TECTONIC EVOLUTION OF THE SOUTHERN AUSTRAL-MAGALLANES BASIN IN TIERRA DEL FUEGO

Rocío E. Gallardo Jara [1], Matías C. Ghiglione [1], Lisandro Rojas Galliani [2]

[1] Instituto de Estudios Andinos-CONICET, Departamento de Ciencias Geológicas, Universidad de Buenos Aires, Argentina. rocio.gallardo.jara@gmail.com

[2] Enap Sipetrol S.A., Santiago, Chile.

ABSTRACT

The evolutionary history of the Austral Magallanes has been object of several studies both in Chile and Argentina, due to its importance as hydrocarbon and gas producer. In the evolution of southern South America, a stage of intracratonic rifting development between the Middle-Late Jurassic has been recognized in a wide part of southern Patagonia that generated an extensional basin (Rocas Verdes basin). Following the creation of a synrift fault system the basins evolved towards an Early Cretaceous postrift sag stage that deposits a thick pelitic succession in a marine shelf environment, constituting these deposits in the main reservoir and source rock for the oil plays. During the middle-Late Cretaceous in the entire Austral Patagonian region took a place a compressional regime over the east and south margin of southernmost South America. Product of Andean growth in this sector were produced a magmatic arc, a Basement domain and fold-and-thrust belt, and a foreland basin related to flexural loading. Since the Neogene to Recent, the Fueguian Andes were affected by transpressive tectonics related to the opening of the Drake Passage. This contribution is a review, and pretend to account the stratigraphic and the structural evolution of the basin of the southernmost Patagonia and its fold-and-thrust belt associated, summarized in a regional stratigraphic correlations for Late Jurassic–Quaternary rock units throughout the southern Austral-Magallanes basin. However, new ideas and interpretation are presented supported by new information at the regional level, using a north-to-south direction seismic-line reflection, well-log data and their regional correlation. The tectonic evolution of the studied depocenters is related to structural phases recognized in the Patagonian-Fueguian Andes and the Burdwood bank, constituting their southern active boundary. These depocenters migrated to the east in the southern Patagonian Andes and towards the north and east in Tierra del Fuego and Malvinas. The thrust advance is evidenced by discordances within the basin fill that coalesce towards the external depocenter and depositional bulge, characteristic geometric stacking patterns and configuration of clinoforms. These key surfaces enabled the definition of four evolutionary stages: Foreland I (Coniacian (?) - Maastrichtian), Foreland II (early-middle Paleocene – middle Eocene), Foreland III (early-middle Eocene - Oligocene) and Foreland IV (early Miocene - Pliocene).

INTRODUCTION

The Patagonian-Fueguian Andes form the *Southern Andean Orogenic Arc* (Maffione, 2016), with a N-S orientation in the area of Última Esperanza Province in Chile, progressively veering towards a ESE-WNW trend in Tierra del Fuego Island (Fig. 1; Dalziel *et al.,* 1973; Ghiglione and Cristallini, 2007; Poblete *et al.,* 2014, 2016; Rapalini *et al.,* 2015; Maffione, 2016; Torres-Carbonell *et al.,* 2016). The orogenic wedge and structural domains are persistent along the arc, and continue towards the offshore along the South America-Scotia plate boundary into the Burdwood bank (Platt and Phillips, 1995; Galeazzi, 1998; Ghiglione *et al.,* 2010). The Austral-Magallanes basin is host in the concave side of the arc (Ghiglione and Cristallini, 2007), and is connected with Malvinas basin through a continuous southern depocenter (Fig. 1; Biddle *et al.,* 1986; Mpodozis and Ramos, 1989; Wilson, 1991; Ghiglione *et al.,* 2010, 2016). The Fueguian fold-and-thrust belt host the proximal facies of the Late Cretaceous-Eocene basal foreland, and is affected by strike-slip tectonics of the Magallanes-Fagnano fault system (MFFZ) since the late Cenozoic (Fig. 1; Cunningham, 1993; Diraison *et al.,* 2000; Ghiglione *et al.,* 2002; Lodolo *et al.,* 2003; Rosello, 2004; Ghiglione *et al.,* 2013; Betka *et al.,* 2016).

During the Middle-Late Jurassic this sector evolved as an intracratonic rift system associated to Gondwana break-up and the opening of the Wedell Sea and the Atlantic Ocean (Dalziel *et al.,* 1974; Bruhn *et al.,* 1978; Biddle *et al.,* 1986; Stern and De Witt, 2003; Calderón *et al.,* 2007). In Tierra del Fuego, volcanic and volcaniclastic Jurassic rocks from the Tobífera/Lemaire Formation (Figs. 2a and 3; Hanson and Wilson, 1991; Wilson, 1991; Moraga, 1996; Féraud *et al.,* 1999; Pankhurst *et al.,* 2000) were deposited in grabens and half-grabens in angular unconformity over previously deformed basement. Subsequent to the earlier synrift stage, the Rocas Verdes back-arc developed between ~140-120 My along the active margin, while the cratonic region was characterized by continuous thermal subsidence and deposition of transgressive systems (Fig. 2b; Caminos *et al.,* 1981; Biddle *et al.,* 1986; Robbiano *et al.,* 1996; Olivero and Martinioni, 2001; Olivero and Malumián, 2008).

The tectonic regime changed in the Late Cretaceous, with the beginning of a compressive period and progressive closure of the Rocas Verdes basin (Dott *et al.,* 1977; Biddle *et al.,* 1986; Wilson, 1991; Mella, 2001; Mpodozis *et al.,* 2011), generating intense deformation and metamorphism of the basement domain, and progressively involving the Mesozoic sedimentary units in its advance (Figs. 2b and 2c) (Nelson *et al.,* 1980; Dalziel and Brown, 1989; Kohn *et al.,* 1993; Cunningham, 1995). During compression that lasted until the Neogene (Ghiglione and Ramos, 2005) the Austral-Magallanes basin can be divided into four foreland stages (widely discussed by Mpodozis *et al.,* 2011), during which the foreland basin system together with the deformation front migrated continuously towards the craton (Álvarez-Marrón *et al.,* 1993; Kraemer, 2003; Rojas and Mpodozis, 2006; Klepeis *et al.,* 2010; Gallardo, 2014; Ghiglione *et al.,* 2016).

Our work presents a review of the stratigraphic and the structural evolution of the southern Austral-Magallanes basin and its associated fold-and-thrust belt, summarized in regional stratigraphic correlations for Late Jurassic–Neogene rock units. Furthermore, new ideas and interpretation are proposed, supported by new information that we present at the regional level, using seismic-line and well-log data and their regional correlation. We recognize four distinctive foreland phases, based on seismic information and surface data, broadly described by an unpublished work from Mpodozis *et al.* (2011), and mentioned by Gallardo (2014). Definition of multiple foreland stages and identification of their main characteristics and stratigraphic relationships represent a move towards a more complete knowledge of the southern depocenter of the Austral-Magallanes basin, a critical location due to its interactions with Malvinas basins and the development of the Scotia arch.

GEOLOGICAL SETTING

The tectonic evolution of the basal sequences of the Austral-Magallanes basin is related to Jurassic - Mesozoic processes that affected Patagonia (Gust *et al.,* 1985; Pankhurst *et al.,* 2000, Barker, 2001; Mpodozis *et al.,* 2011). During this extensional phase a series of grabens and half-grabens of NW-SE direction were developed in Tierra del Fuego (Moraga, 1996; Navarrete-Rodríguez, 2006), and associated transfer zones of NE-SW orientation (Ghiglione *et al.,* 2013). The synrift corresponds to volcanic and
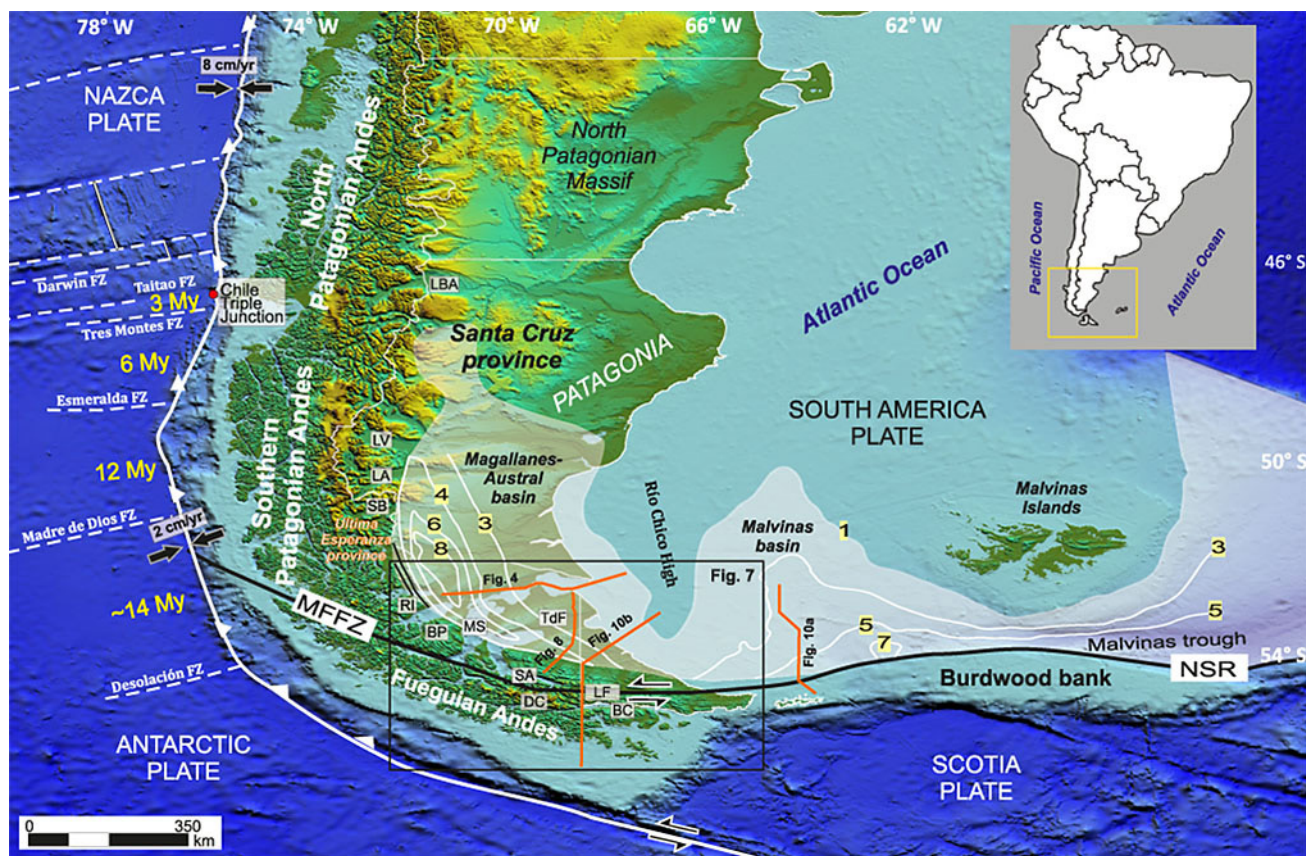
Figure 1. Location map of main morphostructural units in the Austral-Magallanes and South Malvinas basins. After Ghiglione *et al.,* (2010). Abbreviations: LV: Lago Viedma; LA: Lago Argentino; SB: Sierra Baguales; MS: Magellan Strait; SA: Seno Almirantazgo; DC: Darwin Cordillera; FL: Fagnano Lake; BC: Beagle Channel; BP: Brunswick Peninsula; RI: Riesco Island; TdF: Tierra del Fuego; FZ: Fault zone; MFFS: Magallanes-Fagnano Fault System; NSR: North Scotia Ridge. Blank contours indicate sediment thickness in Kilometers; Orange Lines are the regional seismic sections; My in yellow indicate the time of collision of each ridge segment.

volcaniclastic sediments of variable thickness (Figs. 2a and 3; Ibañez, Tobífera, Le Maire and Complejo El Quemado Formations) (Caminos *et al.,* 1981; Uliana *et al.,* 1986; Hanson and Wilson, 1991; Féraud *et al.,* 1999; Pankhurst *et al.,* 2000; Olivero and Martinioni, 2001; Olivero and Malumián, 2008). Presently, the major extensional sub-basins are located in Tierra del Fuego, and corresponds among others to Oriental, Gaviota, Calafate and Fueguino. The Jurassic fault system was reactivated during Neogene, generating the Magellan Strait (Diraison *et al.,* 1997, 2000) and the transverse segmentation of the fold-and-thrust belt (Ghiglione *et al.,* 2013).

As a consequence of the extensional phase, oceanic crust emerged along the western margin of the southernmost Patagonian Andes. Remains of this basin, known as Rocas Verdes basin (Bruhn *et al.,* 1978; Stern and De Witt, 2003; Calderón *et al.,* 2007, 2016), are registered as discontinuous string

outcrops of ophiolitic complexes south of 51° SL (Fig. 2b) (Sarmiento complex in Última Esperanza, Tortuga complex in south of Tierra del Fuego, and the Larsen Harbour formation of the South Georgia Island) (Dalziel *et al.,* 1974, 1975; Suárez and Petigrew, 1976; Stern, 1980; Dalziel, 1981; Suárez *et al.,* 1985; Kraemer, 2003; Calderón *et al.,* 2007, 2016). Nonetheless, the idea that the South Georgia Island being part of the Rocas Verdes basin is currently discussed (Eagles, 2010; Eagles and Jokat, 2014; Poblete *et al.,* 2016). Since the Early Cretaceous to Paleogene the southernmost Patagonia was affected by a progressive tectonic rotations and bending, related with the closure of the Rocas Verdes basin or sinistral strike–slip tectonics in the Cenozoic (Dalziel *et al.,* 1974; Burns *et al.,* 1980; Cunningham, 1993; Poblete *et al.,* 2016). Paleomagnetic studies for the Upper Cretaceous and Paleocene evidence a counterclockwise rotation of the Fueguian Andes
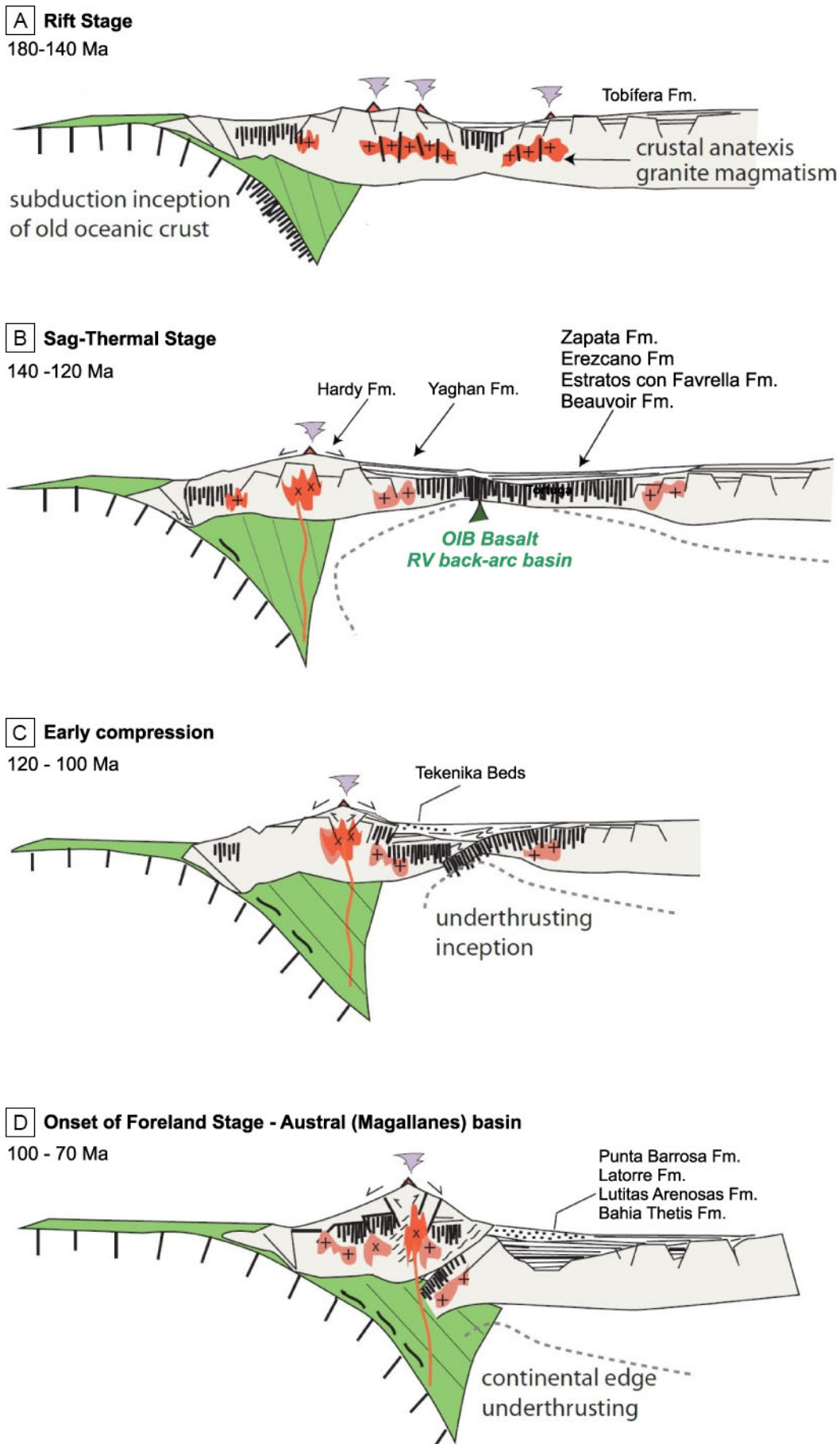
Figure 2. Schematic diagram of the evolution of the basin geometry for the Rocas Verdes Austral-Magallanes basin. **a**) Rift stage (Middle-Upper Jurassic) with extensional phase and crustal stretching, **b)** Sag-thermal and back-arc stage (Lower Cretaceous), oceanic crust emplacement and formation of structurally controlled rift sub-basins, **c)** Early compression (Lower-Upper Cretaceous), **d)** Onset of foreland stage, Austral-Magallanes foreland basin (Upper Cretaceous). Modified from Calderón *et al.* (2016).

relative to the southern Patagonian Andes and related with the closure of the Rocas Verdes basin (Poblete *et al.,* 2014; 2016). The basin subsequently evolved towards a postrift sag stage developed on top of the Jurassic volcanic and volcaniclastic rocks (Biddle *et al.,* 1986; Robbiano *et al.,* 1996; Harambour, 1998; Olivero and Martinioni, 2001; Olivero and Malumián, 2008), characterized by continuous thermal subsidence (Fig. 2b). During this Late Jurassic and the Early Cretaceous events, hundreds of meters of marine clastic sediments were deposited in a retrogradacional marine shelf and deep marine environment (Biddle *et al.,* 1986; Robbiano *et al.,* 1996; Olivero and Malumián, 2008) that spreads towards the east and north in Austral-Magallanes basin (Mpodozis *et al.,* 2011).

The beginning of this transgressive event is marked by the fluvial to transgressive shallow marine deposits of the Springhill Formation characterized by quartzitic sandstones with clasts of pyramidal quartz (Thomas, 1949a,b; Biddle *et al.,* 1986; Schwarz *et al.,* 2011**;** Richiano *et al.,* 2016). Shallow deposits grade laterally into a deep-sea marine successions represented mainly by claystones (Fig. 3; Zapata Formation in Última Esperanza; Erezcano in Península Brunswick and Isla Riesco; Estratos with *Favrella* in Magallanes subsurface; Río Mayer Inferior in El Calafate city and Argentino Lake, Yaghán and Río Jackson in Tierra del Fuego in Chile and Beauvoir in Argentina) (Katz and Watters, 1966; Biddle *et al.,* 1986; Macellari *et al.,* 1989; Wilson, 1991; Olivero and Martinioni, 2001; Harambour, 2002; Kraemer, 2003; Rojas and Mpodozis, 2006; Olivero and Malumián, 2008; Richiano *et al.,* 2012, 2015). During the Aptian-Albian occurs a fast oceanic expansion both in the Atlantic Ocean and the Weddell Sea, along with an acceleration in convergence rate between the Pacific and South America plates (Bartoloni and Larson, 2001; Ghiglione *et al.,* 2015).

Additionally, this phase was defined by the beginning of western subduction at the inner edge of Rocas Verdes basin, ending between ~101-88 My(Wilson, 1991; Fildani *et al.,* 2003; McAtamney *et al.,* 2011; Varela *et al.,* 2012). Evidence of this evolutionary stage has been documented to the south of the Beagle Channel in the Tierra del Fuego, in the Yaghán and Hardy formations (Katz, 1963; Dott *et al.,* 1977; Suárez *et al.,* 1985; Olivero and Martinioni, 2001; Olivero and Malumián, 2008) and in the Canal Bertrand Formation in Riesco Island

(Castelli *et al.,* 1992; Mella, 2001). As a consequence of the subduction system along the western margin of South America, the Patagonian Batholith magmatic arc was developed (Stern and Stroup, 1982; Suárez *et al.,* 1985; Bruce *et al.,* 1991). The PB record volcanic activity associated with subduction since 165 Ma, with a pick of activity between 110 to 90 My (Hervé, 2005; Hervé *et al.,* 2007; González-Guillot, 2016). The compressional regime caused intense deformation and metamorphism in both the basement and the Mesozoic sedimentary cover (Nelson *et al.,* 1980; Dalziel and Brown, 1989; Cunningham, 1995), constituting three major tectonic elements: a magmatic arc, a complex fold and thrust belt, and a foreland basin by flexural loading (Mella, 2001) over the entire Patagonian region. The development of the Austral-Magallanes foreland basin is related to the uplift of the Southernmost Andes, along with tectonic stacking of material derived from Rocas Verdes Basin and the basement domain (Dott *et al.,* 1977; Biddle *et al.,* 1986; Wilson, 1991; Calderón *et al.,* 2007; Gombosi *et al.,* 2009; Barbeau *et al.,* 2009).

Four foreland phases have been recognized during the foreland stage, based on seismic information and surface data, where depocenters migrated to the east in the southern Patagonian Andes (Mpodozis *et al.,* 2011; Gallardo, 2014) and towards the north and east in Tierra del Fuego (Álvarez-Marrón *et al.,* 1993; Kraemer, 2003; Ghiglione and Ramos, 2005; Rojas and Mpodozis, 2006; Klepeis *et al.,* 2010). These Foreland stages, broadly described by Mpodozis et al. (2011), from oldest to the youngest are named as follows (Figs. 3 and 4; Foreland I (Coniacian (?)-Maastrichtian), Foreland II (early-middle Paleocene–middle Eocene), Foreland III (early-middle Eocene - Oligocene) and Foreland IV (early Miocene- Pliocene). Successive foreland discordances coalesce towards the external depocenter and depositional bulge, associated to developmental stages of the foreland basin (Fig. 4; Mpodozis *et al.,* 2011; Gallardo, 2014).

STRATIGRAPHY AND DEPOCENTER

Paleozoic-Jurassic sequences

Deformed rocks develop on the crystalline substratum in the Basement thick-skinned domain to the south, which comprises ophiolitic ocean floor, Jurassic volcanic rocks and Cretaceous infill from the Rocas Verdes basin, the Patagonian Batholith,
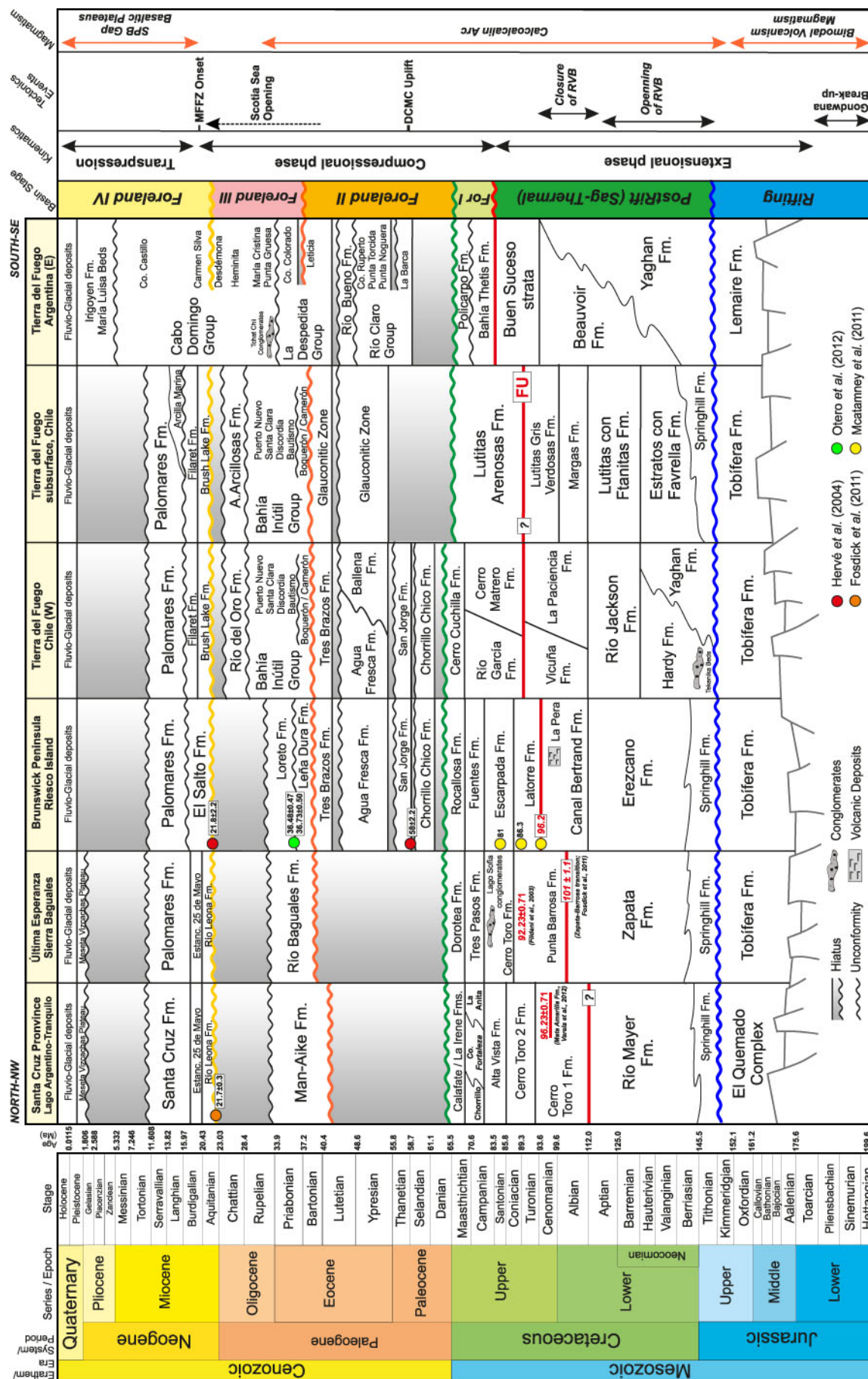
and the Darwin Cordillera Paleozoic metamorphic complex (Calderón *et al.,* 2016).

The *Patagonian Batholith* (PB) comprises a large volume of Late Jurassic to Neogene subduction-related plutonic rocks emplaced along the Pacific margin between 40° and 56°SL (Suárez, 1978; Stern and Stroup, 1982; Hervé *et al.,* 1984; Bruce *et al.,* 1991; Hervé *et al.,* 2007). The PB presents trench-side arc and rear-arc suites relative to the paleo-trench, with a complex time distribution (González-Guillot, 2016). Relicts of the Rocas Verdes basin remains including its oceanic mafic floor (Bruhn *et al.,* 1978; Stern, 1980; Dalziel, 1981; Biddle *et al.,* 1986; Grunow, 1993; Mukasa and Dalziel, 1996) are interspersed within the Patagonian Batholith in the basement domain.

The *Darwin Cordillera Metamorphic Complex* (DCMC) extends between Canal Beagle and Seno Almirantazgo (Fig. 5) (Nelson *et al.,* 1980; Dalziel and Brown, 1989; Cunningham, 1995), uplifted ~1 km higher than the surrounding mountains (Klepeis, 1994a, b; Klepeis *et al.,* 2010). The DCMC is thrusted to the north by the Glacial Marinelli fault over Jurassic rocks from Tobífera/Lemaire Formations (Rojas and Mpodozis, 2006). It is characterized by metasedimentary and metavolcanic rocks (Kohn *et al.,* 1995) from a Paleozoic to early Mesozoic suite of shales, pelitic schists, amphibolites and orthogneisses (Nelson *et al.,* 1980; Dalziel and Brown, 1989). Kohn *et al.* (1995) describes the metamorphism in zones of biotite, staurolite, kyanite and sillimanite. Several stages of deformation are recognized for the DCMC, being the oldest between ~125-80 My (Hervé *et al.,* 1984; Cunningham, 1995; Kohn *et al.,* 1995), responsible of metamorphism of amphibolite facies (Kohn *et al.,* 1993). Afterwards, a brittle-ductile transtensional regime is identified between ~68-50 My, and a brittle regime of normal faulting since ~50 My (Cunningham, 1995; Kohn *et al.,* 1995), that are related to advances of the orogenic front (Ghiglione and Ramos, 2005).

The Jurassic extensional event is registered by outcrops of Lemaire Formation with NW-SE to W-E orientation south of Fagnano Lake (Kraemer, 2003; Mpodozis and Rojas, 2006) and in Beagle Channel towards the southeast (Caminos *et al.,* 1981; Olivero and Martinioni, 2001; Olivero and Malumián, 2008). In Chile, the Jurassic is represented by the Tobífera Formation that includes mostly volcanic and volcaniclastic rocks (Fig. 3) (Wilson, 1991; Hanson and Wilson, 1991).

The Late Jurassic-Early Cretaceous Yaghán Formation (Bruhn *et al.,*1978; Stern, 1980; Suárez *et al.,* 1985; Biddle *et al.,* 1986) rest over the Tortuga ophiolitic complex south of the Beagle Channel (Fig. 3) (Kranck, 1932; Suárez and Pettigrew, 1976; Suárez *et al.,* 1985) and overlies in unconformity over the Middle Jurassic in Tierra del Fuego (Figs. 3 and 5) (Dott *et al.,* 1977; Caminos *et al.,* 1981; Olivero and Malumián, 2008). This unit consists of fine-to-coarse grained facies and volcaniclastic rocks, affected by greenschist metamorphic facies and intense deformation in Navarino Island (Hervé *et al.,* 1984; Suárez *et al.,* 1985). The Yaghán Formation grade laterally to the south to the deposits of arc of the Hardy Formation (Figs. 3 and 5) (Suárez and Pettigrew, 1976; Suárez *et al.,* 1985; Miller *et al.,* 1994), which corresponds to volcaniclastic rocks interbedded with rhyolites and basaltic lavas (González-Guillot, 2016), and includes levels of recycled conglomerates (Tekenika Beds; Dott *et al.,* 1977; Winn and Dott, 1979) (Fig. 3)**.**

In the central strip of Tierra del Fuego the Early Cretaceous is represented by the Beauvoir Formation (Fig. 3) (Olivero and Martinioni, 2001; Olivero and Malumián, 2008), which corresponds to dark slates and grays tuff in an external platform environment that deepens to the south (Olivero and Malumián, 2008). These units are represented to the north of Seno Almirantazgo by the Río Jackson Formation (Álvarez-Marrón *et al.,* 1993) overlain by deposits of shallow-marine environments and distal volcanic rocks of the Vicuña and La Paciencia formations (Fig. 3) (Barwick *et al.,* 1951; Álvarez-Marrón *et al.,*1993).

Figure 3. Stratigraphic correlations for Late Jurassic-Quaternary rock units throughout the southern Magallanes (Austral) basin. Compiled from: Von Goetsche and Huca, 1953; Céspedes, 1957; Álvarez-Marrón *et al.,* 1993; Fildani *et al.,* 2003; Hervé *et al.,* 2004; Hervé, 2005; Álvarez *et al.,* 2006; Olivero and Malumián, 2008; Le Roux *et al.,* 2010; Cuitiño *et al.,* 2010, 2012, 2015; Fosdick *et al.,* 2011, 2015; McAtamney *et al.,* 2011; Mpodozis *et al.,* 2011; Otero *et al.,* 2012; Varela *et al.,* 2012; Bostelmann *et al.,* 2013; Malumián *et al.,* 2013; Velásquez, 2016; Sáez, 2017; Pinto *et al.,* 2018. Abbreviations: FU: foreland unconformity; RVB: Rocas Verdes basin; DCMC: Darwin Cordillera Metamorphic Complex; MFFZ: Magallanes-Fagnano Fault Zone; SPB: South Patagonian Batholith.
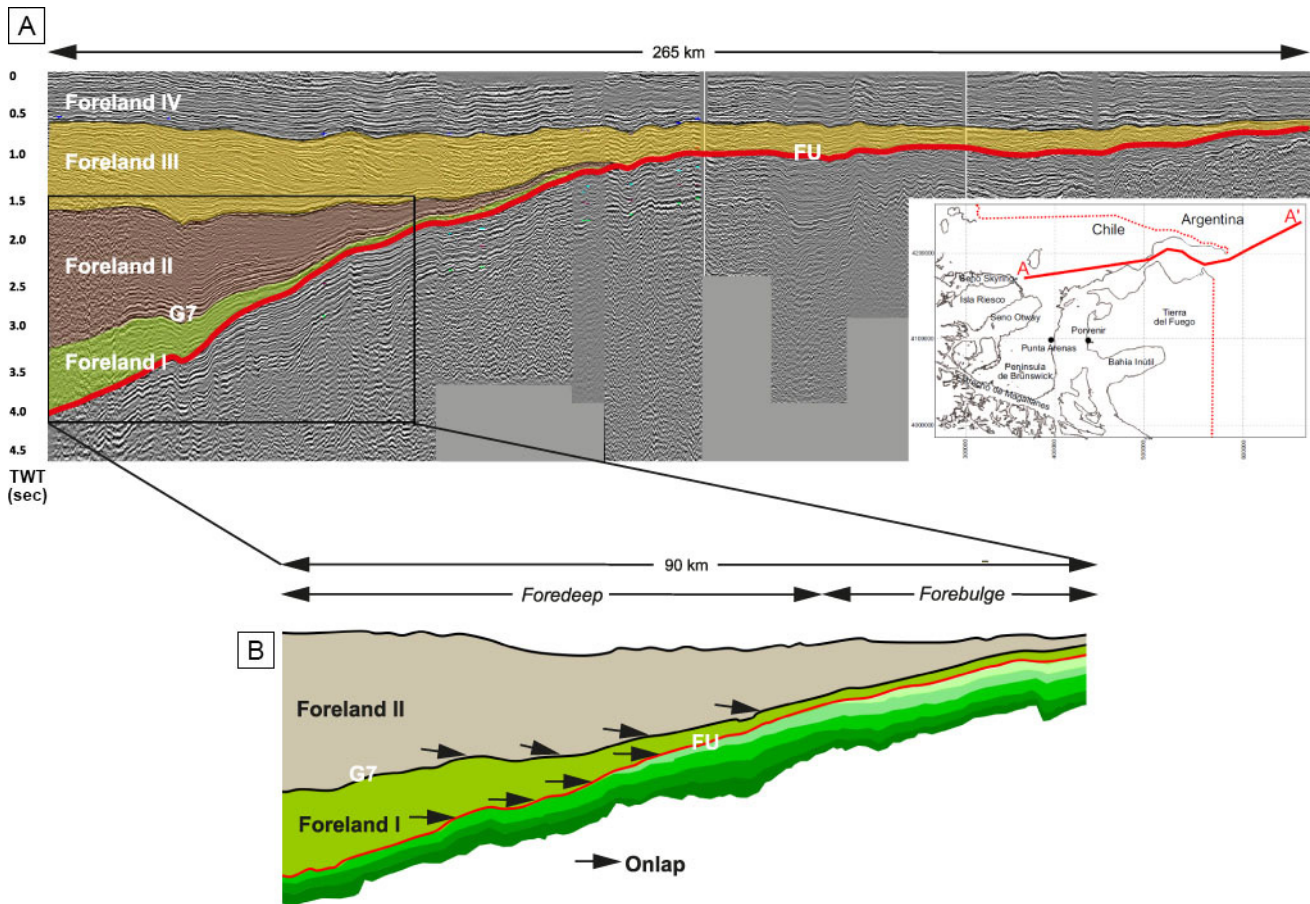
Figure 4. a) General regional seismic configuration of the Austral-Magallanes Basin. The regional seismic line and the interpreted line shown in **b)** illustrate the geometric wedge-shape of the early Foreland Stage strata onto previous sag-thermal deposits. TWT: reflection transit time in seconds. From Gallardo (2014), modified after Mella *et al.* (2010). See location in Fig. 1 or 7. Abbreviations: FU: foreland unconformity; G7: Mesozoic - Cenozoic limit.

LATE CRETACEOUS-CENOZOIC STRATIGRAPHY OF THE FORELAND STAGE

Foreland I Units (Coniacian (?) -Maastrichtian)

The onset of the foreland stage deposits is marked by a regional angular unconformity and erosional truncation over the underlying Cretaceous sediments of the sag-thermal stage (Figs. 2 and 3). This unconformity define an onlap surface towards the east and hence the foreland I units thins in that direction (Gallardo, 2014).

The deposits of foreland I are composed in Última Esperanza province by slope fans and basin-floor deposits migrating from the north-northwest since 101±1.1 My (Fosdick *et al.,* 2011). These successions are represented by Punta Barrosa and Cerro Toro formations, and Lago Sofía Conglomerates

(Katz, 1963; Wilson, 1991; Sohn *et al.,* 2002; Fildani *et al.,* 2003; Choe *et al.,* 2004; Romans *et al.,* 2009) and shallow marine systems of the Mata Amarilla Formation in Santa Cruz province (Fig. 3) (Varela *et al.,* 2012). In subsurface of Tierra del Fuego, the wedge of foreland I forms a wedge that wedge that thickens slightly to the south, represented by the Lutitas Arenosas Formation (Fig. 3) (González, 1965; Natland *et al.,* 1974).

The basal stage of the foreland basin in Tierra del Fuego is characterized by subsidence due to initial tectonic loading, which conditioned the deposits of axial and perpendicular turbidites and source of detritus into the basin from the erosion of Mesozoic deposits (Mella, 2001; Mpodozis *et al.,* 2011). These turbiditic facies are represented in Tierra del Fuego (Lynch and Blanco lakes) by the Cerro Matrero Formation from the Coniacian-Campanian
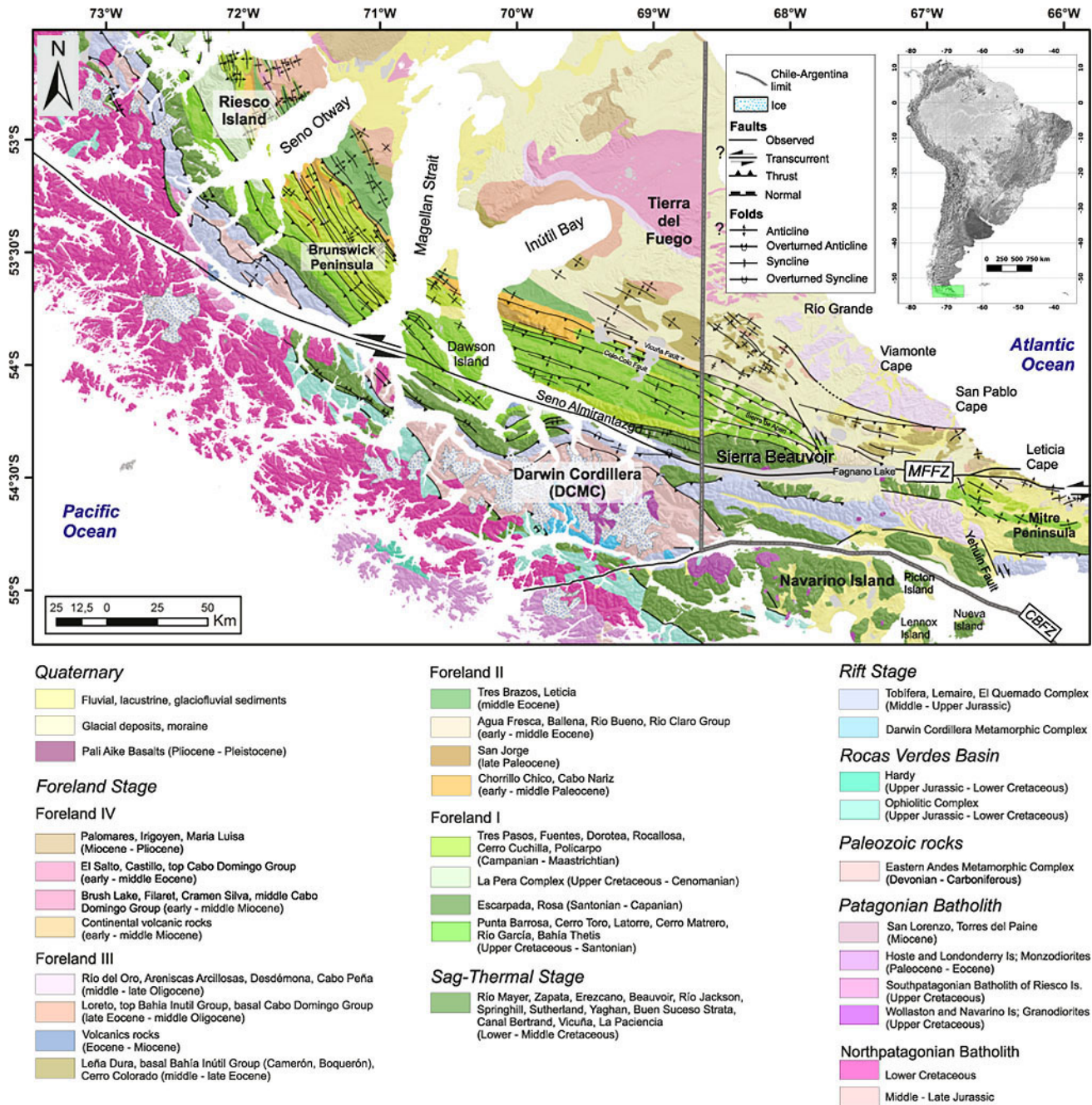
Figure 5. Map of the fold and thrust belt (FTB) in Magallanes and Tierra del Fuego, showing the sedimentary units that are part of the pre-foreland units and filling of the foreland basin. Abbreviations: MFFZ: Magallanes-Fagnano Fault Zone; CBFZ: Canal Beagle Fault Zone; DCMC: Darwin Cordillera Metamorphic Complex. Modified from: Céspedes, 1957; SERNAGEOMIN, 2003; Mpodozis and Rojas, 2006; Rojas and Mpodozis, 2006; Olivero and Malumián, 2008; Betka *et al.,* 2016; Velásquez, 2016; Sáez, 2017; Pinto *et al.,* 2018.

(Fig. 3) coming from the southwest (Rojas, 1990; Álvarez-Marrón *et al.,* 1993). Northwards, the Río García Formation (Fig. 3) is compose by fine-grained deposits (Rojas, 1990; Álvarez-Marrón *et al.,* 1993) interpreted as developed in outer shelfal and shallower setting than the Cerro Matrero Formation.

While during the Turonian to Campanian deep-water facies were deposited in western Tierra del Fuego, towards the east fine-grained facies from the Buen Suceso strata were accumulate in an outer shelfal and slope settings (Olivero and Medina, 2001; Olivero and Malumián, 2008). The Buen Suceso strata are cover by upper Campanian deep-water facies with conglomerates, turbiditic sandstone and

mudstones of the Bahía Thetis Formation (Figs. 3 and 5) representing deep-water channels levee of the first Andean exhumation (Olivero *et al.,* 2003; Olivero and Malumián, 2008).

The transition to the Foreland II stage is recorded in sandy and fine-grained facies from the Cerro Cuchilla Formation prograding northwards (Fig. 3: Rojas, 1990; Álvarez-Marrón *et al.,* 1993). These rocks represent shallow marine deposits that overlie the mudstones of the Río García Formation. In the Atlantic shore, this transition of the Maastrichtian-Danian is identified as the Policarpo Formation (Fig. 3) (Olivero *et al.,* 2003; Olivero and Malumián, 2008; Torres-Carbonell *et al.,* 2008), characterized by dark gray sandy mudstones and silty sandstones, and tuffs. These rocks rest in unconformity over the Bahía Tethys Formation, in an outer shelf and/or slope depositional setting (Olivero and Malumián, 2008).

Foreland II Units (early-middle Paleocene- middle Eocene)

The base of the foreland II corresponds to a regional angular unconformity that represents an onlap surface towards the east and north of the basin. Consist in a transgressive asymmetric wedge that increases its thickness towards the south and west (Fig. 4). In the early Paleocene a northward migration of the orogenic front is registered by an angular unconformity within Paleocene successions (Prieto and Moraga, 1990; Ghiglione and Ramos, 2005), and towards the east in Magallanes and Última Esperanza province (Hervé *et al.,* 2004; Fosdick *et al.,* 2011). The thrust advanced of the orogenic front in Tierra del Fuego was probably ensuing from the rapid uplift and cooling of Darwin Cordillera at ~65 My (Kohn *et al.,* 1995; Barbeau *et al.,* 2009).

The units for this period in the Atlantic shore and Mitre Peninsula are described as conglomerates and coarse-grained sandstones of the late Paleocene from the Tres Amigos Formation (Fig. 5) (Olivero *et al.,* 2002; Olivero and Malumián, 2008; Torres-Carbonell *et al.,* 2008). This formation rest in angular unconformity over the Policarpo Formation (Fig. 3) (Ghiglione and Ramos, 2005; Olivero and Malumián, 2008), correlated with the conglomerates of Sierra de Apen in the northern shore of Fagnano Lake (Martinioni *et al.,* 1999), probably representing a submarine fan-delta system (Olivero and Malumián, 2008). The foreland basin system includes a wedge

top in Sierra de Apen and Península Mitre (Ghiglione and Ramos, 2005), and a foredeep of the Paleocene-early Eocene (Olivero and Martinioni, 2001).

Meanwhile, in the Paleocene foredeep towards the west of Tierra del Fuego (Vicuña area in Chile), outcrops in the front of the external fold-and-thrust belt deposits of fine-grained sandstones, siltstones and mudstone of the Chorrillo Chico Formation (Figs. 3 and 5) (Thomas, 1949a; Álvarez-Marrón *et al.,* 1993) and mudstone and siltstones of the San Jorge Formation (Fig. 3) (Von Goetsche and Huca, 1953) are deposited over the Upper Cretaceous sediments. Recently, Pinto *et al.,*(2018)using the U-Pb method dated detrital zircons from the base of Chorrillo Chico Formation yield an early-to-middle Paleocene age, and identifies a depositional hiatus between the early Selandian to Thanetian in the Paleocene secessions (Fig. 3).

Facies of the middle Paleocene to the early Eocene, are described in the Río Claro Group: Cabo Leticia, La Barca, Punta Noguera; Punta Torcida and Cerro Ruperto formations, well exposed along the Atlantic shore and rest in angular unconformity over the Policarpo Formation (Figs. 3 and 5) (Malumián and Caramés, 2002; Olivero *et al.,* 2002; Ghiglione and Ramos, 2005; Olivero and Malumián, 2008; Torres-Carbonell *et al.,* 2009). The succession of the Río Claro Group represents a regressive sequence with relatively deep-water turbidite systems at the base and shallower shelfal deposits at the Cerro Ruperto Formation (Olivero and Malumián, 2008).

In the middle Eocene, a new phase of deformation was develop in Tierra del Fuego. Probably, this orogenic front migration towards the north by multiples unconformities produced the uplift of the Fueguian Andes (Basement domain) (Ghiglione *et al.,* 2002; Olivero *et al.,* 2002; Ghiglione and Ramos, 2005). Towards the west in Chile, over the San Jorge Formation were deposited the Agua Fresca and Tres Brazos formations in the late Eocene (Fig. 3) (Decat and Pomeyrol, 1931; Prieto and Moraga, 1990; Pinto *et al.,* 2018) compose by siltstones and mudstone in the base and glauconitic sandstones with interbedded limestone at the top. In subsurface, this succession correspond to fine-grained sandstones, siltstones and mudstone of the Glauconitic Zone Formation (Hauser, 1964; Biddle *et al.,* 1986).In the foredeep of Tierra del Fuego, these formation grades laterally to the southwest to the Ballena Formation (Fig. 3) (Barwick *et al.,* 1951; Prieto and Moraga, 1990).

In the north part of the Fagnano area this succession is described as sandstones and siltstones with conglomerates at the top, interpreted as channels levee of a deltaic system that advanced northward (Rojas, 1990). Outcrops of these Eocene successions are exposed in the Campo del Medio Cape and Punta Gruesa, in the Despedida Group (Leticia and Cerro Colorado formations) (Figs. 3 and 6) (Furque and Camacho, 1949; Olivero and Malumián, 1999; Ghiglione, 2003; Ghiglione and Ramos, 2005; Torres-Carbonell *et al.,* 2009). Thus, these units deposited between the middle to-late Eocene in Tierra del Fuego represent internal progressive migration toward the north and syntectonic unconformities developed in the front of the fold-and-thrust belt (Prieto and Moraga, 1990; Ghiglione *et al.,* 2002). At the south of the Despedida Group, in the Atlantic shore (Leticia Cape in Mitre Peninsula), rocks of the early to-middle Eocene are exposed in the Río Bueno Formation (Fig. 3) (Furque and Camacho, 1949). Río Bueno Formation are composed by grainstones, bioturbated marls, and micrites (Malumián and Olivero, 1998; Olivero *et al.,* 2002; Olivero and Malumián, 2008). This units were deposited in shallow shelf (Olivero and Malumián, 2008), in angular unconformity over the Río Claro Group.

Finally, at the top of the foreland II, Gombosi *et al.,* (2009) recognized a rapid cooling and exhumation caused by shortening and rock-uplift of the Fueguian Andes between the middle and late Eocene (~48 to 34 Ma).

Foreland III Units (early-middle Eocene -Oligocene)

The middle Eocene progradational marine systems are established at north-northeast direction from the southern depocenter in the basin (Malumián, 2002; Rojas y Mpodozis, 2006; Fosdick *et al.,* 2011; Gallardo, 2014; Sáez, 2017). This succession form an asymmetric sedimentary wedge-shape widely distributed across the basin, which is thinning towards the east and the north (Gallardo, 2014), associated with thrust advanced and topographic growth of the Fueguian fold-and-thrust belt (*eg.* Mercedes fault).

These successions are accumulated towards north and east of the front of the fold-and-thrust belt, and are formed by marine shelf sediments of the basal Bahía Inutil Group in Tierra del Fuego (Camerón and Boquerón formations; Barwick, 1955; Céspedes,

1957) and Leña Dura Formation in Magallanes (Fig. 3) (Thomas, 1949a; Barwick, 1955). The depositional age for this basal unit, based on a biostratigraphic study of a nannofossil assemblage (González, 1965; Cañón and Ernst, 1975) is late Eocene to Oligocene. The western portion of these progradational foreland system during the middle-late Eocene was associated with shelf sediments of the Loreto Formation (Keidel and Hemmer, 1931; Otero *et al.,* 2012; Gallardo, 2014), while in the central-east part the distal facies of the upper Bahia Inutil Group were deposited (Fig. 3; Santa Cara Formation) (Gallardo, 2014; Sáez, 2017). In subsurface, northeast-directed prograding sandstone of the Areniscas Arcillosas Formation are deposited in the Oligocene in Tierra del Fuego (Fig. 3) (Mordojovich, 1951; Céspedes, 1957; González, 1965; Cañon and Ernst, 1975). Similar progradational stacking pattern is recognized by a clastic-wedge that advanced from the west between late Oligocene to Miocene in the Malvinas basin (Galeazzi, 1998).

Towards the east, in the Atlantic shore, rocks of this foreland stage are exposed in the front part of the Fueguian fold and thrust belt, named Cabo Domingo Group (Fig. 3: Codignotto and Malumián, 1981; Olivero and Martinioni, 2001; Olivero and Malumián, 2008). The basal part of the Cabo Domingo Group is represented by the Desdemona Formation (Figs. 3 and 6) (Olivero *et al.,* 1999; Olivero and Malumián, 2008) and consists of folded conglomerates, sandstones and mudstones, interpreted as deep-marine depositional system. This basal unit rest in unconformity over the Cabo Domingo Group, and represents the final stages of the compression and deformation in the fold-and-thrust belt in the Fueguian Andes (Malumián and Olivero, 2005; Olivero and Malumián, 2008). In the same way, to the southeast, the Puesto San Jose Formation (Oligocene) is characterized by a succession of mudstones with interbedded sandstones (Torres-Carbonell *et al.,* 2009). Thus, during the early Oligocene the foredeep was filled with deep-marine mudstones and sandstones (Olivero and Malumián, 2008).

Foreland IV Units (early Miocene - Pliocene)

In this stage the sedimentary deposits presents geometry with less wedge-shape than the underlying foreland stages. Moreover, it shows a relatively less shortening and minimum regional slopes (Thomson *et al.,* 2001; Fosdick *et al.,* 2011). The associated
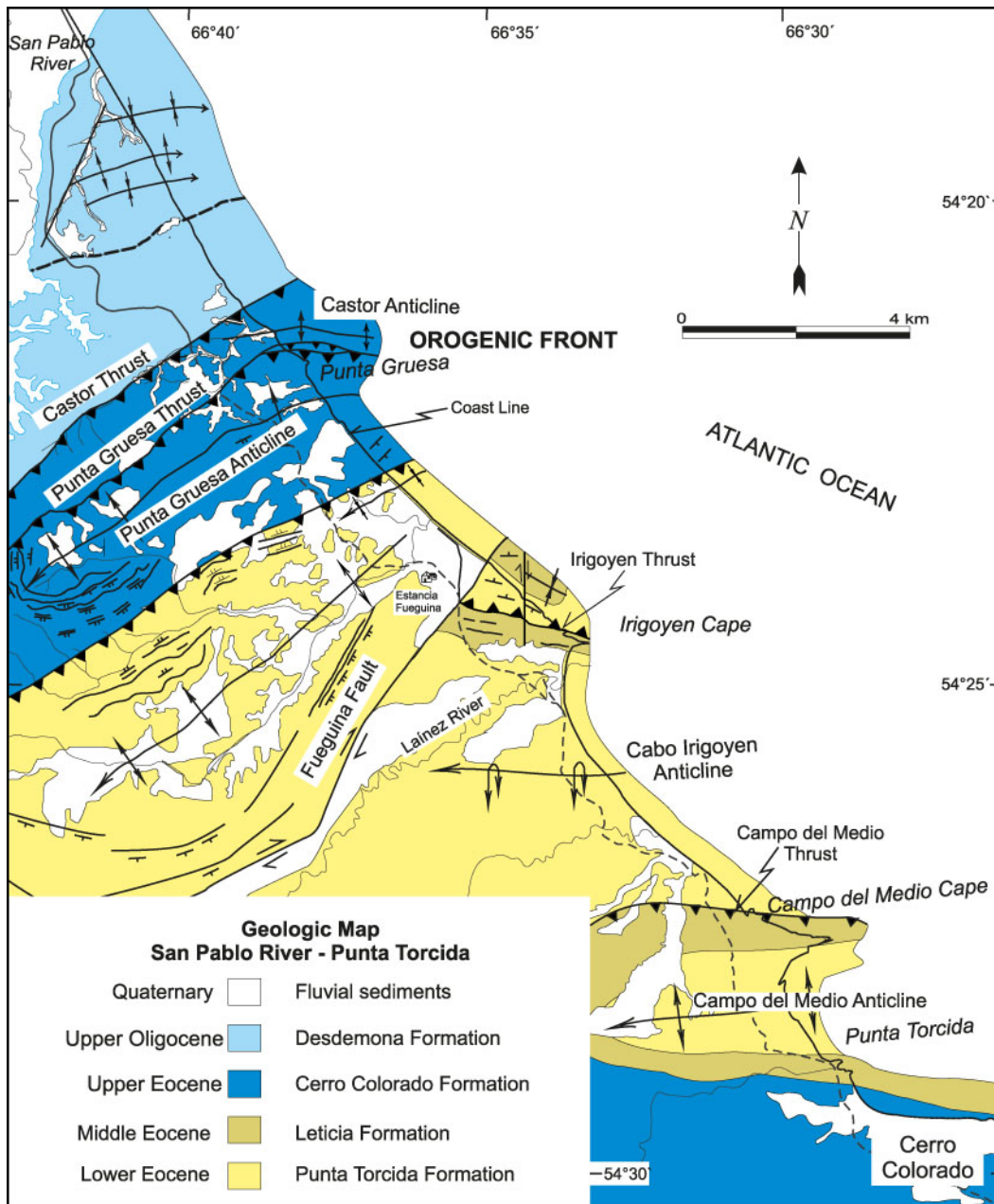
Figure 6. Geology map and structural section of the Atlantic shore of Tierra del Fuego between Cabo Campo del Medio and Punta Gruesa, showing stratigraphic and structural relations. Modified from Ghiglione and Ramos (2005). For map location see Fig. 7.

deposits are exposed in the central part of Tierra del Fuego and correspond to the Miocene Patagonian Atlantic transgression, which flooded over the eastward margin of South America (Malumián *et al.,* 1999; Cuitiño *et al.,* 2012). These successions of the early-middle Miocene are dominantly mudstones, siltstones, and sandstones interbedded with coal levels and limestone of shallow-marine environments, that in Tierra del Fuego in Chile are represented by the Brush Lake and Filaret formations (Figs. 3 and 5) (Céspedes and Cortés, 1956; Malumián *et al.,* 2013; Malumián and Nañez, 2011). To the

westward, these units evolved contemporaneously with deltaic and fluvial systems of the El Salto Formation composed by sandstone, conglomerates and interbedded with siltstones (Fig. 3) (González, 1965; Mella, 2001).

The upper part of the Cabo Domingo Group is exposed in the Atlantic shore in rocks of the middle-late Miocene (Fig. 3; Castillo and Carmen Silva formations) (Codignotto and Malumián, 1981; Olivero and Malumián, 2008), characterized by shallow marine and deltaic mudstones to fluvial deposits. Towards the southeast, the Malengueña Formation

is composed by a succession of conglomerates and sandstones of the late Oligocene-early Miocene in age (Torres-Carbonell *et al.,* 2009). Thus, during the middle-to-late Miocene the filling in this foreland stage indicating a change from deep-marine to dominantly shallow marine, deltaic system and fluvial deposits (Olivero and Malumián, 2008).

In the westward, fluvial sediments pass laterally into volcanic deposits in Santa Cruz, Magallanes and Tierra del Fuego provinces (Fig. 3). The Palomares Formation corresponds to volcanic and volcaniclastic successions of continental environments that prograding to the eastward over the fluvial and deltaic facies (Cuitiño *et al.,* 2012; Velásquez, 2016), whose age has been assigned to Burdigalian (Fosdick *et al.,* 2011; Bostelmann *et al.,* 2013; Velásquez, 2016).

STRUCTURAL DOMAINS

The Andes of Tierra del Fuego can be divided in three main structural domains differentiated by their stratigraphy and structural style (Kraemer, 2003; Álvarez-Marrón *et al.,* 1993; Mpodozis *et al.,* 2011), that can be followed offshore in the underwater structural blocks along the North Scotia ridge (Ghiglione *et al.,* 2010): (i) a Basement thick-skinned domain to the west and south (ii) a Fold and Thrust Belt (FTB) Domain (internal and external) (Fig. 7). The boundary between the Basement domain and the thin-skinned fold-and-thrust belt is the basement thrust front (Kraemer, 2003; Ghiglione *et al.,* 2010). The Foreland Domain corresponds to the scarcely deformed depocenter from the Austral-Magallanes basin north from the frontal thrusts (Mpodozis *et al.,* 2011; Gallardo, 2014).

The basement domain is controlled by basement faults and high amplitude folds oriented northeast, and out-of sequence structures, such as the Glacial Marinelli fault (Kraemer, 2003; Rojas and Mpodozis, 2006). The sedimentary filling affected by the FTB in Tierra del Fuego involves Jurassic to Mesozoic rocks, units that are thrusted northward through a series of thrust sheet that producing uplift and erosion of the sediments deposited in the foredeep (Álvarez-Marrón *et al.,* 1993; Kraemer, 2003; Rojas and Mpodozis, 2006; Klepeis *et al.,* 2010; Mpodozis *et al.,* 2011).

The FTB domain can subdivided into a thick-skinned internal domain and a thin-skinned external domain (Figs. 8 and 9) (Álvarez-Marrón *et al.,* 1993; Klepeis and Austin, 1997; Kraemer, 2003; Rojas and Mpodozis, 2006; Ghiglione *et al.,* 2010; Klepeis *et al.,* 2010). Finally, the Foreland domain corresponds to the scarcely deformed Mesozoic to Cenozoic foreland depocenter (Álvarez-Marrón *et al.* 1993; Mpodozis *et al.,* 2011). In general, the orientation of the developed structures in different domains is parallel to the orientation of the orogenic belt.

The Fueguian Andes extends towards the east in the North Scotia Ridge and the north limit of the Scotia plate. North of this area, the Malvinas Basin is developed, separated from the Austral-Magallanes Basin by the Alto Río Chico Dungeness. The Malvinas basin is filling principally by Cenozoic synorogenic wedge (Galeazzi, 1998). In the Malvinas Basin, it is possible to identify a similar structural style with development of structural domains comparable in Tierra del Fuego. Galeazzi (1998) and Tassone *et al.* (2008), describes in detail the Malvinas Basin, identified the evolutionary stages that cause it and determine its development (Fig. 9; rifting, rift-sag transition, sag-foredeep transition, and foredeep) considering the Foreland Domain and the thrust front). From Malvinas Basin to the south, Fish (2005) describes a fold-and-thrust belt domain verging northward, that affects rocks at the Tertiary sediment filling, and a Foreland domain with a southward slope, similar to what took place in Tierra del Fuego (Fig. 10).

Basement Domain

The Basement Domain in Tierra del Fuego extends around from the Magallanes-Fagnano fault zone at the north to Cape Horn at the south. In Tierra del Fuego, comprising the Darwin Cordillera, Rocas Verdes basin, the Patagonian Batholith, and Jurassic to Mesozoic rocks and is bounded by the Glacial Marinelli basement thrust to the north. The Basement Domain is affected by a series of strike-slip faults active during the Cretaceous such as the Beagle Channel fault zone (Cunningham, 1995) and secondary faults related to the Neogene Magallanes-Fagnano fault zone (Yehuin and Tierra Mayor faults; Diraison *et al.,* 1997; Rosello, 2004; Lozano *et al.,* 2018). Mpodozis and Rojas (2006) estimated the displacement of the Yehuin fault in ~27 km to the south, NW-SE direction (Fig. 5), and active during the late Eocene-early Oligocene (Rosello, 2004).
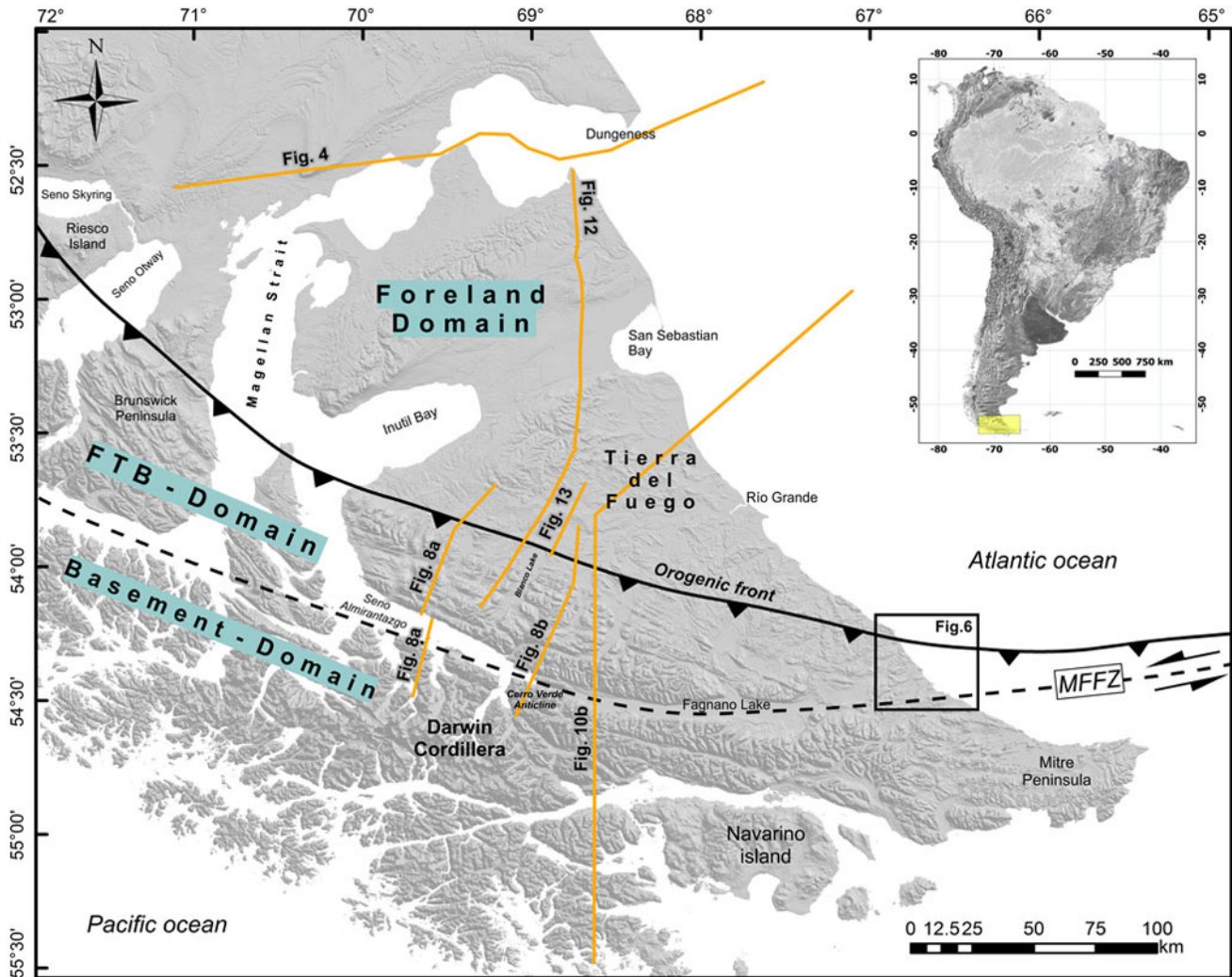
Figure 7. Map of location of seismic lines in Tierra del Fuego province described in the text. Abbreviations: MFFZ: Magallanes-Fagnano Fault Zone; FTB: Fold-and-thrust Belt.

The Basement Domain is made-up by northeast verging thrust sheets and dip to the south (Álvarez-Marrón *et al.,* 1993; Kraemer, 2003; Rojas and Mpodozis, 2006). At the south extreme, affects rocks of the Paleozoic Basement, discontinuous ophiolites derived from the sea floor of Rocas Verdes basin (Tortuga Formation) and rocks of the Tobífera/Lemaire Formation, while towards the north comprises rocks of the Cretaceous thermal subsidence stage (Klepeis *et al.,* 2010).

This domain is characterized by intense compressive deformation, including areas with ductile deformation and rocks of high-grade metamorphism that represent the Darwin Cordillera complex (Mpodozis and Rojas, 2006; Rojas and Mpodozis, 2006). The dominant tectonic style is thick-skinned (Rojas and Mpodozis, 2006). To the

western sector, a structure out-of sequence known as Glacial Marinelli fault was produced, uplifting and involved polyphase deformation from the Darwin Cordillera metamorphic complex over Jurassic volcanic rocks of the Tobífera/Lemaire Formation (Rojas and Mpodozis, 2006). This thrust fault of low angle and north-northeast verging, extends for over 120 km along the dip-direction (represent the Basement Thrust front; Klepeis, 1994b).

Towards the north, this thrust fault is connected to a decollement level identified as Dp, originating a large hanging wall anticline denominated Cerro Verde Anticline (Fig. 8; Klepeis, 1994a,b; Kraemer, 2003; Rojas and Mpodozis, 2006). This large anticline located at the south of Fagnano Lake (Klepeis, 1994a.b; Kraemer, 2003), extends for ~100 km to the west of Sierra Valdivieso, with NW-SE orientation.
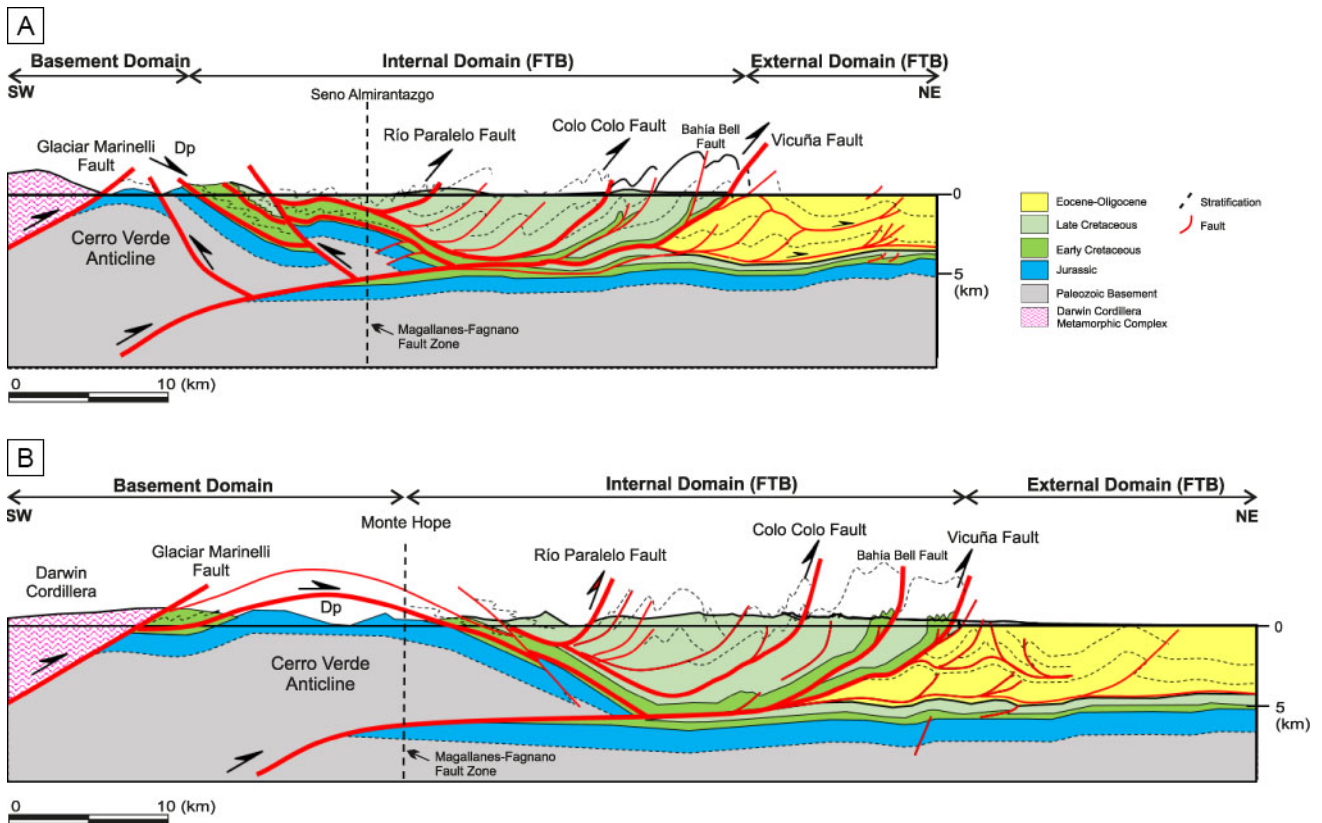
Figure 8. Structural sections through the Tierra del Fuego in Chile. **a)** Structural section interpreted in seismic line j-5009 and surface geology of ENAP, and **b)** Structural section interpreted in seismic line J-5001 and surface geology of Klepeis (1994b) and ENAP. FTB: Fold-and-thrust belt. Modified from Rojas and Mpodozis (2006). For location, see Fig. 7.

This anticline is formed by volcanites from Tobífera/Lemaire Formation, which are underlain by Lower Cretaceous rocks from Río Jackson and La Paciencia formations (Rojas and Mpodozis, 2006). Kraemer (2003) indicates this anticline shows inverse faulting at its north flank, and it might have been formed during the Eocene as an rooted basement anticline, and transferred deformation and shortening to sequences of the internal FTB domain of the Late Cretaceous (Fig. 8b). Rojas and Mpodozis (2006) recognize a decollement level located on the base of the Cretaceous sequence over Jurassic volcanites for the innermost zone of the Basement Domain near of the Brooks Fiord, south of the Seno Almirantazgo. Above the decollement level a basal duplex verging to the north is developed, affecting Lower Cretaceous rocks (Río Jackson Formation), which are strongly folded and imbricate. The fault at the upper part of the duplex transferred shortening towards siltstones and turbidites from the Late Cretaceous (La Paciencia and Cerro Matrero formations), conforming the basal thrust of a major imbricate system that includes thrust sheets up to ~5 km thickness. The same decollement level is recognized by Álvarez-Marrón *et al.* (1993) at the top of Tobífera Formation in the Vicuña area, identifying it as decollement surface D3, and by Kraemer (2003) immediately to the south of Fagnano fault system, bounded Late Jurassic and Lower Cretaceous rocks. According to Rojas and Mpodozis (2006), the oldest deformation stage in the FPC on Tierra del Fuego is a result of the decollement of the sedimentary Cretaceous sequence over Jurassic volcanites, probably between the Paleocene and Eocene.

The advancing of the tectonic wedge towards the foreland area over the cover previously deformed might have generated the reactivation out-of sequence of some of the preexistent thrust fault (Fig. 8; Río Paralelo fault). At the Vicuña area it is possible to identify rocks from the Early and Late Cretaceous thrusted over Eocene-Oligocene sediments of the Cenozoic foredeep basin, showing the migration of the front of FTB limited by the Vicuña fault at the north (Fig. 8; Rojas and Mpodozis 2006). Thickness
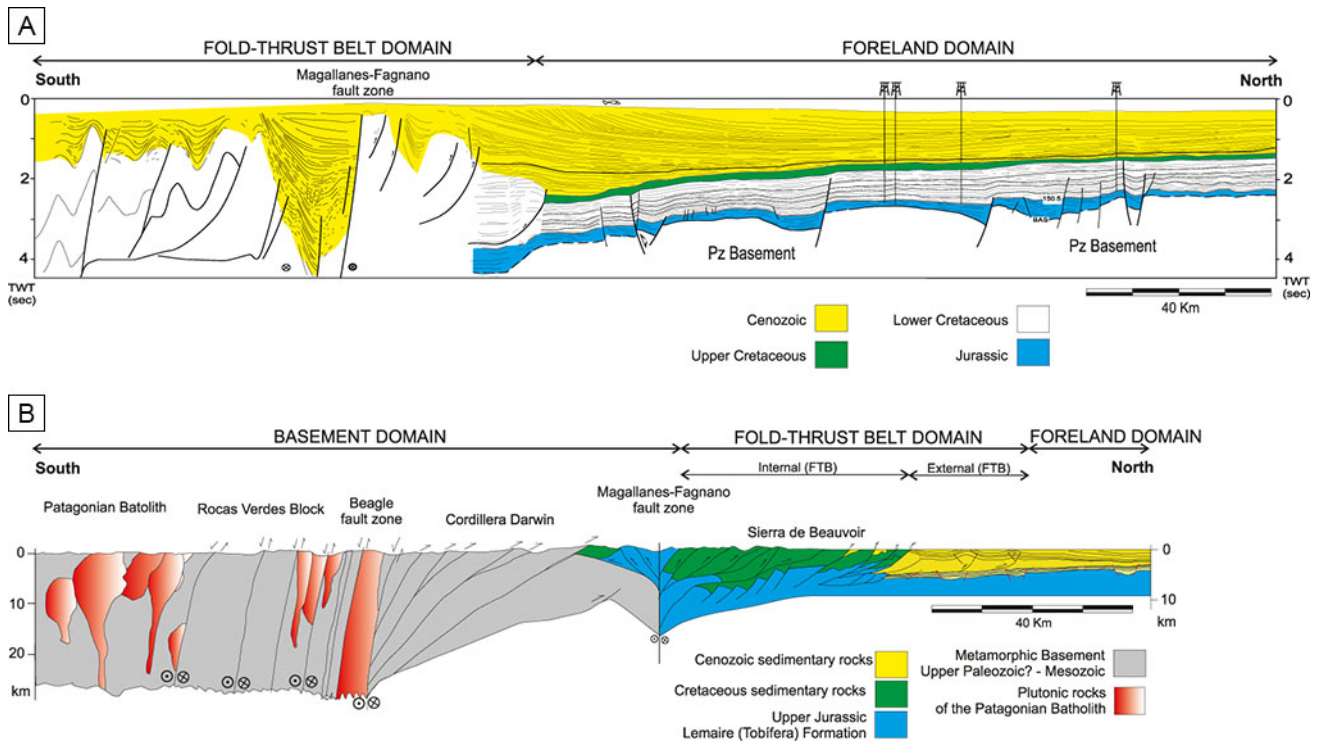
Figure 9. a) Structural cross-section in the Malvinas basin from Ghiglione *et al.* (2010). Fold-and-thrust belt modified from Tassone *et al.* (2008), foreland basin from Galeazzi (1998), **b)** Regional cross-section showing the Andean tectonics domain in the Austral-Magallanes basin. Basement domain is after Cunningham (1995) and Kraemer (2003) fold and thrust belt and foreland domain is modified From Kraemer (2003). For location see Fig. 1.

difference observed between Cretaceous strata of the hanging wall (>4,000 m) compared to those of the footwall suggest that the Vicuña fault might have formed from a discontinuity or palaeogeographic break in the Cretaceous platform (Álvarez-Marrón *et al.,* 1993; Rojas and Mpodozis, 2006).

Internal Fold-and-Thrust Belt Domain

The internal domain of deformation at the FTB in Tierra del Fuego expands approximately from Monte Hope and Magallanes-Fagnano system fault on the south, to the Vicuña area on the north through Vicuña fault that separates it from the Foreland Domain. Develops an orientation NW-SE, with folding and imbrications forming tight folds anticline and synclines whose intensity of deformation decreases from west to east, deforming Jurassic to Eocene-Oligocene rocks (Álvarez-Marrón *et al.* 1993; Kraemer, 2003; Rojas and Mpodozis, 2006). In the same way as it occurs in the basement domain, the internal domain of the FTB is affected by Yehuin fault (Fig. 5). In the internal domain of the

FTB in Tierra del Fuego, described as thin-skinned tectonic style (Klepeis and Austin, 1997; Kraemer, 2003; Mpodozis and Rojas, 2006), a series of sheets verging to the north forming an imbricate fan system (Fig. 8) Álvarez-Marrón *et al.,* 1993; Kraemer, 2003; Rojas and Mpodozis, 2006; Klepeis *et al.,* 2010).

At the area of Vicuña (Lynch and Blanco lakes) three major structures north-northeast verging thrust sheets that configures the fold-and-thrust belt: Vicuña, Bahía Bell and Colo-Colo faults, from north to south, respectively (Figs. 5 and 8) (Álvarez-Marrón *et al.,* 1993; Rojas and Mpodozis, 2006). Meanwhile, Rojas and Mpodozis (2006) describe in the south of Cerro Colo-Colo fault the denominated *Río Paralelo fault* (out-of sequence thrust), result of the displacement of the preexistent thrust towards the north (Fig. 8). The northernmost of this thrusting, named *Vicuña fault*, uplifted Lower and Upper Cretaceous rocks (Río Jackson and Vicuña formations) over Eocene rocks (Ballena Formation) (Figs. 5 and 8). The *Bahía Bell fault,* defined by Álvarez-Marrón *et al.* (1993), puts in contact Lower Cretaceous rocks (Río Jackson Formation) over deposits of the Upper Cretaceous
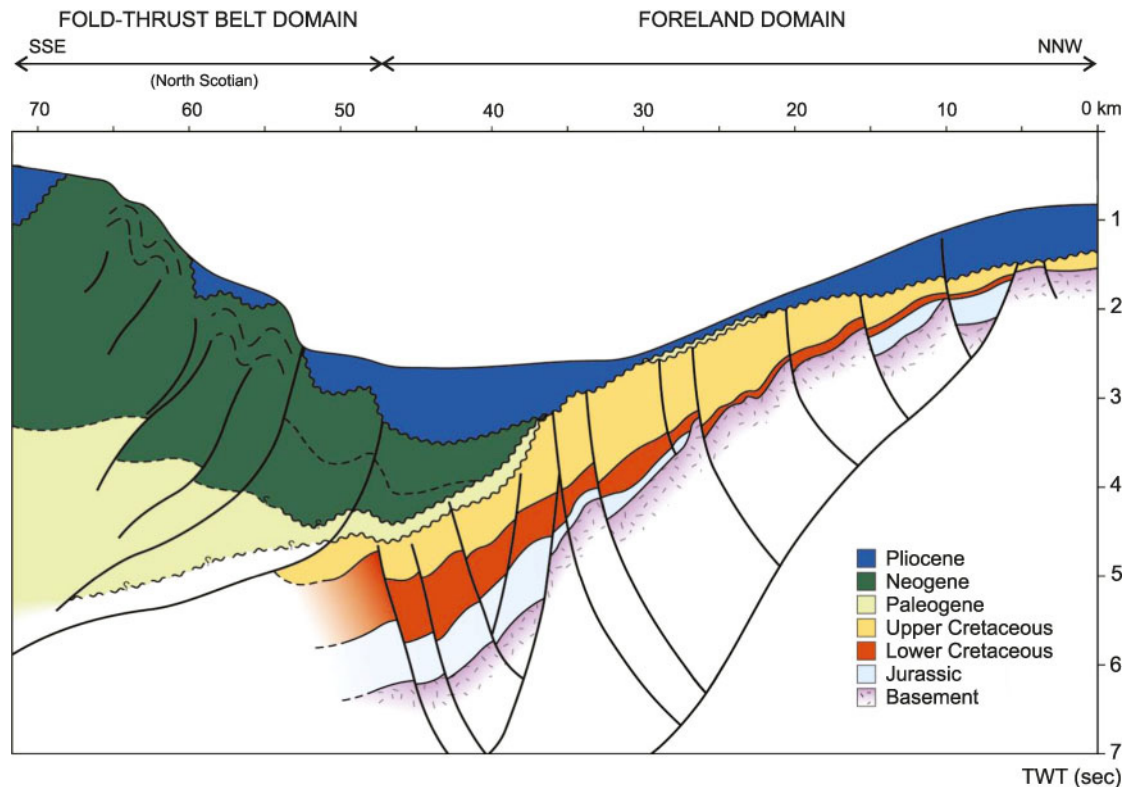
Figure 10. Structural section to south of the Malvinas Basin, showing Fold-and-thrust domain to the south and Foreland Domain to the north. TWT: reflection transit time in seconds. Modified from Fish (2005).

(Río García Formation). Finally the *Colo-Colo fault*, the southernmost thrust of this system, puts in contact Lower Cretaceous turbiditic rocks (Cerro Matrero Formation) with shelfal deposits of the Upper Cretaceous (La Paciencia Formation), indicating a horizontal displacement of several kilometers (Figs. 5 and 8) (Rojas and Mpodozis, 2006).

On the other hand, Álvarez-Marrón *et al.* (1993), describe for the lower part of the external domain, to the ~5-6 km deep, duplex of gently slope at the south, affecting Cretaceous rocks near to the Jurassic-Cretaceous contact or decollement level D3 (Fig. 11). At the Chilean-Argentinean border in the north of Fagnano Lake, Lower Cretaceous rocks rest over Upper Cretaceous rocks along the Deseado fault (Klepeis, 1994a; Kraemer, 2003). For the internal domain of the FTB of Tierra del Fuego in Chile, the position of the Dp is variable. At the west of the FTB, the position of Dp remains at the base of the Cretaceous, rising gradually towards the west until positioning at the Lynch Lake in the late Cretaceous and in the Nariz Cape in the Maastrichian (Rojas and Mpodozis, 2006).

External Fold-and-thrust Belt Domain

The external deformation domain is bounded at the south by the internal domain of FTB (limited by the Vicuña fault). North of the Vicuña fault (and in the Tierra del Fuego in Argentina), sequences of the Cretaceous shelfal and Cenozoic fill consists of large amplitude fold-and-thrust showing several levels of decollement overlapped that gently affected the foreland fill (Fig. 8, 12) (Robbiano *et al.,* 1996; Kraemer, 2003; Rojas and Mpodozis, 2006; Menichetti *et al.,* 2008). The deepest one of this thrust represents the continuity to the north of the basement thrust of the Jurassic-Cretaceous limit (Dp: Rojas and Mpodozis, 2006; or D3: Álvarez-Marrón *et al.,* 1993), which is associated to duplex (Fig. 11; Álvarez-Marrón *et al.,* 1993) and minor imbrications. The foreland tertiary successions is detached from the Cretaceous in a level of pressured pelitic rocks of the Eocene (basal deltaic sediments), which is rooted towards the south with Vicuña fault and the imbricate fan system of the internal domain (Fig. 13; Rojas and Mpodozis, 2006).
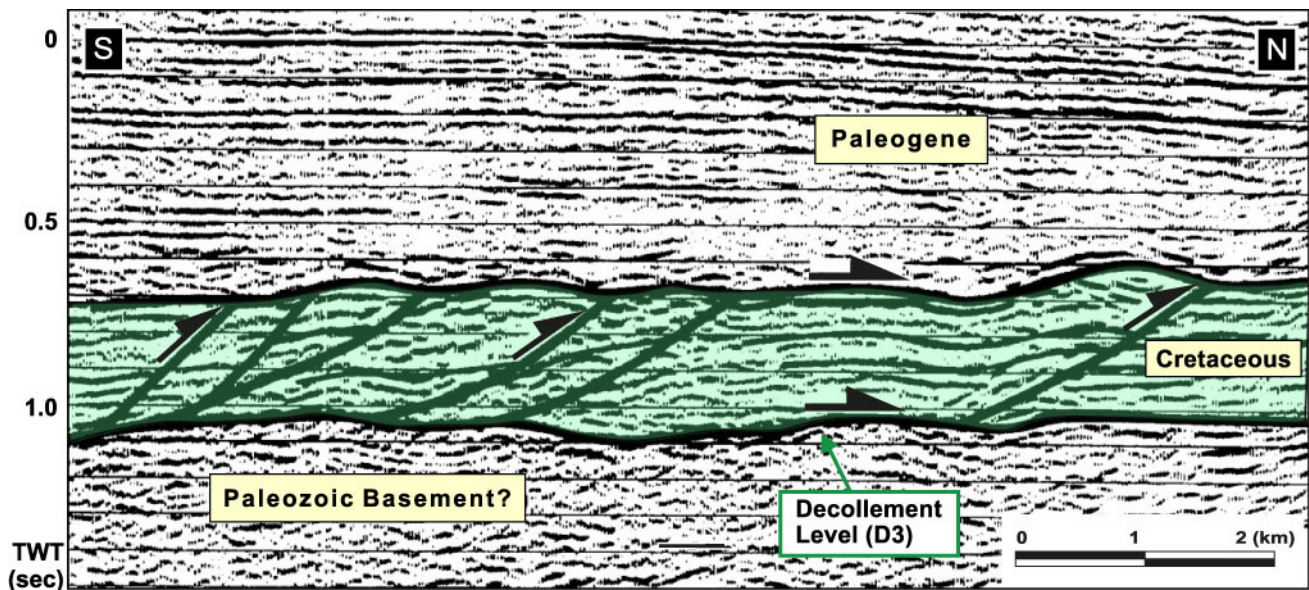
Figure 11. Duplex thrusting Cretaceous rocks over decollement level D3 over contact Jurassic-Cretaceous. TWT: reflection transit time in seconds. Modified from Álvarez-Marrón *et al.* (1993).

This succession is deformed internally in a system of thrust sheets that pass laterally to the north to anticlines by detachment folding and whose horizontal shortening increases to the east (Rojas and Mpodozis, 2006). In the Atlantic shore these units are discussed by Ghiglione *et al.* (2002) and Ghiglione and Ramos (2005) in the Campo del Medio Cape and Punta Gruesa (Fig. 6). The structures are developed during the middle-early Eocene, characterized by development of detachment folding with limb rotation over a decollement level of pelitic rocks. The folded units, near to the Magallanes-Fagnano fault system, involves sedimentary rocks from the Eocene (Punta Torcida, Leticia formations) and are characterized to be dissected by high-angle thrust faults out-of sequence. During the Oligocene, the shortening resulted in the propagation of thrust faults and migration northward of the foreland basin system under transpressive conditions, associated probably, to the Magallanes-Fagnano fault system.

Foreland Domain

The foreland domain in Magallanes is extended from the north limit of the external domain. Currently, the foredeep is developing towards the east and the north of the orogenic front, and is not affected significantly by the compressive tectonic processes. It is a large region composed by Jurassic to Cenozoic rocks scarcely deformed, decreasing deformation from south to north towards the area called Platform. Regional slopes increase towards the west and south, at the areas where the influence of tectonic loading is higher due to flexure (Figs. 8, 9 and 12) (Mella, 2001; Mella *et al.,* 2010; Mpodozis *et al.,* 2011). Towards the west, at the platform area and far from the FTB domain, regional slopes decrease. In the foreland area, the fill consists in an assemblage of marine and non-marine deposits, and volcanic and volcaniclastic rocks that reaches up to ~8 km of sediment thickness (Fig. 1) (Biddle *et al.,* 1986; Wilson, 1991). Through of seismic lines it is possible recognize parallel to sub-parallel seismic reflectors with gently slope to the south in Tierra del Fuego and towards the west (Álvarez-Marrón *et al.,* 1993; Mella, 2001; Mpodozis *et al.,* 2011; Gallardo, 2014). The foreland area registers processes linked to tectonic events that occur in the hinterland, causing migration of peripheral bulge with reactivation of normal faults (Moraga, 1996; Ghiglione *et al.,* 2010) and transcurrent reactivation of extensional high-angle faults (Mpodozis *et al.,* 2011).

The Paleozoic basement is divided into structural blocks limited by high-angle normal faults, defining half-grabens where the synrift volcaniclastic sediments are deposited (Moraga, 1996; Navarrete-Rodríguez, 2006). The sedimentary loading in turn originated extensional reactivation of Jurassic faults,
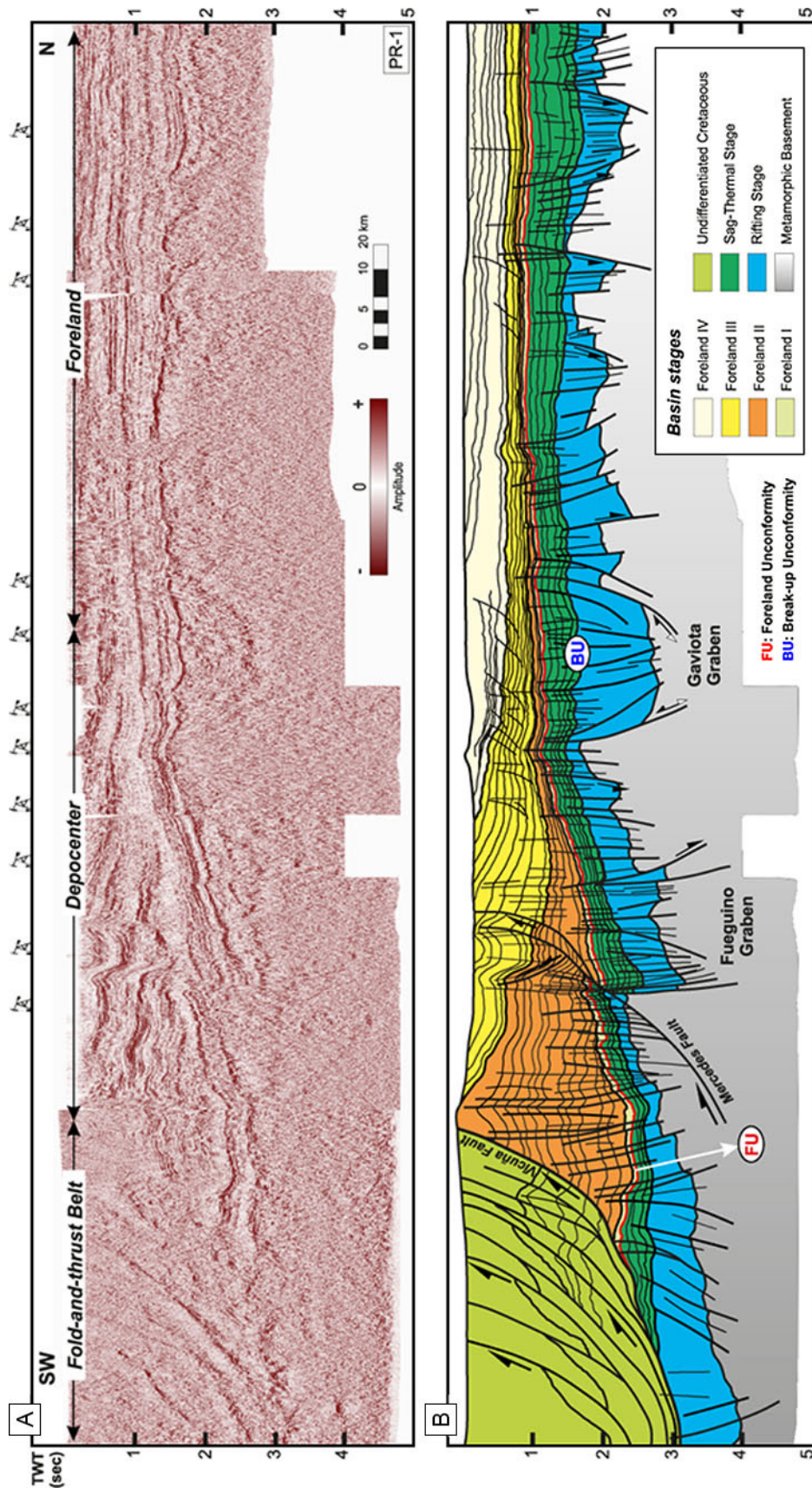
Figure 12. Regional seismic line PR-1.**a)** uninterpreted and **b)** interpreted section through of Tierra del Fuego in Chile showing Rifting, Sag-thermal and Foreland stages. Note the wedge-shape and thinning of the successive foreland stage towards the foreland domain through the section. TWT: reflection transit time in seconds. For map location see Fig. 7.
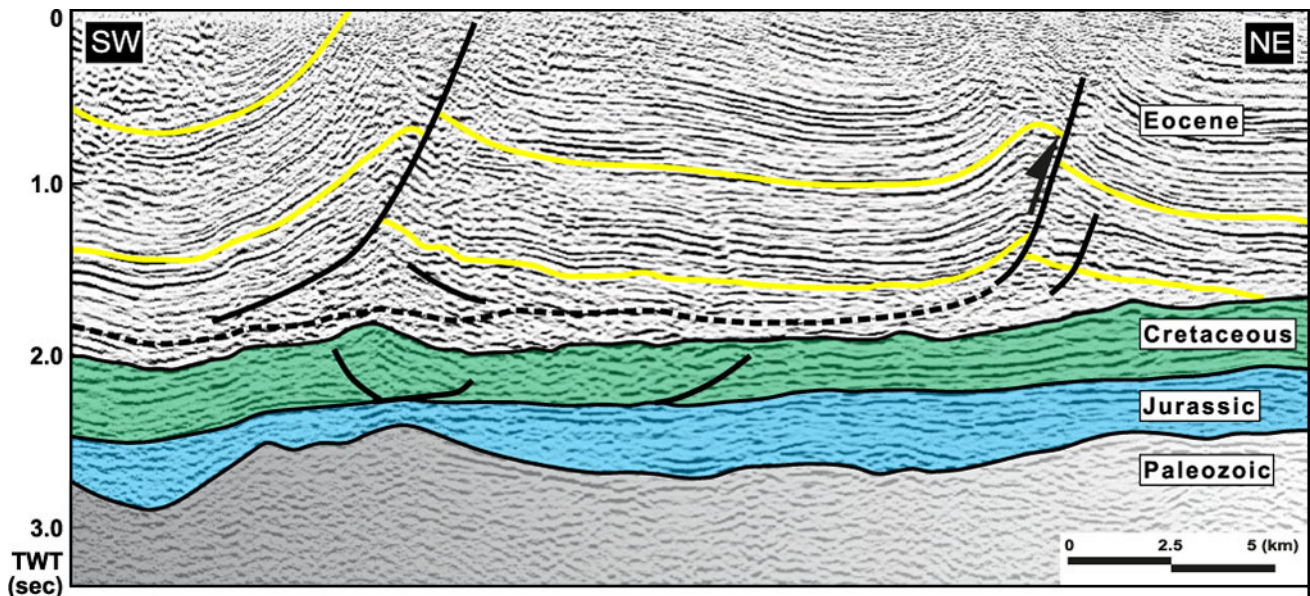
Figure 13. Detachment folding in Eocene deltaic sediments, external domain of the Fold-and-thrust Belt. TWT: reflection transit time in seconds, 2 seconds ≈ 4 km. For location see Fig. 7. Modified from Rojas and Mpodozis (2006).

which in some cases affected the Cretaceous units, increasing even more the uplift of the folds generated at early stages (Mpodozis *et al.,* 2011). Within of the Foreland III units (in Chile) of the Oligocene in age, it is possible to recognize in localized areas, characteristic configuration in progradation towards the basin and aggradation on the shelf, with development of turbidites fans and slope sequences (Dorado-Riquelme area; see Gallardo, 2014).

AMOUNT OF SHORTENING

The external FTB of Tierra del Fuego reveals a complex Mesozoic structural history, where the first stage of tectonic of thin-skinned is followed by thick-skinned stage that reactivates preexistent structures (Rojas and Mpodozis, 2006). Álvarez-Marrón *et al.,*(1993), by means of the palimpastic reconstruction of three structural sections in the external area of Vicuña estimates an amount of shortening between 57-60%, from east to west respectively, estimating ~30 km of shortening. In turn, Rojas and Mpodozis (2006) determine that the sum of shortening in the Glaciar Marinelli fault, the outcropping part of the basal duplex and the Cerro Colo-Colo and Vicuña faults reaches ~50 km at least. For the Darwin Cordillera metamorphic complex in the internal domain, the crustal shortening estimate is ~25 km (Nelson, 1982; Kohn *et al.,* 1995), and Klepeis

(1994b) suggest ~83 Km of shortening at north of the Glaciar Marinelli fault thrust. Meanwhile, Kraemer (2003) estimates the post-Jurassic cortical shortening of the Fueguian Andes between ~300 to ~600 km, with an increase in the shortening value north to south (~400 km during the middle-Cretaceous, ~40 km in the early-Cretaceous, ~50 km in the Paleogene and ~80 km in the Neogene). On the other hand, Klepeis *et al. (*2010), suggest a minimum of ~50 km of horizontal shortening (~70%) in cover rocks is accommodated between the Beagle Channel and Seno Almirantazgo.

In the easternmost part of the Tierra del Fuego in Argentina, Torres-Carbonell *et al.* (2011) estimated a minimum shortening of ~41.8 Km product of structures in the base of Cretaceous and within Paleocene rocks. Recently, Torres-Carbonell *et al.* (2017), in the southeastern tip of Tierra del Fuego recognize a minimum regional shortening in the Paleogene cover that increased from west to east, and vary between 16% and 43%.

SYNTHESIS AND DISCUSSION

The tectonic evolution of the Andes of Tierra del Fuego is related to the collapse close of a marginal basin (Rocas Verdes basin) during the Early Cretaceous (Dalziel *et al.,* 1974; Stern, 1980; Dalziel, 1981; Biddle *et al.,* 1986; Uliana *et al.,* 1986;

Calderón *et al.,* 2007). The first evolutionary stage is associated to a rifting phase affecting the whole southernmost part of the Patagonia, between the Late Jurassic and the Early Cretaceous, which is followed by a Foreland Basin stage, resulting from tectonic loading linked to the uplift of the Fueguian Andes during the Late Cretaceous (Katz, 1963; Wilson, 1991; Biddle *et al.,* 1986).

Structural Domains

While in the Turonian to Campanian in Tierra del Fuego in Chile were deposited facies of deep basin, at the Argentinean sector fine-grained facies were deposited in an outer shelfal and slope settings, indicating an advance the progression of the deformation towards the east in the Late Cretaceous. Thus, a hiatus in the sedimentation of the Cretaceous foreland basin is registered in the Tierra del Fuego (Ghiglione *et al.,* 2002; 2014), probably generated by the effects of the rapid uplift and cooling in the Darwin Cordillera at the ∼65 My. (Kohn *et al.,* 1995; Barbeau *et al.,* 2009; Gombosi *et al.,* 2009) as shown by the angular unconformity within early Paleocene units (Ghiglione and Ramos, 2005).

The subsequent erosion filled the wedge top in Sierra de Apen and Península Mitre (Olivero *et al.,* 2002), and the foredeep of the Paleocene-early Eocene, contemporaneous with the shortening in the fold-and-thrust belt (Klepeis and Austin, 1997; Kraemer, 2003; Ghiglione and Ramos, 2005; Gombosi *et al.,* 2009) and transpression along the Beagle Channel fault-zone (Cunningham, 1993; 1995). A new major phase in the deformation in the late-early Eocene to late Eocene in Tierra del Fuego is represented by the internal progressive migration towards the north and syntectonic unconformities developed in the front of the fold-and-thrust belt (Prieto and Moraga, 1990; Ghiglione *et al.,* 2002). In the same, Gombosi *et al.,* (2009) recognized a rapid cooling and exhumation caused by shortening and rock-uplift of the Fueguian Andes between the middle and late Eocene.

Subsequently, in the Oligocene the reactivation of detachment levels, the migration of the tectonic wedge to the Cenozoic sequence and the uplift of the Darwin Cordillera occurs (Rojas and Mpodozis, 2006). Post-compressive tectonic stage, between Antarctic Peninsula and the southernmost South America finished with the opening of the Drake Passage in the Neogene that affected the evolution of Cenozoic rocks in the Austral-Magallanes Basin during the Miocene.

Seismic geometry and Depocenter

Based on regional seismic data and well-log (Fig. 12; seismic line PR-1) it was possible to identify the evolutionary stages for the southernmost depocenter of the Austral-Magallanes basin in Tierra del Fuego. The *rifting stages* are established over a basement controlled by normal faulting of northwest-direction of Middle to Late Jurassic age. Figure 8 (PR-1) shows that the thickest thicknesses of the volcanic filled are located close to the main faults, and the top of the volcanic rocks is marked by a reflector of high-amplitude that represents a regional break-up unconformity.

In discordance to the rifting stage, a thick succession of *sag-thermal stage* is deposited in the Lower Cretaceous. These fine-grained successions represent a regional transgressive event deposited in platform environment that cover the volcanic and volcaniclastic rocks of the underling stage. The seismic reflectors show a tabular-shape with medium-to-high amplitude and cover entire the region, and are slightly thicker to the north.

The onset of *foreland I stage* is characterized in Última Esperanza in Chile by an asymmetric basin with deposition of thick turbiditic successions (Katz, 1963; Wilson, 1991; Sohn *et al.,* 2002; Fildani *et al.,* 2003; Choe *et al.,* 2004; Romans *et al.,* 2009) migrating from the north-northwest since 101±1.1 My (Fig. 3) (Fosdick *et al.,* 2011). At north-edge of the basin, the turbiditic system is represented by the Punta Barrosa formation that is prolonged towards the south in the outcrop of the Latorre Formation in Magallanes (Castelli *et al.,* 1992; McAtamney *et al.,* 2011), and the turbiditic facies of Cerro Matrero Formation coming from the southwest in the Coniacian-Campanian (Rojas, 1990; Álvarez-Marrón *et al.,* 1993). In subsurface of Tierra del Fuego, the Lutitas Arenosas Formation represent the first deposits of the foreland stages (González, 1965; Natland *et al.,* 1974). Meanwhile, in the eastward of Tierra del Fuego, the Bahía Thetis Formation of the upper Campanian was deposited in deep-water channels environments (Olivero *et al.,* 2003; Olivero and Malumián, 2008). Therefore, a diachronic age in the onset of the compressional stage is evidenced in

the foreland basin, being youngest towards the south and east in Austral-Magallanes Basin (Fig. 3). The initial tectonic loading is accompanied as well by a pulse of rapid cooling and uplift between ~90-70 My (Nelson, 1982; Kohn *et al.,* 1995; Cunningham, 1995).The seismic reflection in Tierra del Fuego shows that the foreland I have poor development with small thickness and tabular-shape in subsurface (Fig. 12). However, this geometry changes drastically to the west of the basin, where it takes a wedge-shape that thickens towards the foredeep zone (Fig. 4).

The *foreland II* is well-represented in subsurface of Tierra del Fuego. Its basal boundary corresponds to a regional angular unconformity over the Cretaceous successions, and represents an onlap surface towards the east and north. It is configured as a wedge-shape that drastically increases its thicknesses towards the south and west (Fig. 12). The base of foreland II corresponds to a regional hiatus that in Santa Cruz and Última Esperanza provinces span between the Paleocene and early-to-middle Eocene (Hervé *et al.,* 2004), in Magallanes province is limited to early Paleocene (Fig. 3) (Pinto *et al.,* 2018), and in Malvinas basin is restricted between late Maastrichian to early Eocene (Galeazzi, 1998). In the early Paleocene the southernmost region of the depocenter was affected by the uplift and cooling of Darwin Cordillera at ~65 My (Kohn *et al.,* 1995; Barbeau *et al.,* 2009), and as a result of this the orogenic thrust front advanced on Tierra del Fuego province in northward-direction unconformities (Prieto and Moraga, 1990; Ghiglione and Ramos 2005; Rojas and Mpodozis, 2006). Meanwhile, in the Última Esperanza and Magallanes provinces the migration of the orogenic front occurs in eastward-direction (Hervé *et al.,* 2004; Fosdick *et al.,* 2011; Mpodozis *et al.,* 2011). Finally, in the middle-to late Eocene a new rapid cooling and exhumation affected the region (Gombosi *et al.,* 2009), and orogenic front migration towards the north by multiples unconformities produced the uplift of the Fueguian Andes (Ghiglione *et al.,* 2002; Olivero *et al.,* 2002; Ghiglione and Ramos, 2005).

The *foreland III* is marked by progradational systems to north-northeast direction and a minimum rate of creation of accommodation space (Malumián, 2002; Fosdick *et al.,* 2011; Gallardo, 2014; Sáez, 2017). Seismic imaging reflects a wedge-shape that increases its thicknesses towards the south and west (Fig. 12). In Tierra del Fuego province, in the middle Eocene

to Oligocene units are uplift and eroded as a result of the orogenic growth of the Fueguian fold-and-thrust belt (Fig. 12), whereas in subsurface of Magallanes province the entire succession of foreland III is preserved as reflected in seismic data (Fig. 4). Evidence of this progradational stacking patterns are the oblique to sigmoid clinoforms in direction to the foredeep in the east since the middle-late Eocene, and supply sediments in the same direction (Gallardo, 2014; Sáez, 2017), and from the west in the late Oligocene to Miocene in the Malvinas basin (Galeazzi, 1998).

The wedge-top succession of the *foreland IV* is deposited over conditions of very low rate of flexural subsidence (Thomson *et al.,* 2001; Fosdick *et al.,* 2011). In this scenario, were deposited the successions of the Patagonian Atlantic transgression in the Miocene, coming from the east (Malumián *et al.,* 1999; Cuitiño *et al.,* 2012), in an environments shallow-marine, deltaic and fluvial system (Olivero and Malumián, 2008; Malumián and Nañez, 2011; Malumián *et al.,* 2013). In a regional context, during the early Miocene a new phase of uplift of the Patagonian-Fueguian Andes is developed (Thomson *et al.,* 2001; Blisniuk *et al.,* 2006; Fosdick *et al.,* 2011). In addition, in Magallanes and Tierra del Fuego provinces occurs the subduction of the Chilean ridge beneath South America between the ~19-17 Ma, which results in dynamic uplift of the western edge of South America (Gorring *et al.,* 1997; Guillaume *et al.,* 2009; Ghiglione *et al.,* 2016).

CONCLUSIONS

On the basis of the compilation of numerous studies and internal reports of ENAP, it was possible to build a chronostratigraphic table for the southernmost depocenter of the Austral-Magallanes basin. The seismic imaging and well-log data are a useful tool to recognize the different of the evolutionary stages in a basin. Collected information from studies in the Malvinas Islands in the east, Tierra del Fuego and Magallanes in the west, allowed to identify the evolutionary stages of rifting, sag-thermal and foreland stages (I to IV).

The purpose of this contribution was to relate the deformation pulses of the orogenic growth stages whit the development of the associated depocenter in the basin from the Late Cretaceous. The basin of the Upper Cretaceous was established over a fine-

grained successions from a sag-thermal phase of the Lower-to-middle Cretaceous in age, that cover a faulting rifting stage of the Upper-to-Middle Jurassic age. Seismically, the post-rift stage is recognized by reflectors that ascent their contact of formations towards the north and east. This configuration is increased in the foreland stages I to III, in conditions of deep-marine environments, to finally horizontalize the reflectors towards shallow-marine and deltaic sedimentation in the foreland stage IV.

As a future venture, it would be important to expand the seismic coverage and to identify the migration and orientation of the axis depocenter through time as the different pre-foreland evolutionary stages (rift and postrift stage) and foreland (stages I to IV). Additionally, it would be interesting to recognize the position and migration of the peripheral buldge, and its relation to the stages of growth of the Patagonian-Fueguian Andes.

Acknowledgments

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