 Ma from a granite dike intruding a penetrative foliation in a schist at southern Cordillera Darwin (Klepeis et al., 2010, see also Hervé et al., 2010b), constrains the pre-Jurassic deformation of the basement (called D_B by Nelson et al., 1980).

2.1.2. Jurassic synrift and Lower Cretaceous back-arc basin volcanic and sedimentary rocks

2.1.2.1. Lapataia Formation

The Lapataia Formation (Figs. 2 and 3) includes greenschists facies metasedimentites and metabasites that are thrust over the Upper Jurassic Lemaire Formation (Bruhn, 1979; Olivero et al., 1997; Cao et al., 2018). The total thickness of the Lapataia Formation is undetermined due to its intense deformation, unknown base, and the tectonic nature of its contact with the Lemaire Formation. Recently published structural and petrographic data suggest that this unit represents a highly deformed section of the synrift Jurassic succession, stratigraphically between the Paleozoic basement and the Lemaire Formation (Cao et al., 2018; see also Olivero et al., 1997; Acevedo, 2019).

2.1.2.2. Lemaire Formation

The Lemaire Formation (Figs. 2 and 3), widely exposed in the central belt domain, is composed of very-low to low grade metasedimentary and metavolcanic-volcaniclastic rocks deposited during the synrift stage (Bruhn et al., 1978; Hanson and Wilson, 1991; Olivero and Martinioni, 1996a; González Guillot et al., 2016; González Guillot, 2017; Cao et al., 2018). This unit is in tectonic contact with the Lapataia Formation, and covered by the Lower Cretaceous Yahgan and Beauvoir formations, although a detachment surface usually overprints this contact (Torres Carbonell and Dimieri, 2013; Cao et al., 2018). The total thickness of the Lemaire Formation is unconstrained.

In Argentine Tierra del Fuego, a U/Pb zircon age in rhyolite yielded an age of 164 ±3.6 Ma (Palotti et al., 2012). The equivalent Tobífera Formation (Fig. 2), by correlation with the Darwin suite (see below), has geochronological ages between 178-152 Ma (Pankhurst et al., 2000; Barbeau et al., 2009a; Hervé et al., 2010b; Klepeis et al., 2010).

2.1.2.3. Yahgan Formation

The Yahgan Formation (Figs. 2 and 3) comprises very low-grade metasedimentary rocks, originated from marine epiclastic and volcaniclastic successions of the Rocas Verdes Basin (Suárez and Pettigrew, 1976; Winn, 1978; Dalziel, 1981; Olivero and Martinioni, 1996a). The unit rests on the Lemaire Formation, the contact usually overprinted by a detachment surface (Torres Carbonell and Dimieri, 2013; Cao, 2019). The top of the formation is unknown.

Estimations of the original thickness of the Yahgan Formation average from 1400 m near Ushuaia and increasing southwards (Winn, 1978; Caminos et al., 1981; Olivero and Malumián, 2008). The formation is not younger than the late Albian, according to its fossils and scarce geochronological data (Olivero and Martinioni, 1996b; Barbeau et al., 2009b).

2.1.2.4. Beauvoir Formation

The Beauvoir Formation (Figs. 2 and 3) comprises slates with a marine protolith, that may interfinger southwards with the Yahgan Formation (Olivero and Malumián, 2008; Martinioni et al., 2013). South of Lago Fagnano, the contact with the underlying Lemaire Formation is a few meters below a north-northeast-dipping detachment surface (Torres Carbonell and Dimieri, 2013; González Guillot et al., 2016; Cao, 2019; this work), whilst at Península Mitre this contact is a south-dipping reverse fault (Torres Carbonell et al., 2017b). Its top is not well defined due to lack of stratigraphic definition north of Lago Fagnano. A minimum thickness of 450 m has been estimated for the formation, which contains Aptian-Albian marine invertebrates, mostly inoceramids (Olivero et al., 2009; Martinioni et al., 2013).

2.1.3. Upper Cretaceous-lower Neogene foreland basin sedimentary rocks

2.1.3.1. Upper Cretaceous-Danian succession

An Upper Cretaceous-Danian sedimentary package forms the oldest sedimentary succession of the Austral foreland basin (Figs. 2 and 3). The older rocks in this succession include several mudstone-dominated units with Turonian-Campanian fossils (Fig. 2, Olivero et al., 2009; Martinioni et al., 2013). The middle part of the succession is formed by coarse-grained deposits interbedded with mudstones, of late Campanian-?early Maastrichtian age according to ammonites and foraminifera (Bahía Thetis Formation, Olivero et al., 2003). The youngest rocks in this package are bioturbated fine sandstone-mudstone intercalations with Maastrichtian-Danian fossils and detrital zircon ages (Policarpo Formation, Olivero et al., 2002, 2003; Barbeau et al., 2009a; Martinioni et al., 2013).

The base of the Upper Cretaceous-Danian succession is not well-defined, whilst the top is marked by an unconformity between the Policarpo Formation and coarse deposits of the Río Claro Group (Fig. 2, Olivero et al., 2003; Martinioni et al., 2013). The accumulated minimum thickness of the succession exceeds 1000 m.

2.1.3.2. Paleocene-lower Miocene succession

The Paleocene to lower Miocene sedimentary rocks of the Austral basin comprise a heterogeneous succession including several units that crop out, or are drilled in subsurface, from the mountain front to northern Tierra del Fuego (Figs. 2 and 3). Minimum estimated thicknesses of each unit are given in Fig. 2, from composite sections. The base of this succession rests on an unconformity with the Policarpo Formation (Olivero et al., 2003; Martinioni et al., 2013).

The upper part of the succession is formed by uppermost Oligocene-Miocene beds coeval with the end of contraction in the thrust-fold belt (Torres Carbonell and Olivero, 2019). They include growth strata formed above the youngest folds (Ghiglione, 2002; Malumián and Olivero, 2006; Ponce et al., 2008; Torres Carbonell et al., 2017a).

2.1.4. Fuegian batholith and peripheral intrusives north of Canal Beagle

2.1.4.1. Darwin suite

The oldest magmatic rocks north of Canal Beagle comprise orthogneisses mostly derived from granites intruded in the basement at Cordillera Darwin (Fig. 3, Nelson et al., 1980; Hervé et al., 1981, 2010b; Klepeis et al., 2010). The rocks are ductilely deformed and intruded by less deformed granitoids of the Beagle suite (Nelson et al., 1980). The Darwin granites are Late Jurassic, with U/Pb zircon ages of 164-153 Ma (Mukasa and Dalziel, 1996; Klepeis et al., 2010).

2.1.4.2. Beagle suite

The Beagle suite is the main unit of the Fuegian batholith (Fig. 3). North of Canal Beagle, the granitoids that compose this suite have U/Pb zircon ages ranging between 86-74 Ma (Hervé et al., 1984; Klepeis et al., 2010; McAtamney et al., 2011). They postdate most of the ductile structures related to the arc-continent collision, although some intrusives overlap with the late stages of that deformation and the associated peak metamorphism (Maloney et al., 2011).

2.1.4.3. Rear-arc suites

2.1.4.3.1. Ushuaia Peninsula Andesites

The Ushuaia Peninsula Andesites (Fig. 3) include small ultramafic to silicic plugs cross-cut by a set of andesitic (the main lithology) and lamprophyre dikes (González Guillot et al., 2011). This suite intrudes the Yahgan Formation. One andesite dike yielded a zircon U/Pb age of 84.1 ± 1.6 Ma (González Guillot et al., 2018). The overprinting relationships between the Ushuaia Peninsula Andesites and the deformation of the Yahgan Formation are reported in this work as a constraint on deformation timing (see section 4.1.1).

2.1.4.3.2. Fuegian Potassic Magmatism

The Fuegian Potassic Magmatism comprises small (< 25 km^2), isolated plutons emplaced in the Yahgan and Beauvoir formations (Fig. 3, González Guillot et al., 2009). The plutons are composite, ranging from ultramafic to felsic facies, and with a characteristic mildly alkaline chemistry (González Guillot, 2016). The intrusives are the Ushuaia, Kranck, Moat and Jeu-Jepén plutons (Fig. 3).

The Kranck pluton has especial interest for this work since it is associated with two sets of dikes and sills (Cerro Rodríguez dikes) that intrude the Beauvoir Formation towards the north of the pluton, within the internal thrust-fold belt domain (Torres Carbonell et al. 2017c). We provide below (section 4.2), and later discuss, the overprinting relationships of these dikes with the deformation of the host rock, as well as new geochronological data of the Kranck pluton and Cerro Rodríguez dikes (section 5). Previously reported U/Pb zircon ages are 75 ± 1.0 Ma to 70.9 ± 1.7 Ma for the Ushuaia pluton (Barbeau et al., 2009b; González Guillot et al., 2018), and 72.01 ± 0.75 Ma for the Jeu-Jepén pluton (Cerredo et al., 2011).

2.2. Tectonic framework

Contractional deformation in the Fuegian Andes started with the northward obduction of the Rocas Verdes Basin oceanic floor in Cordillera Darwin, which was also associated with southward underthrusting of the continental margin of the basin, both processes comprising a first deformation phase in the region associated with arc-continent collision (Fig. 1b, Klepeis et al. 2010). At mid-crustal depths, underthrusting and obduction caused high shear strain and peak metamorphism under upper-amphibolite facies conditions, reaching 12 kbar and ~600 °C, and later decompressing to 9 kbar during peak temperatures of more than 600 °C. This is recorded in Bahía Pía (all localities shown in Fig. 3), where a high-grade shear zone has been described (Kohn et al., 1993, 1995; Klepeis et al., 2010; Maloney et al., 2011).

Modelled Ar/Ar ages of hornblende, muscovite, biotite and K-feldspar from metamorphic rocks of Cordillera Darwin indicate that first-phase deformation was ongoing by 90 Ma, with a stage of rapid cooling between 90-70 Ma (Fig. 4, Kohn et al., 1995; see also Nelson, 1982). Other evidence of this rapid cooling trend, and associated uplift and erosion of the orogenic core, is recorded in the Campanian-?lower Maastrichtian Bahía Thetis Formation and equivalent Cerro Matrero Formation in Chile (Fig. 2). These units contain clasts of eroded metavolcanic and metasedimentary rocks, and detrital zircons in the Cerro Matrero Formation with the younger ages in the range of 82-145 Ma, derived from the back-arc basin fill, basaltic floor and older synrift sequence (Fig. 4, Olivero et al., 2003; McAtamney et al., 2011).

The first-phase structures are intruded by Beagle suite granites without ductile deformation, which suggests an age older than 86-74 Ma for this phase (Klepeis et al., 2010). However, some contemporaneity between Beagle granite intrusions and first-phase structures is indicated by an age of 72.6 ± 2.2 Ma from U-Th-Pb in-situ dating of a late first-phase metamorphic monazite from Bahía Pía (Fig. 4, Maloney et al., 2011). In Argentina, first-phase structures are intruded by the Ushuaia pluton, with a well-developed contact-metamorphism aureole that overprints a previous foliation (Fig. 4, González Guillot et al., 2018). In Península Mitre, the Bahía Thetis Formation is the youngest unit affected by first-phase deformation (Fig. 4, Torres Carbonell et al., 2017b). This broadly suggests a late Campanian-?early Maastrichtian age for the end of this deformation phase.

The Beagle suite granites are affected by a second, more brittle deformation phase associated with at least three major thrust sheets in the Cordillera Darwin region (Klepeis et al., 2010). Similar structures from Argentina, and their relationship with the second phase, are reported in this work. The thrusts in Cordillera Darwin are responsible for uplift of the high-grade metamorphic rocks simultaneously with retrograde metamorphism (Kohn et al., 1993) since at least ~70 Ma (Fig. 4, Klepeis et al., 2010; Maloney et al., 2011). Nonetheless, there are structures in Bahía Pía related to retrogression of metamorphic assemblages (thus second-phase), which are cut by the Beagle suite (F3/S3 in Klepeis et al., 2010). Therefore, we notice a possibly contemporaneous development between early second-phase thrusting and intrusion of some Beagle granites in that region. This probable contemporaneity between the Beagle suite and the transition from the first collision-related phase and the second thrust-related phase highlights the need for additional independent age constraints from different portions of the Fuegian Andes. This is especially important to document a possible diachronic progression of deformation in the orogen.

The second thrusting phase has been compared with the 60-40 Ma rapid cooling trend modelled from Ar/Ar closure temperature ages on K-feldspar, hornblende, muscovite, and biotite, Rb/Sr closure temperature ages on biotite, and fission track ages of titanite, zircon and apatite, from metamorphic rocks of Cordillera Darwin (Fig. 4, Kohn et al., 1995; see also Nelson, 1982). More recent zircon and apatite fission track and (U-Th-Sm)/He ages of samples from southern Cordillera Darwin, Isla Gordon and the Argentine central belt, suggest the onset of a rapid cooling stage since ~48 Ma, ending by ~34 Ma (Fig. 4, Gombosi et al., 2009). These cooling trends are consistent with further uplift, erosion, and a more prominent supply of detritus eroded from the basement and especially Jurassic components of the orogen to the foreland basin, as recorded from 150-180 Ma detrital zircons and from the petrography of Paleocene-Eocene sedimentary rocks (Barbeau et al., 2009a; Torres Carbonell and Olivero, 2019). Additional evidence of thrust-related uplift in the central belt comes from the documented Oligocene thrusting affecting the Lemaire Formation at Bahía Sloggett (Fig. 4, Olivero et al., 1998).

Development of the foreland thrust-fold belt is coeval with both phases of deformation in the central belt of the orogen (Fig. 4). The thrust-fold belt is subdivided into an internal and an external portion (Figs. 1a and 3), given their different structural styles (cf. Torres Carbonell et al., 2017a). Both portions and the central belt, however, are structurally linked, as we will discuss in this work.

The internal thrust-fold belt comprises structures between the central belt and a major structure called Apen-Malvinera thrust system (Fig. 3) that roughly defines the mountain front in Tierra del Fuego. Previous structural work in the internal thrust-fold belt has been published by Klepeis (1994), Zanella et al. (2014) and Torres Carbonell et al. (2013b, 2017b). The structure of the internal thrust-fold belt will be addressed in the following sections together with new structural and stratigraphic data from this region.

The external thrust-fold belt comprises the shallowest structures of the Fuegian Andes. These structures, as observed in seismic sections, are rooted in two main detachments localized below Paleocene strata and below the Cretaceous succession, respectively (Álvarez-Marrón et al., 1993; Zanella et al., 2014; Torres Carbonell et al., 2017a). Below these detachments, some deeper structures appear to be splays associated with the deep thrusts emplaced in the central belt (Torres Carbonell et al., 2017a).

The structures in the external thrust-fold belt have been interpreted as fault-propagation and fault-bend folds, with both foreland and hinterland vergence. Most of the thrusts are rarely exposed, except at the Apen-Malvinera thrust system and at the Atlantic coast, where few of them display cataclastic fabrics (Torres Carbonell et al., 2011). No penetrative fabrics (foliations) have been recognized in the external thrust-fold belt.

Several fracture sets, analyzed for paleostress directions, indicate compression perpendicular to most of the structures during the Paleogene (Maestro et al., 2019). In Península Mitre, on the other hand, the curvature of the thrust-fold belt forms a recess (Península Mitre recess). Based on fracture paleostress directions and strain measurements, this recess has been interpreted as a progressive arc with development of superposed deformations related to tangential longitudinal strain (Torres Carbonell et al., 2019).

In the Atlantic coast, previous work defined several contractional stages (Df2-Df6 in Fig. 4) based on the overprinting relationships of structures with well-exposed unconformity-bounded units (Torres Carbonell et al., 2011). The latter units, in turn, have well-constrained ages based on foraminifers, nanoplancton, dinocysts, and in some cases detrital zircon ages (Malumián and Olivero, 2006; Olivero and Malumián, 2008; Barbeau et al., 2009a; Torres Carbonell and Olivero, 2019).

These contractional stages, further grouped as D2 phase in Torres Carbonell et al. (2017a), developed from the early Eocene to the latest Oligocene-earliest Miocene. During these times, contractional deformation ceased simultaneously with deposition of growth strata in the deformation front (Df6, Fig. 4, Ghiglione, 2002; Torres Carbonell et al., 2011, 2013a).

According to balanced cross-sections, accumulated shortening in the Paleogene sequence vary between 11 and 28 km (16-45%, Torres Carbonell et al. 2017a). Torres Carbonell and Dimieri (2013), and later Torres Carbonell et al. (2017a), argued that this shortening must necessarily be generated by transference of major structures in the hinterland, carried on ramps above the main detachments below the Cretaceous and Paleocene sequences. According to this model, the second-phase structures of the central belt are associated with uplift and transference of shortening to the foreland through formation of an antiformal stack of basement and Upper Jurassic rocks (Fig. 1b, Torres Carbonell and Dimieri, 2013). The upper detachment of this first-order duplex is located near the contact between the Upper Jurassic synrift sequences and the Lower Cretaceous fill of the Rocas Verdes Basin (Klepeis, 1994; Kley et al., 1999; Rojas and Mpodozis, 2006; Torres Carbonell and Dimieri, 2013; this work).

3. Methods and new data

New data used in this paper come from fieldwork in the Argentine Fuegian Andes. Field data consist of attitudes and cross-cut relationships between different generations of structures, and between structures and several igneous bodies. Oriented samples have been studied under the microscope in order to define metamorphic assemblages and/or microstructural relationships. In particular we present here detailed descriptions of two previously unmapped areas of the Fuegian Andes (located in Fig. 3): Cañadón Bianchi, at Montes Martial, and a cross-section along a creek in northern Sierra Alvear (Arroyo Velazquito). In these areas we obtained new supporting evidence for the superposition of younger, brittle-ductile thrust-related structures on older ductile structures. All spherical projections shown were constructed with the software Stereonet 10.1.6 from R. W. Allmendinger.

In order to constrain the ages of both structural generations, we studied the cross-cutting relationships of selected intrusives that due to their position in the Fuegian Andes, allow a spatiotemporal control on the progression of deformation. On one hand, we studied the Ushuaia Peninsula Andesites, which constitute the southernmost intrusives north of Canal Beagle in Argentine Tierra del Fuego, with an available crystallization age. On the other hand, we studied the northernmost intrusives in the thrust-fold belt: the Kranck pluton and related dikes and sills between the pluton and Cerro Rodríguez (Cerro Rodríguez dikes). We present new structural descriptions, and three new radiometric ages that constitute key constraints on the chronology of deformation in the Fuegian thrust-fold belt.

A U/Pb zircon age was obtained from a quartz monzonite of the Kranck pluton at the Geochronology Laboratory of the University of Brasilia (Brazil), by LA-ICP-MS. Other two hornblende Ar/Ar ages were obtained from a hornblendite of the Kranck pluton, and from an undeformed hornblende lamprophyre from the Cerro Rodríguez dikes, described in this work. Both Ar/Ar ages were obtained at the Earth Sciences Institute at Orléans (ISTO), INSU-CNRS, University of Orléans (France), by step heating. The methodological details and the tabulated results are given in the Supplementary File 1.

A balanced cross-section is presented in section 7.2. This cross-section was constructed with Move 2018.2 software by sequential restoration of individual structures, with conservation of shortening transferred from deeper structures to shallower detachments as a premise. After initial construction, the cross-section was tested by forward modelling using Move-on-Fault tools in Move. The method selected was fault-bend folding, except from a few frontal structures modelled with trishear.

4. New structural data

4.1. New structural data of the central belt

Our new structural data from the central belt includes detailed structural descriptions of, on one hand, the cross-cutting relationships between the Ushuaia Peninsula Andesites and deformation in their host rock, and on the other hand the superposition of brittle-ductile thrusts on prior ductile deformation, as well as the connection between these thrusts and a main upper detachment below the Cretaceous rocks. These latter brittle-ductile structures are described in two different areas of the central belt (Cañadón Bianchi and Arroyo Velazquito). Even though some thrusts and the detachment have been reported without much detail in other areas of the Fuegian Andes (e.g. Torres Carbonell and Dimieri, 2013; Torres Carbonell et al., 2017b), we provide here the first detailed description of these structures, and their superposed nature on previous ductile structures, in the area between Lago Fagnano and Canal Beagle.

4.1.1. Deformation of the Ushuaia Peninsula Andesites

The Ushuaia Peninsula Andesites were previously thought to postdate ductile deformation, based on unreported deformation or metamorphism in the intrusive rocks (González Guillot et al., 2011). Indeed, the host rock (Yahgan Formation), affected by contact metamorphism, preserves its original well-stratified character, without recognizable centimeter-scale folds (Fig. 5a-b) such as it is observed elsewhere surrounding Ushuaia, and along the Canal Beagle only a few kilometers away from Península Ushuaia (e.g. surrounding the Ushuaia pluton). Only occasionally the Yahgan Formation shows a spaced rough cleavage away from the main body of the intrusive suite (Fig. 5c). Farther away (> 1 km), however, at the southeastern tip of the peninsula, the Yahgan Formation reveals a more intense deformation, with centimeter-scale folds and a closely spaced cleavage formed by pressure-solution seams. At this location, an isolated, 1.5 m thick andesite dike, shows spaced pressure-solution cleavage parallel to the foliation in the Yahgan Formation (Fig. 5d-f).

A comparison between the poorly deformed host rock, with only a spaced, pressure-solution cleavage of stylolitic morphology (Fig. 5e-f), and the stronger deformation in the Yahgan Formation away from the main intrusive, suggests that the host rock has been protected from ductile deformation due to the existence of a coherent, very competent igneous rock. The absence of penetrative structures in the stronger rheologies, with selective development in the weaker rocks, is typical of this part of the central belt, and consistent with the temperature conditions suggested by the low-grade metamorphism (see section 6.1).

4.1.2. Brittle-ductile thrusts and detachment superposed on ductile structures

At Montes Martial, in the area known as Cañadón Bianchi, we have mapped three brittle-ductile fault zones that constitute thrusts below a common upper detachment (Fig. 6a-b). The thrusts cut up-section metavolcaniclastic and metasedimentary rocks of the Lemaire Formation. These fault zones are composed of cohesive cataclastic rocks (Fig. 6c-d), with folded and deflected older foliations, forming characteristic s-c type fabrics with top-to-north shear sense (Fig. 6e). A clear superposition of these brittle-ductile structures on the prior ductile fabrics is observed in outcrop as well as under the microscope (Fig. 6f-g).The older foliations are continuous cleavages formed mostly by white micas and chlorite, as well as deformed quartz and plagioclase. In the metasedimentary facies this cleavage transposes bedding forming a characteristic banded fabric (Fig. 6f).

The southernmost thrust joins a detachment located near the base of the Yahgan Formation, just below a thick basic sill known as Puente Quemado Gabbro (described in González Guillot et al., 2016, Fig. 6b). The detachment comprises a brittle-ductile fault zone about 5 meters thick, characterized by cataclastic fabrics similar to the ones described for the thrusts, but affecting in this case slates of the Yahgan Formation. A notorious feature is the presence of faulted folds (classes 2 or 1C) in the detachment zone (Fig. 6h), as well as crenulation of the prior slaty cleavage (Fig. 6i). Kinematic indicators (deflected foliation in s-c type fabrics) indicate top-to-north movement (Fig. 6j). Both the thrusts and the detachment are folded by first-order structures, and in a SW-NE cross section they are involved in a large synform that plunges to the SE (Fig. 6a, k).

At the northern face of Sierra Alvear, along Arroyo Velazquito, the same detachment horizon is observed at the base of the Beauvoir Formation (Fig. 7). At this location, the detachment surface is folded and exposed in the vertical, frontal limb of an antiform affecting metavolcaniclastic facies of the Lemaire Formation, covered by lapillitic mudstones of the Beauvoir Formation (Fig. 7a). Towards the north, the Beauvoir Formation attains a gentle northward dip, thus the detachment dips below Lago Fagnano in that direction (see Fig. 3). The detachment itself is characterized by cataclastic fabrics, faulted folds, and deflected older foliations with s-c type fabrics showing top-to-north shear sense (Fig. 7b-d, see also Fig. 8b).

4.2. New structural data of the internal thrust-fold belt

We report here new detailed descriptions of the structures affecting Cretaceous rocks in the internal thrust-fold belt (Sierra Beauvoir), and their overprinting relationships with dikes intruding the Beauvoir Formation nearby Cerro Rodríguez (Cerro Rodríguez dikes, Fig. 9). The general deformation in this area has been described for the Upper Cretaceous rocks by Torres Carbonell et al. (2013b). Detailed descriptions of the deformation in older rocks have not been published so far, except from brief mentions in Torres Carbonell et al. (2017c). Further descriptions are included within the new data presented below.

Towards the lower stratigraphic horizons of Sierra Beauvoir (e.g. Beauvoir Formation), the rocks reveal a continuous cleavage formed mainly by very fine sericite. Folds across Sierra Beauvoir are involved in at least five orders, and in general they present NE vergence across the range. Wavelengths are of a few kilometers in the first order folds, and a few meters in the highest order (Fig. 8a). Competent beds form parallel folds, however multilayers can be classified as 1C or 2 Ramsay folds, since less-competent layers accommodate deformation forming class 3 folds between class 1B (parallel) competent folded beds. A wide spectrum in fold style is observed, however, with both angular and rounded hinges, and tightness varying between tight and open.

At least three thrusts have been recognized at Sierra Beauvoir, involved in the stacking of the Cretaceous sequence. The thrusts have NE vergence, and occasionally cut the frontal limb of the first order folds. Thrusts are characterized by shear zones several tens of meters thick, where a deflection of prior cleavage planes or bedding (forming folds and s-c fabrics), disrupted stratigraphy, and widespread cataclastic fabrics are observed (Fig. 8b). Shear sense is always top-to-NE. These characteristics are similar to those described for thrusts affecting the same sequence in Chile (Klepeis, 1994), and at Península Mitre (e.g. Bahía Thetis thrust in Torres Carbonell et al., 2017b).

Between Cerro Rodríguez and the Kranck pluton (Fig. 9) two distinct sets of dikes and sills crop out (Cerro Rodríguez dikes, first reported by Martinioni et al., 1999). The dikes intrude the Beauvoir Formation and have thicknesses of 0.2-2.5 m. The abundance of intrusions increases towards the Kranck pluton (Fig. 9). As briefly reported by Torres Carbonell et al. (2017c), we identified two dike generations. One of these generations is composed of clinopyroxene-biotite or clinopyroxene lamprophyres, affected by spaced pressure-solution cleavage parallel to the continuous cleavage in the host rock. These dikes are here called “deformed set” (Figs. 9 and 10). The second generation has no cleavage and is composed of hornblende-clinopyroxene lamprophyres and felsic dikes of andesite and trachy-andesite (“undeformed set”). The deformed set is concentrated surrounding Cerro Rodríguez, whereas the undeformed set has a more uniform distribution, but is more abundant close to the Kranck pluton (Fig. 9). Martinioni et al. (1999) obtained a whole rock K/Ar age of 104 ±4 Ma for one undeformed, hornblende-phyric dike, which we discuss below. On the basis of hornblende chemical composition, Acevedo et al. (2007) correlated the hornblende undeformed dikes with hornblende gabbros from the Kranck pluton.

5. Geochronological results

Sample BR47 (Fig. 9) is a quartz monzonite of the Kranck pluton, which lacks penetrative deformation. Cross-cutting relationships indicate that it represents one of the youngest facies of the pluton (a thorough description of the facies was presented by González Guillot et al., 2012). A total of 47 zircon grains were analyzed. The data set shows a constant $^{206}Pb/^{238}U$ age between 64 and 72 Ma, with a weighted average at 68.01 ± 0.52 Ma (2σ, MSWD 11.8, Fig. 11a, Supplementary File 1). We interpret this as the age of emplacement and crystallization of the rock.

Sample BR29 (Fig. 9) is an undeformed hornblendite from the Kranck pluton. It is intruded by other facies, thus represents one of the earliest pulses of crystallization (see more details in González Guillot et al., 2012). The sample has a weighted mean age, integrated over the steps between arrows in Fig. 11b, of 73.4 ± 1.6 Ma (2σ, MSWD 0.81, Supplementary File 1). Sample 104, an undeformed hornblende lamprophyre of the Cerro Rodríguez dikes, has a weighted mean age, integrated over the steps between arrows in Fig. 11c, of 74.0 ± 0.8 Ma (2σ, MSWD 0.79, Supplementary File 1). Both $^{40}Ar/^{39}Ar$ ages are indistinguishable; therefore the undeformed hornblende lamprophyres of Cerro Rodríguez were emplaced at the same time than hornblendites in the Kranck pluton, and before the quartz monzonite.

6. Integration of previous and new structural data from the Fuegian thrust-fold belt

In the following section we integrate our new structural and geochronological data with previous work, which allows us to define structural generations and correlate them across the Fuegian Andes. Based on previous work (Torres Carbonell and Dimieri, 2013), we refer to the Fuegian Andes as a thrust-fold belt that involves basement and thickens toward the south (hinterland). For convenience, we address separately the central belt from the internal thrust-fold belt.

6.1. Central belt

The central belt of the Fuegian Andes reveal multiple generations of structures with complex correlations between different regions. This is especially so in the highly metamorphosed and deformed area of Cordillera Darwin, were glacier cover adds difficulty in connecting structures from different coastal outcrops. However, two major deformations can be roughly defined in Cordillera Darwin, called $D1_{CD}$ and $D2_{CD}$, each of them comprising one or more generations of structures. This distinction follows the criteria and data of Nelson et al. (1980), Cunningham (1995), Kohn et al. (1995), Klepeis et al. (2010), and Maloney et al. (2011), and correlates with the first and second deformation phases mentioned in section 2.2.

$D1_{CD}$ comprises foliations and folds formed during the obduction and underthrusting of the oceanic floor and continental margin, respectively, with evidence of a southward-dipping mid-crustal shear zone nearby Bahía Pía (Nelson et al., 1980; Cunningham, 1995; Klepeis et al., 2010). This process formed an initial S1 metamorphic fabric and superposed S2 crenulation cleavage and F2 folds (Nelson et al., 1980; Kohn et al., 1993; Klepeis et al., 2010; Maloney et al., 2011), during what we interpret as a phase of progressive deformation with two generations of structures (S1 + S2/F2). Away from the zone of higher metamorphic grade at Bahía Pía, $D1_{CD}$ structures are limited to a single generation of S1 structures associated to top-to-northeast obduction and ductile shear (Nelson et al., 1980; Klepeis et al., 2010).

The second deformation, $D2_{CD}$, includes crenulation, kink bands, thrusts and folds that deform the prior $D1_{CD}$ structures. At Bahía Pía and in northern Cordillera Darwin $D2_{CD}$ structures have NE vergence and are coeval with retrograde metamorphism (Nelson et al., 1980; Kohn et al., 1993). West of Bahía Pía (at SW Cordillera Darwin)

$D2_{CD}$ structures are associated with backfolds and backthrust shear zones (Klepeis et al., 2010). $D2_{CD}$ developed during uplift of Cordillera Darwin, caused by at least three identified major thrusts (Garibaldi -blind-, Parry and Marinelli thrusts, Fig. 3), which together with the backfolds and backthrusts recognized in SW Cordillera Darwin form a doubly-vergent wedge (Nelson et al., 1980; Klepeis et al., 2010).

Formation of $D1_{CD}$ structures, as detailed in section 2.2, started before ~90 Ma (Kohn et al., 1995) and acted at least until ~73 Ma, coeval with the last intrusions of the Beagle suite (Fig. 4, Klepeis et al., 2010; Maloney et al.,2011; McAtamney et al., 2011). Thus, mid-crustal shearing during $D1_{CD}$ may be transitional with the beginning of thrusting during the following deformation ($D2_{CD}$), which has ambiguous overprinting relationships with the Beagle suite (Klepeis et al., 2010).

The thrusting stage related to $D2_{CD}$ progressed through the Paleogene, as evidenced by thermochronology results detailed in section 2.2 (Fig. 4, Kohn et al., 1995; Gombosi et al., 2009). An appraisal of previous work, however, shows no clear connection with the structures towards the foreland, which have been interpreted as structures formed prior to out-of-sequence uplift of Cordillera Darwin (Klepeis, 1994; Kley et al., 1999; Klepeis et al., 2010).

In Argentine Tierra del Fuego, overprinting structural relationships from the central belt also allowed to define two main structural styles. An older, ductile deformation, which we will call $D1_{CB}$ (first deformation -D1- recorded in the central belt -CB- excluding Cordillera Darwin), and a younger, brittle-ductile deformation that we call $D2_{CB}$. $D1_{CB}$ is characterized by ductile NE-vergent folds and axial-plane foliations associated with low-grade regional metamorphism, and with the development of shear zones with mylonitic foliations in sectors of localized higher strains (Fig. 8a, Kranck, 1932; Bruhn, 1979; Dalziel and Palmer, 1979; Torres Carbonell and Dimieri, 2013; Torres Carbonell et al., 2017b; Cao et al., 2018; Cao, 2019). Between Canal Beagle and Lago Fagnano, $D1_{CB}$ folds range from tight or isoclinal in the Lapataia and Lemaire formations, to tight or very tight folds with NE vergence, usually classes 1C to 2, in the Yahgan and Beauvoir formations. The axial-plane foliation is defined by low-grade metamorphic minerals, and occasionally transposes bedding (Fig. 8a). An exception occurs in the more competent coherent volcanic-subvolcanic bodies of all the formations of this region of the central belt, in which the folds and cleavage are not uniformly developed; some of these bodies show poor cleavage or none at all. The metamorphic grade in this part of the central belt is within prehnite-pumpellyite to greenschist facies (Bruhn, 1979; Cao et al., 2018; Cao, 2019).

In the zones of higher strain, especially localized in quartz-rich lithologies, the main structures are mylonitic fabrics with top-to-north or northeast shear sense (Fig. 8a). These mylonites, first recognized by Kranck (1932) and Bruhn (1979), led the latter author to interpret formation of the central belt between Canal Beagle and Lago Fagnano as a result of progressive simple shear. An alternative interpretation based on scattered and undetailed data suggested that these mylonites formed part of the $D2_{CD}$ thrusting of Cordillera Darwin (Torres Carbonell and Dimieri, 2013). However, as will be addressed below, the correlation of the $D2_{CD}$ brittle-ductile structures with the brittle-ductile thrusts reported in section 4.1.2, suggests that these mylonites are older. Therefore, they can be interpreted as zones of concentrated $D1_{CB}$ deformation in the simple shear scheme proposed by Bruhn (1979, cf. Torres Carbonell et al., 2017b; Cao et al., 2018).

In southern Península Mitre, the $D1_{CB}$ structures and metamorphic grades in the Lemaire and Beauvoir formations are similar to those between Lago Fagnano and Canal Beagle, with a NW-SE structural trend (Torres Carbonell et al., 2017b). Moreover, in this region it is clear how the intensity of the $D1_{CB}$ structures decrease from mylonitic foliations and transposition cleavage to spaced pressure-solution cleavage towards upper structural levels, affecting rocks as young as late Campanian-?early Maastrichtian (Bahía Thetis Formation, Figs. 2 and 8a, Torres Carbonell et al., 2013b, 2017b). These NW-SE structures are included in the first deformation phase of Torres Carbonell et al. (2017b).

Previous constraints on the age of the $D1_{CB}$ structures were limited to their inclusion in the "main phase of deformation" ("mid" Cretaceous in Bruhn, 1979; Dalziel and Palmer, 1979), and the statement that they affected rocks not younger than the Campanian-?Maastrichtian Bahía Thetis Formation (Torres Carbonell et al., 2017b). González Guillot et al. (2018) established that these structures are older than the Ushuaia pluton (75-71 Ma), giving a stronger constraint for the southern portion of the central belt (Fig. 4). The same overprinting relationship is observed in other pluton of the Fuegian Potassic Magmatism, the Jeu-Jepén pluton, which has a contact metamorphism aureole that overprints cleavage in the host rocks (Fig. 5g).

The deformed dike depicted in Fig. 5d-f confirms that ductile structures ($D1_{CB}$) affected the Ushuaia Peninsula Andesites. From correlation of that dike with the dated andesite at the main body of the intrusion (84.1 ± 1.6 Ma, González Guillot et al., 2018), we can establish an oldest time constraint on the age of these structures (Fig. 4).

The younger deformation, $D2_{CB}$, includes large folds (up to tens of kilometers of wavelength) and crenulation cleavages that grade from a pervasive development in the lower structural levels (Lapataia Formation), to spaced crenulation cleavages localized in high-strain zones in the upper structural levels (Bruhn, 1979; Cao et al., 2018). These high-strain zones comprise thrusts and detachments (Fig. 8b), the former include the thrust zones of Cañadón Bianchi (section 4.1.2), as well as thrusts previously reported at the contact between the Lapataia and Lemaire formations (Beatriz thrust, Fig. 3, Cao et al., 2018; Cao, 2019), within the Lemaire Formation at Sierra Sorondo and Sierra Alvear (Cao, 2019), and between the Lemaire and Beauvoir formations at Montes Negros (Torres Carbonell et al., 2017b). The detachments are consistently located in the surroundings of the contact between the Lemaire and Yahgan or Beauvoir formations, as stated in section 4.1.2 (cf. Torres Carbonell and Dimieri, 2013; Cao, 2019). In Chile, the same detachment level was identified between the Tobífera and Río Jackson formations and has been called Río Jackson detachment by Klepeis (1994).

The $D2_{CB}$ thrusts form characteristic zones of protracted deformation during decreasing temperature conditions. Accordingly, while crenulation cleavages and deflected foliations formed in the lower structural levels, these structures were overprinted by cataclastic fabrics in shallower levels. For example, as shown in Fig. 6f, ductile $D2_{CB}$ folds affecting the older $D1_{CB}$ transposition foliation are faulted and incorporated in a brittle $D2_{CB}$ cataclasite. In the more brittle settings and especially near detachment horizons, the crenulations affecting previous $D1_{CB}$ foliations are localized within a few meters from the detachment surfaces or shear zones, and dissipate away from the fault surfaces (Fig. 8b). Our data from Cañadón Bianchi and

Arroyo Velazquito (Figs. 6 and 7) confirm the superposition of these thrusts and detachment on the prior ductile $D1_{CB}$ deformation, thus constraining $D2_{CB}$ to a post-Campanian age (Fig. 4).

A third generation of structures in the Argentine central belt has been described by Cao (2019) and Cao et al. (2018), characterized by small (cm-scale) folds, kink bands and shear zones of deflected $D1_{CB}$ cleavage. These structures consistently have a N-S orientation, which is almost perpendicular to the regional structural trend. They have been interpreted as a distinct phase by the cited authors, but it is also possible that they are cross-folds or similar structures (see for example Butler, 1982) formed during the same $D2_{CB}$ deformation.

6.2. Internal thrust-fold belt

The connection between the central belt and the internal thrust-fold belt has been described north of Seno Almirantazgo and Lago Fagnano, in Chile (Klepeis, 1994; Kley et al., 1999; Rojas and Mpodozis, 2006). This connection, as mentioned in the previous section, involves a detachment at the base of the Lower Cretaceous shaly sequence, mapped as the Río Jackson detachment by Klepeis (1994) and reported in Argentina in this work (Fig. 7). Previous work by Klepeis (1994) and Torres Carbonell and Dimieri (2013), defined this detachment as the base of the cover sequence deformed in the foreland thrust-fold belt (Fig. 8b).

Between Lago Blanco and Lago Fagnano, the deformation sequence comprises folding and axial plane, pressure-solution cleavage development (S1 in Klepeis, 1994) and refolding of these structures by open folds (F2). Both generations developed, according to Klepeis (1994), during progressive shortening associated with thrust emplacement in the Cretaceous succession. Thrusts in this region are recognized as brittle-ductile structures such as s-c type, and brittle cataclastic fabrics. Klepeis (1994) also interpreted two backthrusts, associated with deformation just above the Río Jackson detachment.

At Sierra Beauvoir, the Upper Cretaceous rocks are deformed by folds and an axial-plane foliation, both with variable degrees of development (Torres Carbonell et al., 2013b). The foliation varies from smooth disjunctive cleavage in the lower structural levels or high-strain zones, to a more spaced cleavage (> 0,05 mm) formed by pressure-solution in the uppermost part of the succession. In the Policarpo Formation, for example, the cleavage is absent or very roughly developed and usually it is only a pencil structure (Torres Carbonell et al., 2013b). Our new data from the internal thrust-fold belt (section 4.2) complements these previous descriptions from Sierra Beauvoir, and show the change to more pronounced cleavages and very low-grade metamorphism in the older units. We recognized no backfolds or backthrusts, however, which could have been correlated with similar structures described in Chile, just tens of kilometers west of our study area (cf. Klepeis, 1994).

At Península Mitre (Bahía Thetis), structures similar to those described at Sierra Beauvoir are included in the second deformation phase described by Torres Carbonell et al. (2017b). These structures comprise NE-SW oriented folds, brittle-ductile shear zones (e.g. Bahía Thetis thrust and Buen Suceso backthrust) and SE-dipping pressure-solution cleavages in the Policarpo Formation and older Upper Cretaceous rocks, which grade to crenulation cleavages in the Beauvoir and Lemaire formations further south. No significant growth of metamorphic minerals is associated with the formation of this crenulation. The thrusts are characterized by zones several hundred meters thick, integrated by shear fabrics superposed on the prior $D1_{CB}$ foliation. These include s-c type fabrics and disrupted strata, evidencing deformation in brittle-ductile conditions (Torres Carbonell et al., 2017b).

Both at Península Mitre and Sierra Beauvoir, the youngest spaced cleavages affect the Policarpo Formation. The Paleocene Río Claro Group, resting on an unconformity above the Policarpo Formation, lacks penetrative deformation (Torres Carbonell et al., 2013b). This led to define a deformation phase of approximately Danian age (D1 in Torres Carbonell et al., 2017a), which in Península Mitre cross-cuts the prior $D1_{CB}$ structures with a highly oblique trend (NE-SW against NW-SE). Here we call this deformation $D1_{FB}$, namely the first deformation distinct to the foreland thrust-fold belt (FB, Fig. 4).

At Sierra Beauvoir, where both $D1_{CB}$ and $D1_{FB}$ are coaxial (NW-SE trend), their distinction is aided with our new geochronological data (section 5). The age of sample 104 is significantly younger than the age obtained for a similar undeformed dike by Martinioni et al. (1999) using K/Ar in whole rock. We consider our age better constrained, whereas previous work in the Fuegian Andes has shown the significant errors associated with K/Ar dating (González Guillot et al., 2018). Therefore, our new age allows us to place the formation of foliations in the deformed set of the Cerro Rodriguez dikes and host rock before ~74 Ma, placing these structures in the $D1_{CB}$ deformation. In this manner, younger spaced cleavages affecting rocks as young as the Policarpo Formation, mentioned before, can be attributed to $D1_{FB}$ consistently with the assignment made in Península Mitre (cf. Torres Carbonell et al., 2017b). Younger deformations in the foreland (Df2-Df6, mentioned in section 2.2), which are not discussed in this work, are grouped within a single deformation $D2_{FB}$ (Fig. 4).

7. Protracted deformation history of the Fuegian thrust-fold belt

The combination of published and new data just presented allows us to integrate the central belt and the foreland thrust-fold belt of the Fuegian Andes in a protracted deformation history, from the Late Cretaceous to the early Neogene. The evidence for structural connections between the central belt and the internal thrust-fold belt, in turn linked with the external thrust-fold belt, permits to analyze these portions of the orogenic front in a coherent manner, using as an example the restored cross-section presented below.

We propose a simplified, regional deformation sequence in which distinct structural styles develop simultaneously at different portions of the orogenic belt. Accordingly, the phases and stages of deformation mentioned throughout this text, which group generations of structures in different sectors of the thrust-belt, are here included in two major events forming this protracted history. The first event (red double-arrows in Fig. 4) involved the closure of the back-arc basin leading to obduction, underthrusting, and arc-continent collision (cf. Nelson et al., 1980; Dalziel, 1986; Cunningham, 1995; Klepeis et al., 2010), during which the orogeny was initiated. The second event (black double-arrows in Fig. 4) involved major uplift of the orogenic core (central belt) leading to formation of a first-order thrust system (antiformal stack) that transferred shortening towards the foreland, expanding the thrust-fold belt into the coeval foreland basin system (cf. Torres Carbonell and Dimieri, 2013).

7.1. First event: Arc-continent collision

Our new data on the overprinting relationships between the Ushuaia Peninsula Andesites and the $D1_{CB}$ deformation (Fig. 5d-f) indicates an age not older than ~84 Ma for the first event in the southern central belt in Argentina (Fig. 4). The youngest age of $D1_{CB}$ in the same area has already been established by the intrusion of the Ushuaia pluton by 75-71 Ma (González Guillot et al., 2018), which is consistent with the Campanian age determined in Península Mitre (first phase in Torres Carbonell et al., 2017b). At the northern border of the central belt, the ~72 Ma Jeu-Jepén pluton (Cerredo et al., 2011) also overprints the $D1_{CB}$ foliation (Fig. 5g).

Even if these temporal constraints are consistent with the correlation of $D1_{CB}$ and $D1_{CD}$, the beginning of ductile deformation in the Argentine part seems to have been delayed in comparison with the development of deep-seated structures in Cordillera Darwin, which started before 90 Ma (Fig. 4). In addition, during the end of the collisional event (by ~73 Ma), deformation in Cordillera Darwin occurred under high-temperature conditions, coincident with decompression from 12 to 9 kbar and initiation of thrust-related uplift (Maloney et al., 2011). Conversely, the coeval deformation between Canal Beagle and Lago Fagnano was milder, especially in the upper stratigraphic levels (Yahgan-Beauvoir formations). This is notorious within and around some competent rock bodies that developed poor cleavage or were almost undeformed (Fig. 5a-d). The more deformed rocks in this region, indeed, are represented by low-grade mylonitic zones in the Lapataia and Lemaire formations (Fig. 8a). This is consistent with a change from high- to low-grade deformation across the orogen, i.e. from the internal and lower structural levels now exposed at Cordillera Darwin to the external, upper structural levels exposed between Lago Fagnano and Canal Beagle. Farther towards the Campanian deformation front, in the internal thrust-fold belt, only very low-grade deformation affects the Beauvoir Formation.

The data presented here in section 4.2 also contribute to constrain the age of the collisional event in the internal thrust-fold belt. Accordingly, the age of the undeformed set of the Cerro Rodríguez dikes constrains the age of collisional deformation in that region to before ~74 Ma (Fig. 11), which is consistent with the ages in the central belt.

In summary, the progression of deformation during the arc-continent collision event can be described as foreland directed, ductile simple shear deformation above the underthrusting continental plate, concurring with Bruhn (1979, see also Tanner and Macdonald, 1982; Storey, 1983, Fig. 8a). Whilst high-grade deformation started prior to 90 Ma in Cordillera Darwin ($D1_{CD}$), in the Argentine Fuegian Andes only the last, Campanian part of this deformation is recorded in the rock structures, comprising low-grade deformation ($D1_{CB}$).

7.2. Second event: Major thrusting and expansion of the orogenic wedge

Our new data from the central belt contributes to the definition of the second event during the orogenic history, which involved thrust-related deformation throughout the orogen. We presented evidence from Cañadón Bianchi (Fig. 6) which confirms part of the thrust faults forming the duplex proposed by Torres Carbonell and Dimieri (2013). This new evidence adds to previous data reported by Torres Carbonell et al. (2017b) and Cao et al. (2018). These thrusts, ramping from an unexposed lower detachment (possibly located in the basement unit), cut through Jurassic syn-rift deposits and join an upper detachment in the vicinity of the contact between the Lemaire and Yahgan or Beauvoir formations (Figs. 6 and 7). The brittle-ductile thrusts and detachment are superposed on previous ductile $D1_{CB}$ structures; therefore they post-date the Campanian (Fig. 4).

In a similar way, the $D1_{CD}$ structures are overprinted by $D2_{CD}$ structures in Cordillera Darwin, which are related to ductile-brittle thrusts emplaced in that region. The northernmost of these thrusts, called Marinelli thrust (Klepeis, 1994), can be laterally traced to join the Beatriz thrust in our map (Fig. 3). Klepeis (1994) suggested that the Marinelli thrust exhumed and placed basement rocks on top of back-arc basin cover rocks, proposing that the thrust timing was out-of-sequence with deformation in the internal thrust-fold belt. Building on that interpretation, it has been proposed that all the $D2_{CD}$ thrusts (Garibaldi, Parry and Marinelli) formed out-of-sequence with the internal thrust-fold belt (Kraemer, 2003; Rojas and Mpodozis, 2006; Klepeis et al., 2010). This has important implications for the transference of shortening (or lack of it) that built the foreland portion of the thrust-fold belt.

An alternative view has been proposed by Torres Carbonell and Dimieri (2013), interpreting the Marinelli thrust as a ramp which, after being actively involved in the duplex, broke up-section as a breaching thrust (cf. Butler et al., 2007), cutting the duplex roof detachment. This interpretation is more adequate to allow additional structures in the hinterland to transfer shortening to the foreland, before being effectively uplifted above the roof thrust (see also Torres Carbonell et al., 2017a).

Our interpretation for the progression of $D2_{CB}$ structures is shown in a balanced cross-section constrained by field and seismic data (Fig. 12). This cross-section uses a depth to the basal detachment controlled by depth-migrated seismic data and wells in the foreland, and with an arbitrary uniform dip towards the hinterland. Notice that the basement-Upper Jurassic contact in the cross-section is speculative. Further details on the balancing method are given in section 3.

The cross-section assumes that all the deformation during $D2_{CB}$ was accommodated by movement on single thrusts. This clearly is an oversimplification, but allows creating a geologically reasonable and viable cross-section that explains the first-order central belt structure and coeval foreland deformation. It also implies amounts of shortening transferred to the foreland that are consistent with balanced cross-sections in the external thrust-fold belt (Torres Carbonell et al., 2017a).

In summary, this regional, balanced cross-section shows that emplacement of brittle-ductile thrusts in the central belt during $D2_{CD}$ and $D2_{CB}$ progressed simultaneously with accommodation of transferred shortening in shallower structures in the thrust-fold belt ($D1_{FB}$ and $D2_{FB,}$ Fig. 8b). The latter argument is consistent with the cooling history of the central belt, as reported in section 2.2, which indicates coeval uplift of the central belt and deformation in the foreland at least during the Late Cretaceous and Paleogene (Fig. 4, Kohn et al., 1995; Gombosi et al., 2009).

The interpretation shown in Fig. 12, with a crustal duplex responsible for uplift of the central belt after the initial closure of the Rocas Verdes Basin, also implies the existence of basement thrust wedges below the central belt as a requisite to explain the structural level at which the Lemaire Formation is uplifted, in comparison with the same horizons in the foreland (Fig. 12). This interpretation has the advantage of explaining the occurrence of rocks uplifted from depths of more than 20 km (12 kbar and ~600 °C according to Kohn et al. 1995) at the current surface (at Bahía Pía), using a reasonable geometric model for this amount of uplift.

Conditions of deformation during the thrusting event varied also with structural position. In the central belt the metamorphic grade was low in Cordillera Darwin (Kohn et al., 1993), to very low or even absent in Argentina, and penetrative deformation was restricted to crenulation cleavages with minor growth of retrograde metamorphic minerals associated with the formation of major brittle-ductile thrusts (Fig. 8b). Towards the foreland, shortening transferred from the duplex to the Cretaceous cover was accommodated by pressure-solution and spaced cleavage development, followed by folding and brittle-ductile thrusting (Fig. 8b). This deformation comprises, in the scheme presented here, the $D1_{FB}$ structures now exposed in the internal thrust-fold belt.

Simultaneous sedimentation and deformation in the Austral basin characterized the following deformation in the external part of the thrust-fold belt, called $D2_{FB}$ in this work. This deformation is mostly related to the development of major thrust systems in the foreland until the early Miocene (Fig. 12, see Torres Carbonell et al., 2017a).

8. Conclusions

An integration of new structural and geochronological data with an analysis of previously published data from the Fuegian Andes, allows us to document the sequence of deformation within a tectonic model of the orogen formed in the southernmost Andes. Accordingly, we constrain the timing of the two main events involved in deformation in the Argentine portion of the orogen. The first event was caused by closure of the Rocas Verdes Basin, with obduction, underthrusting, and arc-continent collision. As previously documented from Cordillera Darwin, this event spanned from ca. 100-90 Ma to ca. 73 Ma ago, causing high-grade deformation (e.g.

Kohn et al., 1995; Maloney et al., 2011). However, in the central belt in Argentina, our new data reveal that only Campanian (post-84 Ma), low-grade structures were developed in the uppermost structural levels of the collision-related deformation. This deformation is also recorded in the internal thrust-fold belt, and we provide a new age constraint for the structures in that region, which are post-dated by intrusives with Ar/Ar hornblende ages of 74 Ma.

The second event was characterized by the formation of a first-order thrust system since the Maastrichtian-Danian. This led to the definitive formation and expansion of the thrust-fold belt until the early Miocene, with major uplift episodes recorded in the hinterland associated with the emplacement of major basement-involved thrust sheets. Our new structural data confirms the occurrence of these thrusts, and their connection with a common upper detachment placed at the base of the Lower Cretaceous rocks, which forms the roof thrust of a major duplex in the central belt.

This scheme explains the different styles of deformation across the Fuegian Andes in the context of a progressive evolution from collisional-style orogenesis to thrust-related deformation. This model also allows explaining the shortening in the deformed Austral-Magallanes foreland basin as a consequence of major thrust emplacement in the central belt. Our new structural and geochronological data, in addition, give key constraints to correlate structure generations across and along the strike of the orogen.

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Figure captions

Figure 1: a. Geologic map of southernmost Patagonia and Tierra del Fuego with regional structural elements discussed in this work. S: Sarmiento Complex, CA: Capitán Aracena Complex. T: Tortuga Complex, LF: Lago Fagnano, CB: Canal Beagle. Based on works cited in the text. **b**. Cartoon showing closure of the back-arc basin and development of the Fuegian Andes during two main tectonic events, involving collision and later thrust-fold belt (TFB) expansion. Known intrusive pulses during both events are schematically depicted (modified from Torres Carbonell et al., 2014).

Figure 2: Stratigraphic framework of the Fuegian thrust-fold belt north of Canal Beagle, with nomenclature used in Argentina and Chile. For a more complete regional correlation see Torres Carbonell and Olivero (2019). References are 1: Biddle et al. (1986), Cañón (2000), Sánchez et al. (2010), McAtamney et al. (2011), Malumián et al.

(2013), 2: Malumián and Olivero (2006), Olivero and Malumián (2008), Martinioni et al. (2013), Cao et al. (2018), 3: Klepeis et al. (2010), McAtamney et al. (2011), Cerredo et al. (2011), González Guillot et al. (2018). An idealized lithologic column is shown, although lateral facies variations exist. Minimum thicknesses reported for reference are from the thicker composite sections and in some cases highly variable.

Figure 3: Geologic map of the Fuegian thrust-fold belt with main structural features and stratigraphic units mentioned in the text. See location in Fig. 1a, and text for details of stratigraphic units. Compiled from Klepeis (1994), SERNAGEOMIN (2003), Olivero and Malumián (2008), Hervé et al. (2010b), Klepeis et al. (2010), González Guillot (2016), Cao (2019), Torres Carbonell and Olivero (2019), and authors' data. Cross-sections x-y and y-z indicate location of Fig. 12a. Pt: Parry thrust, MM: Montes Martial, UP: Ushuaia pluton, UPA: Ushuaia Peninsula Andesites, JP: Jeu-Jepén pluton, MP: Moat pluton, BP: Bahía Pía, BT: Bahía Thetis.

Figure 4: Time constraints for the deformations recorded in the Fuegian thrust-fold belt, north of Canal Beagle, as addressed in this work. Modified from Torres Carbonell and Dimieri (2013). Bold bars indicate 2σ uncertainties. UPA: Ushuaia Peninsula Andesites, FPM: Fuegian Potassic Magmatism. References: 1: Nelson (1982), 2: Kohn et al. (1995), 3: Gombosi et al. (2009), 4: Klepeis et al. (2010), 5: Olivero and Martinioni (1996b), 6: Nelson et al. (1980), 7: Olivero et al. (2003), 8: McAtamney et al. (2011), 9: Torres Carbonell et al. (2011), 10: Maloney et al. (2011), 11: Cerredo et al. (2011), 12: Barbeau et al. (2009b), 13: González Guillot et al. (2018), 14: Torres Carbonell et al.

(2017b), 15: Olivero et al. (1998), 16: this work. Red and black double arrows labeled “D” are discussed in sections 6 and 7.

Figure 5: a-d. Outcrop photographs of the Ushuaia Peninsula Andesites (UPA) and host rock (Yahgan Formation, YG). Notice the lack of intense deformation in pictures **a** (person for scale) and **b**, from the main body of the intrusion. In picture **c** the Yahgan Formation shows slight folding and cleavage away from the main body of the intrusion (scale is 6 cm long). Picture **d** shows a dike and its host rock affected by pressure-solution cleavage (parallel to compass), farther away from the main intrusion. **e-f.** Photomicrographs of cleavage in the dike of picture **d**, plane-polarized light. Note horizontal pressure-solution seams with wriggly morphology defined by opaque insoluble residue. Pl: plagioclase, Hbl: hornblende (chloritized), Aln: allanite. g. Hornfels from the Jeu-Jepén pluton (Beauvoir Formation) with scarce pressure-solution seams (from upper-right to lower-left) reflecting the prior cleavage, which is obliterated by recrystallization of the plagioclase + quartz (Qz) groundmass, dissemination of insoluble residue inherited from the pressure-solution seams, and growth of biotite (Bt) parallel to the preexisting cleavage planes.

Figure 6: a. Geologic map of the Cañadón Bianchi area (location in Fig. 3). Equal area, lower hemisphere projection shows orientation of crenulation folds in the area. Brittle-ductile shear zones (BDZS) are numbered for reference to picture **b**. Location of photographs **c-j** is shown. **b.** Panoramic photograph with depiction of major structures as shown in **a**. Acronyms are for stratigraphic units in the map. **c-d.** Outcrop (backpack for scale) and close-up view of cataclastic fabrics in thrust zones. **e.** S-C type fabric

showing top-to-north component of movement. **f.** Cataclasite block revealing faulted folds (horizontal trace) affecting an older transposition foliation (alternating lighter and darker bands). Encircled 23-mm coin for scale. **g.** Photomicrograph of a cataclasite from a thrust zone affecting older quartz-mica schist, cross-polarized light. **h.** Faulted folds in the detachment at the base of the Yahgan Formation. Notice the style of folding with thickened hinge and thinned limbs in the lower left of the photograph. **i.** Crenulation of a previous foliation in the upper flat of the BDSZ 1. Scale is 6 cm long. **j.** S-C type fabric showing northeastward component of displacement in the detachment zone. **k.** Cross-section (located in **a**) showing the first-order synform affecting the detachment.

Figure 7: a. Panoramic photograph of the structure at Arroyo Velazquito. The detachment near the base of the Beauvoir Formation is folded by a large antiform. Towards the north, the beds dip northwards with progressively shallower angles (values given in dip direction/dip). **b-d.** Details of brittle-ductile fault fabrics in the detachment zone (located in **a**), superposed on older foliations and folds. In **b**, s-c type fabrics show a component of northward displacement (notice that north points to the lower left). 6-cm scale highlighted. Brecciated folds (arrows) and cataclastic fabric are shown in **c** and **d**.

Figure 8: Schematic description and examples of $D1_{CB}$ structures (**a**) and $D2_{CB}$-$D1_{FB}$ structures (**b**), further explained in section 6. S0: bedding, J: Jurassic and older, Kl: Lower Cretaceous, Ku: Upper Cretaceous. Cross-sections are idealized and not to scale.

Figure 9: Map of the Kranck pluton and Cerro Rodríguez dikes, with distribution of deformed and undeformed dike sets mentioned in the text. Location of dated samples is shown. Equal area projection shows poles to cleavage in the Beauvoir Formation (black) and the deformed dike set (red), with n number of measurements.

Figure 10: a-c. Outcrop examples of deformed Cerro Rodríguez dikes. Notice the good development of pressure-solution cleavages parallel to the cleavage in the host rock. **d-f.** Photomicrographs (plane-polarized light) showing the stylolitic or wriggly pressure-solution seams defining the spaced cleavage. Phenocrysts are very altered pseudomorphs of plagioclase, clinopyroxene or hornblende. In picture **f** a detail of bended biotite is shown, with the axial planes of the microfolds subparallel to cleavage (subvertical).

Figure 11: a. Wetherill concordia plot for zircon age determination from a quartz monzonite of the Kranck pluton (sample BR47). **b-c.** Hornblende (Hbl) Ar/Ar plateau ages for (**b**) sample BR29 (hornblendite, Kranck pluton) and (**c**) sample 104 (Hbl lamprophyre, Cerro Rodríguez dikes). The weighted mean age was integrated over the steps between the arrows.

Figure 12: a. Balanced cross-section of the Fuegian thrust-fold belt. The cross-section was constructed along an assumed continuous trace x-z (see location in Fig. 3), considering that the segment y-z was located behind x-y before the c. 50 km left-lateral strike offset produced by the Neogene Fagnano transform fault system (cf. Torres Carbonell et al., 2014). AMTS: Apen-Malvinera thrust system. **b.** Sequential

forward modelling of the interpreted structures shown in **a**, using Move-on-Fault algorithms in MOVE software. Eroded spaces are left blank for simplicity.

Arc-continent collision related orogenesis caused high-grade to mild deformation

New structural data and Ar/Ar - U/Pb ages of intrusives is reported

First deformation in the central belt of Argentina occurred from 84 to 74 Ma

Subsequent deformation involved a brittle-ductile to brittle thrust system

These thrusts join a common upper detachment transferring shortening to foreland

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: