Tectonic development of the North Patagonian Andes and their related Miocene foreland basin (41°30′-43°S)

Darío Leandro Orts,[1] Andrés Folguera,[1] Alfonso Encinas,[2] Miguel Ramos,[1] Jonathan Tobal,[1] and Víctor A. Ramos[1]

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[1] The Northern Patagonian Andes have been constructed through multiple mechanisms that range from tectonic inversion of extensional structures of Early to Middle Jurassic age in the Main Andes to Oligocene in the Precordilleran region. These have acted during two distinctive orogenic stages, first in late Early Cretaceous and later in Miocene times Late Oligocene extension separates these two contractional periods and is recorded by half-grabens developed in the retroarc region. The last contractional stage coexists with an eastward foreland expansion of the late Miocene arc whose roots are presently exposed as minor granitic stocks and volcanic piles subordinately in the Main Andes, east of the present arc. As a consequence of this orogenic stage a foreland basin has developed, having progressed from 18 Ma in the main North Patagonian Andes, where the mountain front was flooded by a marine transgression corresponding to the base of the Ñirihuau Formation, to 11 Ma in the foreland area. Cannibalization of this foreland basin occurred initially in the hinterland and then progressed to the foreland zone. Blind structures formed a broken foreland at the frontal zone inferred from growth strata geometries. During Pliocene to Quaternary times most of the contractional deformation was dissipated in the orogenic wedge at the time when the arc front retracted to its present position.

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1. Introduction

[2] The knowledge and understanding of the mechanisms by which the central Andes have evolved have been substantially improved in the recent years. These comprise changes in the subduction geometry through time [*James and Sacks*, 1999; *Kay and Coira*, 2009; *Ramos and Folguera*, 2009; *Capitanio et al.*, 2011], changes in the absolute displacement of the overriding South American plate [*Oncken et al.*, 2006; *Ramos*, 2010], and climatic factors [*Lamb and Davis*, 2003; *Strecker et al.*, 2009; *Hain et al.*, 2011], variable structural controls and availability of sedimentary prisms that yielded differentially under shortening [*Allmendinger et al.*, 1997; *Kley et al.*, 2005; *Ramos et al.*, 2004; *Giambiagi et al.*, 2009], and to sublithospheric processes [*Sobolev et al.*, 2006]. Even remote factors such as the closure of the Tethyan ocean have been invoked in explaining episodic Andean contraction [*Silver et al.*, 1998]. Thus, the Andean system is revealed as a complex system in which different factors could be acting superimposed, exhuming differentially the upper crust and causing its eventual collapse. In these analyses, the Patagonian Andes have been almost ignored. Their contractional mechanisms were barely addressed in most of the geological studies carried out in the area, with the exception only of those of *Diraison et al.* [1998], *Giacosa and Heredia* [1999; 2004a] and *Giacosa et al.* [2005], while shortening values, as well as precise deformational stages, are unknown. This work is focused on addressing these key points through a study of the geology and structure in a segment through the North Patagonian Andes. The inferred orogenic models for this segment allow comparison with to other neighboring Andean segments, in particular in relation to changes in slab dip, nature of subducting oceanic crust, and inherited crustal structures, and allow further comparison to similar mechanisms in other worldwide subduction mountain systems. Additionally, we fill a significant gap in along-strike shortening gradients along the Southern Andes to the Patagonian Andes, allowing them to be more completely understood, as well as identifying orogenic stages to be compared to those found at different latitudes. Finally, our work allows past shortening rates as a function of time to be compared to modern rates.

[3] The North Patagonian Andes are ascribed in the literature as having undergone several different deformational stages during at least the last 100 Ma [*Feruglio*, 1947, 1949;

[1]Instituto de Estudios Andinos "Don Pablo Groeber," Departamento de Ciencias Geológicas, FCEN, Universidad de Buenos Aires–CONICET, Buenos Aires, Argentina.

[2]Departamento de Ciencias de la Tierra, Universidad de Concepción, Concepción, Chile.

Corresponding author: D. L. Orts, Instituto de Estudios Andinos "Don Pablo Groeber," Departamento de Ciencias Geológicas, FCEN, Universidad de Buenos Aires–CONICET, Intendente Güiraldes 2160, Ciudad Universitaria Pabellón II, 1er piso, Buenos Aires C1428EGA, Argentina. (dlorts@gl.fcen.uba.ar)

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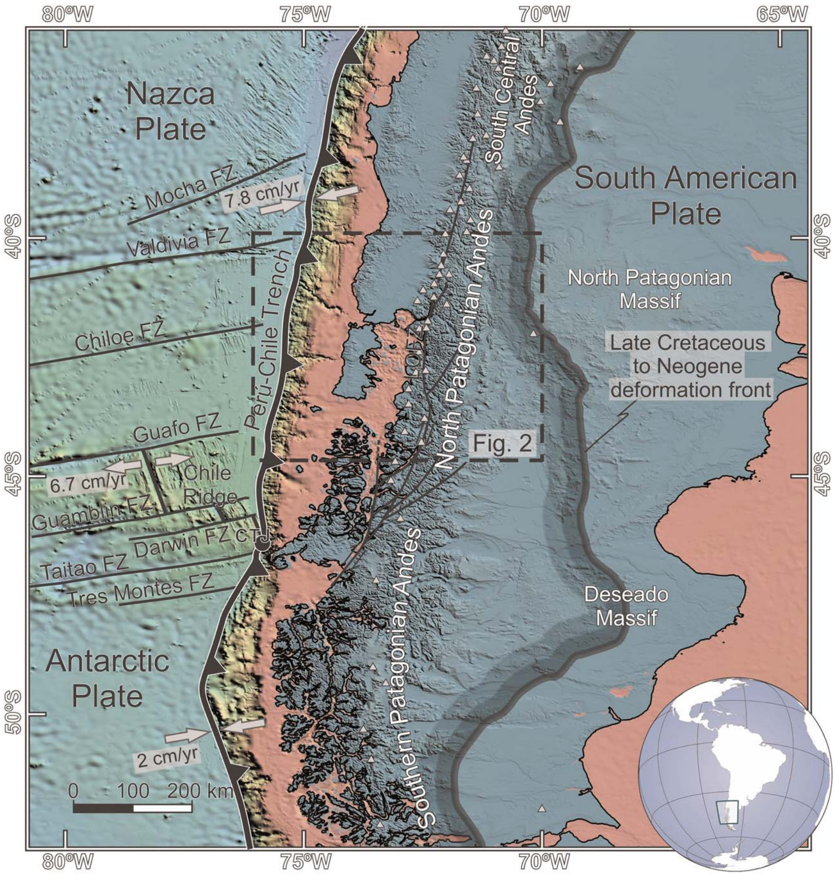


Figure 1. Tectonic setting of the Patagonian Andes, showing the study area hosted in its northern section (Figure 2) and present configuration of the zone of interaction among the South American, Nazca and Antarctic plates. Thick gray line denotes the variable extent of the Late Cretaceous to Neogene deformational front based on *Coutand et al.* [1999], *Zapata et al.* [1999], *Ghiglione et al.* [2010], *Giacosa et al.* [2010], and *Fosdick et al.* [2011]. The Liquiñe-Ofqui fault zone (LOFZ), near the cordilleran axis, accommodates most of the present oblique convergence between plates north of the triple junction (CTJ) as strike slip displacements, leaving a mainly fossil fold and thrust belt to the east, where this work is focused. Light gray triangles represent the location of active volcanoes. Arrows denote the relatively present-day plate convergence and mid-ocean spreading rates (after *Thomson et al.* [2001], from *Cande and Leslie* [1986] and *Somoza* [1998]). The base hill shade map was constructed from global bathymetric and topographic elevation data from NOAA [*Becker et al.*, 2009].

Ramos and Cortés, 1984; *Giacosa and Heredia*, 1999]. A Late Cretaceous-Cenozoic fold and thrust belt is recorded in the retroarc area, mainly in the eastern slope of the North Patagonian Andes (Figure 1), as a direct consequence of shortening. This work focuses on this area, where the fold and thrust belt particularly has a differential eastward development, creating a foreland curved feature, in comparison with northern and southern sections of the Andes [*Feruglio*, 1947; *Coira et al.*, 1975; *Nullo*, 1979; *Peroni et al.*, 1995; *Figari*, 2005; *Giacosa et al.*, 2010] (Figures 1 and 2). The reason for this contrasting expression is not clear and constitutes one of the main scopes of this work. This task requires integrated structural and tectonic studies to unravel potential processes that could associate magmatism, sedimentation, and deformation through time.

[4] Even though the deformational mechanisms associated with the development of the fold and thrust belt during the Neogene have been discussed, no complete consensus has yet been reached. While strike-slip displacements were inferred in the development of the main contractional

Figure 2. Simplified regional geological map of North Patagonian Andes that shows main structures and geological units (see Figure 1 for a regional perspective). Compilation of published fission track ages depicted as colored dots, from *Thomson et al.* [2010] (for further references, see therein). Note that youngest (Neogene) exhumation is located across the Liquiñe-Ofqui fault zone, whereas in the coastal zone as well as the retroarc zone, older ages were determined. Note also a variable expansion of different arc successions through time, particularly in the Late Cretaceous, late Eocene, and late Miocene, which have led to different proposals of slab shallowings in the area [*Llambías and Rapela*, 1989; *Suárez and de la Cruz*, 2001; *Folguera and Ramos*, 2011].

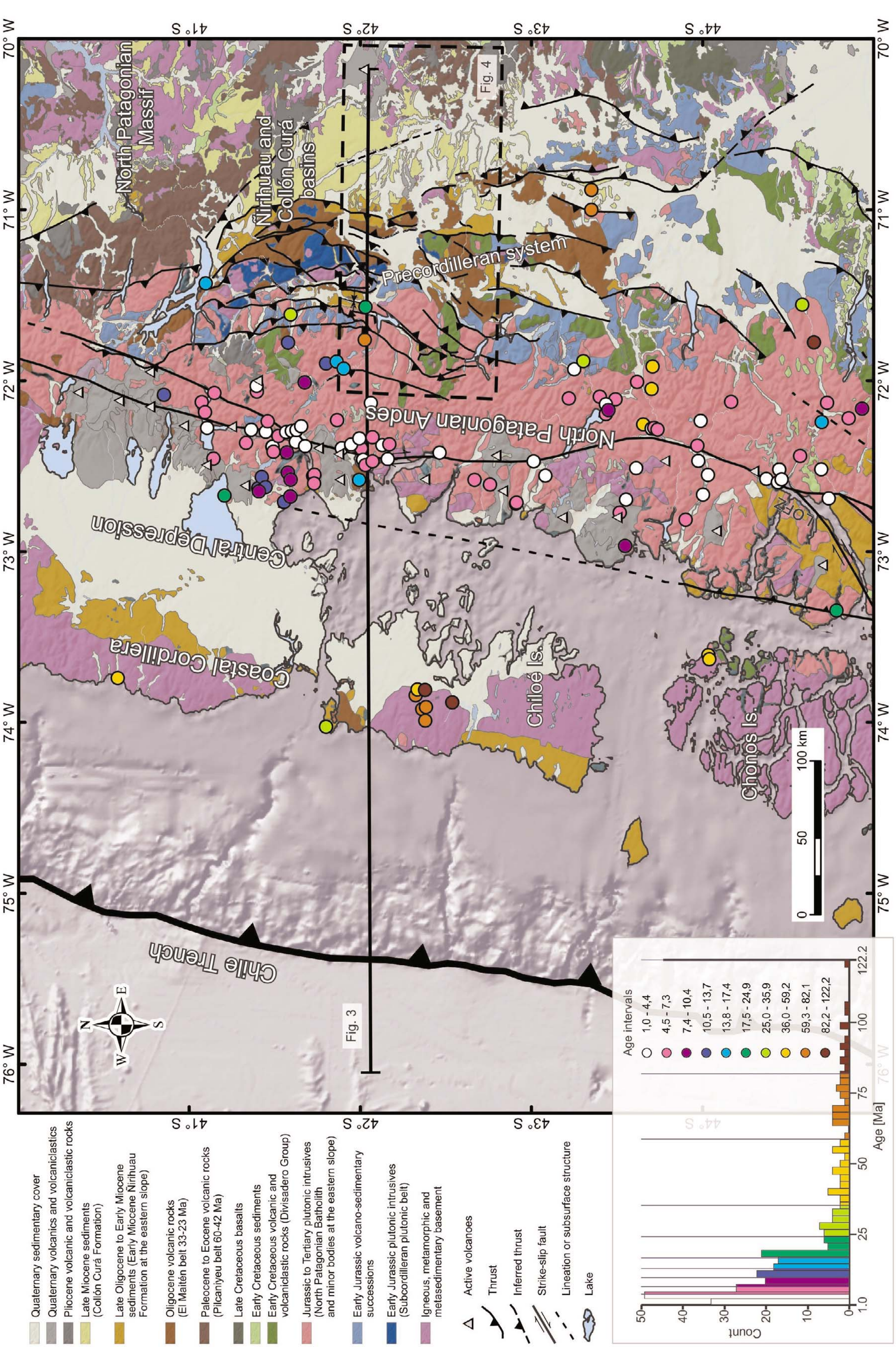

North Patagonian Massif
Ñirihuau and Collón Curá basins
Precordilleran system
North Patagonian Andes
Central Depression
Coastal Cordillera
Chiloé Is.
Chonos Is.
Chile Trench
LOFZ
Fig. 3
Fig. 4
0 50 100 km
70° W
71° W
72° W
73° W
74° W
75° W
76° W
41° S
42° S
43° S
44° S
Quaternary sedimentary cover
Quaternary volcanics and volcaniclastics
Pliocene volcanic and volcaniclastic rocks
Late Miocene sediments (Collón Curá Formation)
Late Oligocene to Early Miocene sediments (Early Miocene Ñirihuau Formation at the eastern slope)
Oligocene volcanic rocks (El Maitén belt 33-23 Ma)
Paleocene to Eocene volcanic rocks (Pilcaniyeu belt 60-42 Ma)
Late Cretaceous basalts
Early Cretaceous sediments
Early Cretaceous volcanic and volcaniclastic rocks (Divisadero Group)
Jurassic to Tertiary plutonic intrusives (North Patagonian Batholith and minor bodies at the eastern slope)
Early Jurassic volcano-sedimentary successions
Early Jurassic plutonic intrusives (Subcordilleran plutonic belt)
Igneous, metamorphic and metasedimentary basement
Active volcanoes
Thrust
Inferred thrust
Strike-slip fault
Lineation or subsurface structure
Lake
Age intervals
1,0 - 4,4
4,5 - 7,3
7,4 - 10,4
10,5 - 13,7
13,8 - 17,4
17,5 - 24,9
25,0 - 35,9
36,0 - 59,2
59,3 - 82,1
82,2 - 122,2
Count
Age [Ma]

Figure 2

structures in the region [*Spalletti and Dalla Salda*, 1996; *Diraison et al.*, 1998], other works invoked dip slip dominant mechanisms for thick-skinned faults [*Giacosa and Heredia*, 1999]. Additionally, inheritance of structural anisotropies that could control the development of the fold and thrust belt is not clear. It has been stated that the main contractional structures were strongly controlled by the anisotropies of the underlying igneous-metamorphic Paleozoic basement [*Coira et al.*, 1975], while others suggest that they are the product of inversion of Mesozoic and/or Tertiary extensional detachments inherited from previous rifts and back-arc basins [*Giacosa and Heredia*, 2004b; *Bechis and Cristallini*, 2006].

[5] One of the most striking characteristics of the study area is the thick successions of late Oligocene to Miocene strata on the eastern fold and thrust belt, at the wedge top zone, reaching 2,000 m, that are condensed up to 300–500 m north of 39°S and south of 43° 30′S (Figure 2) [*Marshall and Salinas*, 1990; *Radic et al.*, 2002; *García Morabito et al.*, 2011; *Flynn et al.*, 2008; *Rojas Vera et al.*, 2010]. These deposits are known as the Ñirihuau and Collón Curá Formations, extensively studied in early regional works [*Feruglio*, 1949; *Mazzoni and Benvenuto*, 1990]. In the last decades, there have been attempts to constrain spatiotemporally this Cenozoic sedimentary infill, hosted at the eastern deformation front, generally interpreted as either a taphrogenic basin [*Cazau*, 1980; *Spalletti*, 1983; *Mancini and Serna*, 1989] or a foreland basin [*Ramos and Cortés*, 1984; *Giacosa and Heredia*, 1999]. After the detailed and pioneering works of *Feruglio* [1947, 1949], carried out in the orogenic front area, the northernmost part of the Ñirihuau-Collón Curá basin (north of 42°S) has generally received most of the attention, due to its better exposures [e.g., *Ramos and Cortés*, 1984; *Diraison et al.*, 1998; *Giacosa and Heredia*, 2004a; *Giacosa et al.*, 2005; *Bechis and Cristallini*, 2006]. This work focuses on its southern section, which has been is much less studied. Here, some interesting characteristics are observable that could help to shed light on previous discussion of the mechanisms associated with the accumulation of thick late Oligocene to Miocene successions in the foreland zone. The present state of discussion points to contrasting tectonic regimes assigned to this basin interval: (a) an extensional back-arc basin superimposed on previous contractional structures [*Cazau*, 1980; *Cazau et al.*, 1989; *Mancini and Serna*, 1989; *Bechis and Cristallini*, 2006]; (b) a pull-apart basin developed in the orogenic front area [*Dalla Salda and Franzese*, 1987; *Spalletti and Dalla Salda*, 1996]; and (c) a foreland basin [*Ramos and Cortés*, 1984; *Giacosa and Heredia*, 1999, 2004a; *Giacosa et al.*, 2005].

[6] This study area in the Northern Patagonian Andes (Figure 2), is additionally characterized by thick successions of late Early Cretaceous and Cenozoic volcanic rocks deposited in three different magmatic belts that show anomalous expansions of the sub-Andean region as previously noted by *Lizuaín* [1983], *Rapela et al.* [1988], *Mazzoni et al.* [1991], *Giacosa and Márquez* [1999], *Suárez and de la Cruz* [2001]. Previous studies on the geochronology and geochemistry of these magmatic units constituted a fundamental contribution required to infer potential changes in the subduction geometry [*Rapela et al.*, 1988; *Suárez and de la Cruz*, 2001]. These eastward arc expansions have been identified in these works as possible shallowings of the subducted plates. Different constructional Andean stages and extensional relaxation periods of the orogenic wedge have therefore been related hypothetically to those changes [*Suárez and de la Cruz*, 2001; *Kay et al.*, 2006; *Litvak et al.*, 2008; *Spagnuolo et al.*, 2012].

[7] Thermochronological data developed mainly from the western slope of the Andes show partly those Cretaceous and Neogene exhumational stages that affected the hinterland zone while the retroarc area was piled up (Figure 2). Initial Late Cretaceous exhumation has affected broad sections of the forearc and arc zones, while late Miocene ones appear more localized along the present arc front (Figure 2) [*Thomson et al.*, 2001, 2010; *Adriasola et al.*, 2006; *Glodny et al.*, 2008; *Duhart and Adriasola*, 2008].

[8] In this work we attempt to integrate our geological mapping, based partially on previous studies, with seismic and geochronological data from the cordilleran axis to the sub-Andean region. Field work has focused on the Main North Patagonian Andes and the frontal zone where synorogenic deposits accumulated, to identify the main constructional stages that affected the fold and thrust belt and relate them to the different geometries that adopted the magmatic arc through time. To achieve these objectives, we i) mapped, correlated, and dated some key sedimentary successions in the hinterland zone by U/Pb techniques to establish a coherent stratigraphy and identify the main structures, ii) dated and described the associated synorogenic deposits hosted in this area as piggyback depocenters, iii) described surficially and seismically the frontal foreland basin at the wedge top zone, and finally iv) gathered structural data to produce two structural transects, subsequently restored to infer the deep mechanisms associated with the exposed structures and quantify their shortening.

2. Geological Framework

[9] The North Patagonian Andes are the expression of the subduction of a series of Pacific plates beneath the South American Plate (Figure 1). Late Cenozoic plate interactions at the Peru-Chile Trench are relatively well constrained by marine magnetic anomalies and plate reconstructions [e.g., *Cande and Leslie*, 1986; *Somoza*, 1998; *Eagles et al.*, 2009], depicting a pattern of relatively uniform convergence between the Nazca and South American plates from the Neogene to the present. The last configuration that could be extrapolated for the last 20 My is depicted in Figure 1, where the Nazca Plate subducts at N78°E beneath the South American Plate at a relative velocity of 7.8 cm/a [*Somoza*, 1998]. However, previous to 26 Ma the Farallon Plate subducted more obliquely with respect to the plate margin [*Pardo-Casas and Molnar*, 1987].

[10] The segment under study (Figure 2) is located north of the Chilean Triple Junction (CTJ) that separates the Nazca Plate to the north from the Antarctic Plate to the south along the subduction border (Figure 1). The Liquiñe Ofqui fault system (LOFZ) [*Hervé et al.*, 1974; *Cembrano et al.*, 1996] is a strike-slip system more than 1,000 km long that concentrates most of the crustal seismic activity at these latitudes (Figures 2 and 3) [*Lavenu and Cembrano*, 1999; *Lange et al.*, 2008]. This fault system splays to the north and through the Andean western slope across the arc front,

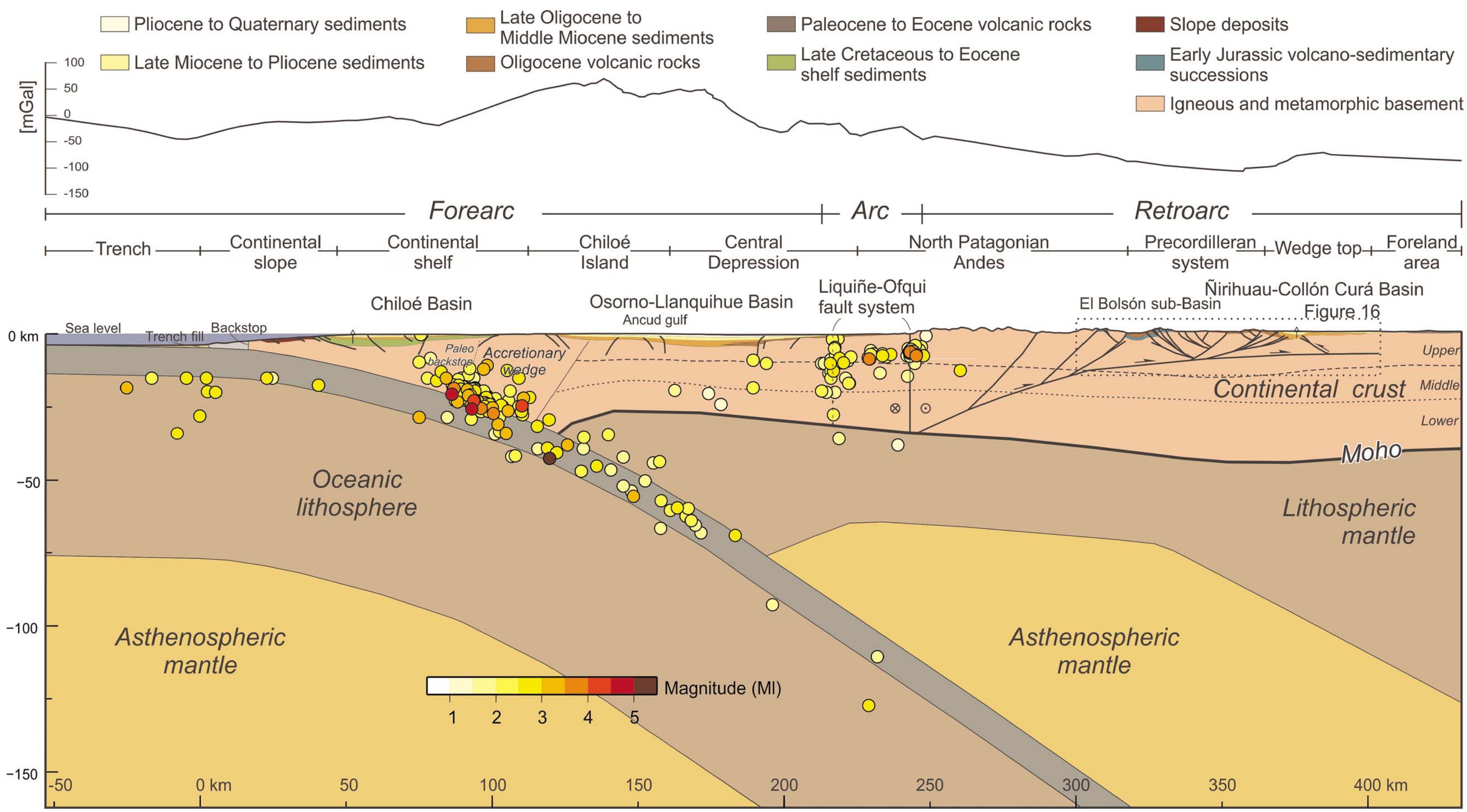


Figure 3. Crustal scale cross section at 42°S. The forearc region is based on *González* [1989] and *Contreras-Reyes et al.* [2010]. Crustal seismicity is taken from *Lange et al.* [2008], and deep lithospheric structure from the density model of *Tašárová* [2007]. Retroarc superficial data are taken from this study. Late Cretaceous and Neogene subsidence has been controlled by normal structures at the forearc region. At the arc region, subvertical strike-slip crustal structures, corresponding to the Liquiñe-Ofqui fault system [*Hervé et al.*, 1974; *Lavenu and Cembrano*, 1999], concentrate the crustal seismicity. To the east, antithetic to the subduction zone, reverse structures deform the retroarc zone, where this study is hosted. This scheme reveals a certain degree of strain partitioning in the region proposed earlier by *Lavenu and Cembrano* [1999]. Note also that crustal shortening is achieved mainly at the retroarc zone.

defining a microplate to the west (Figure 2) [*Melnick et al.*, 2008]. The forearc region corresponding to this microplate comprises, from west to east, the offshore continental shelf composed of Latest Cretaceous to Pliocene marine successions [*González*, 1989], a metamorphic core exposed at the Coastal Cordillera [*Thomson and Hervé*, 2002], the Central Depression formed by Miocene and Pliocene strata [*González*, 1989], and the Patagonian Batholith [*Munizaga et al.*, 1988; *Pankhurst et al.*, 1992, 1999; *Castro et al.*, 2011], affected and exhumed by Neogene transpression (Figures 2 and 3) [*Cembrano et al.*, 1996; *Lavenu and Cembrano*, 1999]. The Coastal Cordillera, south of ~38°S, constitutes a Carboniferous accretionary prism metamorphosed in Late Paleozoic to Late Triassic times [*Thomson and Hervé*, 2002; *Willner et al.*, 2004; *Hervé et al.*, 2007a; *Duhart and Adriasola*, 2008]. South of 42°S this feature submerges partially under the Pacific ocean, leaving the Chiloé and Chonos islands as remnants isolated from the continent (Figure 2). The Coastal Cordillera was first regionally exhumed in Late Cretaceous times [*Duhart and Adriasola*, 2008] and subsequently uplifted in Neogene times based on apatite and zircon fission track data [*González*, 1989; *Finger et al.*, 2007; *Duhart and Adriasola*, 2008; *Glodny et al.*, 2008; *Nielsen and Glodny*, 2009]. The Central Depression intermontane basin is delimited at the eastern slope of the Chiloé Island, south of the Gulf of Ancud, and constitutes the prolongation of the onshore Osorno-Llanquihue Basin to the south [*McDonough et al.*, 1997]. The Central Depression contains approximately 4 km of marine Cenozoic volcaniclastic rocks and glacial sediments in a 70 km wide depocenter parallel to the trench [*Jordan et al.*, 2001; *Duhart and Adriasola*, 2008] (Figure 3). The eastern border of the Central Depression is defined by the Patagonian Batholith and the present volcanic arc in the North Patagonian Andes, where the LOFZ is developed [*Lavenu and Cembrano*, 1999; *Lange et al.*, 2008] (Figure 2 and 3). The Patagonian Batholith is a 2,000 km long, 200 km wide north–south feature comprised of Middle Jurassic to Miocene calc-alkaline plutonic rocks [*Munizaga et al.*, 1988; *Pankhurst et al.*, 1992, 1999; *Rolando et al.*, 2002; *Rapela et al.*, 2005; *Castro et al.* 2011]. South of 39°S, this batholith shows a Miocene to Recent steep N-S exhumation gradient [*Glodny et al.*, 2008] that continues across the LOFZ, reflecting a rapid exhumation at the internal parts of the orogen [*Glodny et al.*, 2008]. This fault system is a strike-slip crustal structure where seismicity is concentrated, whose focal mechanisms confirm wrench dynamics (Figure 3) [*Lavenu and Cembrano*, 1999; *Quezada and Bataille*, 2008; *Lange et al.*, 2008].

[11] The eastern slope of the Andes is formed by the eastern continuation of the Patagonian Batholith, locally intruding a Late Paleozoic basement (Figure 2) [*Pankhurst et al.*, 1992] that is thrust over thick Mesozoic volcaniclastic successions (Figure 3) [*Giacosa et al.*, 2001; *Tobal et al.*, 2012]. This region forms the internal part of the North Patagonian fold and thrust belt, developed mainly in the eastern slope of the Andes at these latitudes (Figure 2, 3 and 4). Deformation in this section is characterized by east-vergent thick-skinned thrusts [*Ramos and Cortés*, 1984; *Giacosa et al.*, 2001] that emplaced Jurassic, Cretaceous, and Cenozoic granitoids in the hinterland zone [*Petersen and González Bonorino*, 1947; *Basei et al.*, 1999; *Giacosa et al.*, 2001, 2005]. Sparse roof pendants of Lower Jurassic volcano-sedimentary successions are engulfed in these plutonic rocks [*González Bonorino*, 1944; *Miró*, 1967; *González Bonorino*, 1974; *Thiele et al.*, 1978; *Lizuaín*, 1980; *Diez and Zubia*, 1981; *Giacosa et al.*, 2001]. Most of the exposed rocks east of the Patagonian batholith are late Early Cretaceous volcanic rocks of the Divisadero Group that unconformably overlie volcaniclastic Jurassic successions and occasionally are intruded by Late Cretaceous granitoids [*Sepúlveda and Viera*, 1980; *Lizuaín*, 1987]. Their composition is calc-alkaline, related to the activity of a magmatic arc [*Skármeta and Charrier*, 1976; *Ramos*, 1982]. Neogene sedimentary rocks are scarce, being the isolated Cerro Plataforma sequence, the only Neogene sedimentary accumulation, developed in the main Andes at the study area (Figure 4). To the east, in the eastern slope of the main Andes, the broader depocenter of the El Bolson subbasin is developed (Figure 4) [*Giacosa and Heredia*, 2004b].

[12] To the east, a Precordilleran system is characterized by a substantially different geology. Widespread outcrops of Upper Paleozoic rocks [*Varela et al.*, 2005; *Pankhurst et al.*, 2006], intruded by Early Jurassic granitoids (Figure 4) [*Gordon and Ort*, 1993] contemporaneous with the clastic successions cropping out to the west, are the most important lithologies. This configuration has led *Giacosa et al.* [2001] to propose an Early Jurassic intraarc basin developed between two arcs. One arc being preserved in volcanic facies at the main Andes, while the roots of an outer arc are exhumed in the Precordilleran system. Middle Jurassic to Cretaceous volcanic and sedimentary successions unconformably overlie Early Jurassic rocks and the Paleozoic basement (Figure 4). South of ~42°S these Middle Jurassic to Cretaceous volcanic rocks reach a wider development over the foreland zone (Figures 2 and 4) [*Lizuaín*, 1987; *Giacosa and Heredia*, 1999]. Late Oligocene volcanic successions (33–23 Ma) are developed in the Precordilleran system along a north to south trending belt (Figure 4). Their composition is calc-alkaline to tholeitic, related to the activity of an expanded arc at these latitudes over a relatively thin crust [*Rapela et al.*, 1988].

[13] The main Neogene clastic depocenters are displaced to the east of the main Andes-restricted exposures, partly covering the eastern Precordilleran system (Figure 4). These occupy two basins, the lacustrine to fluvial Ñirihuau basin of late Oligocene to Miocene age [*Cazau et al.*, 1989; *Mancini and Serna*, 1989; *Paredes et al.*, 2009] and the fluvial, lacustrine to pyroclastic Collón Curá basin of middle to late Miocene age [*Mazzoni and Benvenuto*, 1990]. These successions unconformably overlie the basement at the foreland area, which is composed of igneous and metamorphic Upper Paleozoic rocks covered by Paleocene to Eocene bimodal volcanic successions [*Mazzoni et al.*, 1991; *Rapela et al.*, 1988; *Wilf et al.*, 2010].

3. Geology of the Study Area

3.1. Eastern Slope of the Main Andes and Precordilleran System

[14] The western part of the study area (Figure 4), where the main Andes are developed, exhibits an abrupt relief influenced largely by Plio-Pleistocene glacial erosion [*Thomson*, 2002; *Adriasola et al.*, 2006]. Through these deep valleys, above the line of vegetation cover, extensive outcrops of Jurassic to Cretaceous calc-alkaline granitoids

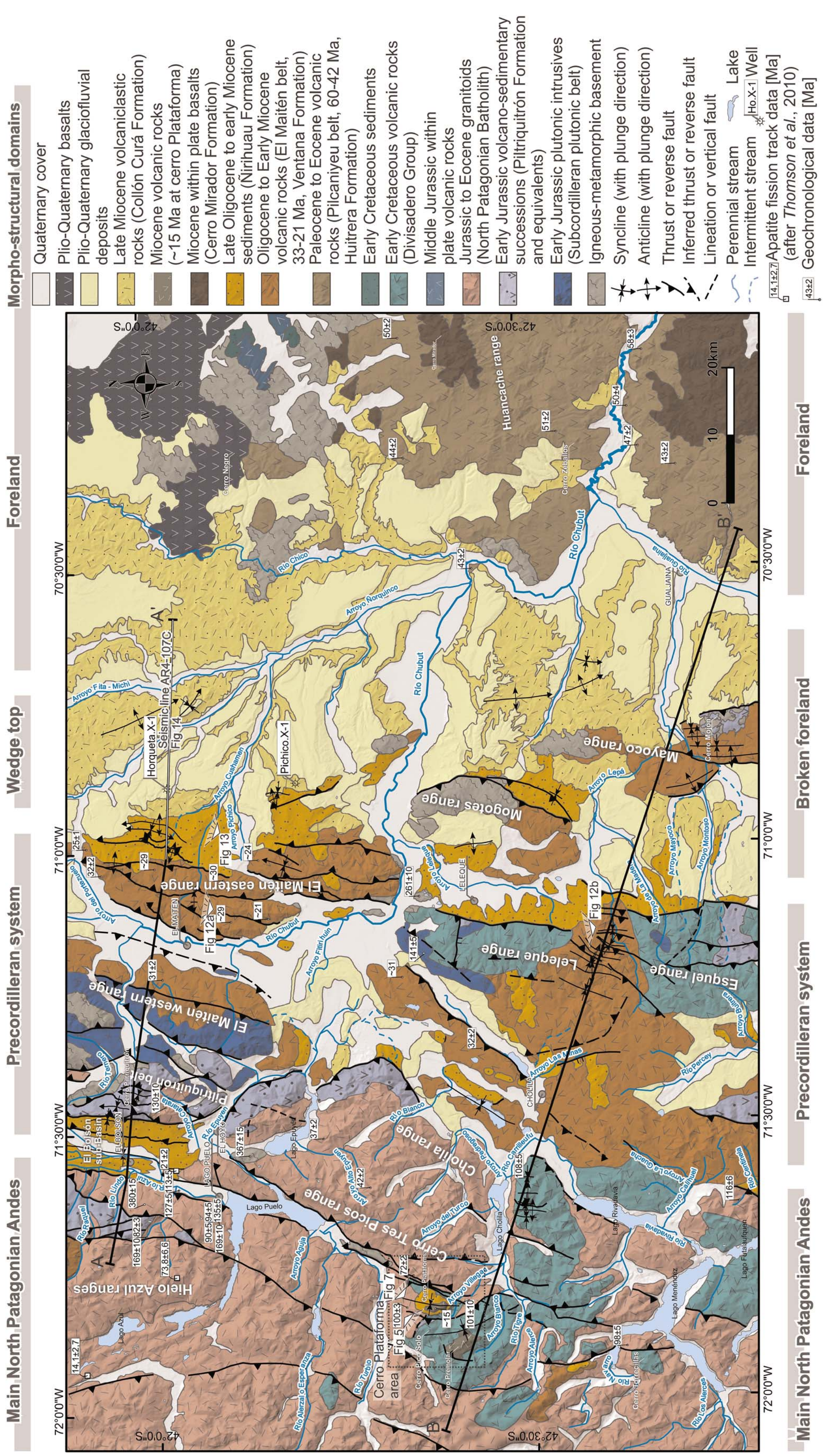

Morpho-structural domains
Quaternary cover
Plio-Quaternary basalts
Plio-Quaternary glaciofluvial deposits
Late Miocene volcaniclastic rocks (Collón Curá Formation)
Miocene volcanic rocks (~15 Ma at cerro Plataforma)
Miocene within plate basalts (Cerro Mirador Formation)
Late Oligocene to early Miocene sediments (Ñirihuau Formation)
Oligocene to Early Miocene volcanic rocks (El Maitén belt, 33-21 Ma, Ventana Formation)
Paleocene to Eocene volcanic rocks (Pilcaniyeu belt, 60-42 Ma, Huitrera Formation)
Early Cretaceous sediments
Early Cretaceous volcanic rocks (Divisadero Group)
Middle Jurassic within plate volcanic rocks
Jurassic to Eocene granitoids (North Patagonian Batholith)
Early Jurassic volcano-sedimentary successions (Piltriquitrón Formation and equivalents)
Early Jurassic plutonic intrusives (Subcordilleran plutonic belt)
Igneous-metamorphic basement
Syncline (with plunge direction)
Anticline (with plunge direction)
Thrust or reverse fault
Inferred thrust or reverse fault
Lineation or vertical fault
Perennial stream
Intermittent stream
Lake
Well
Apatite fission track data [Ma] (after Thomson et al., 2010)
Geochronological data [Ma]
Main North Patagonian Andes
Precordilleran system
Wedge top
Foreland
Broken foreland
Hielo Azul ranges
Cerro Tres Picos range
Cholila range
Piltriquitrón belt
El Maitén western range
El Maitén eastern range
Leleque range
Esquel range
Mogotes range
Mayoco range
Huancache range
Cerro Plataforma area
Horqueta X-1
Seismic line AR4-107C
Pichico X-1
Río Chubut
Río Chico
Lago Puelo
Lago Cholila
72°0'0"W
71°30'0"W
71°0'0"W
70°30'0"W
42°0'0"S
42°30'0"S
20km

Figure 4

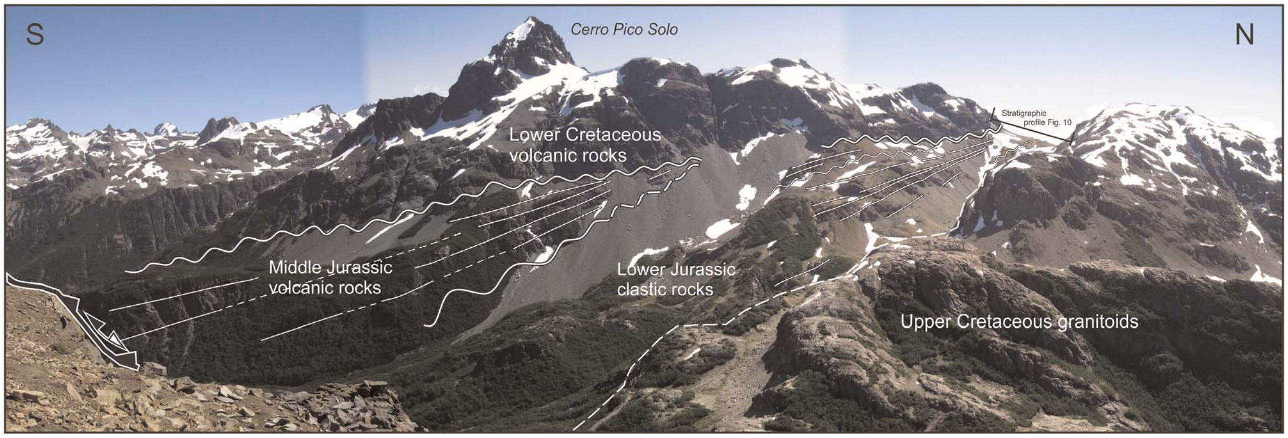


Figure 5. Geology at the eastern slope of the main North Patagonian Andes represented by Mesozoic and Cenozoic units cropping out in Cerro Pico Solo (see Figure 4 for location). Note underlying synextensional growth strata represented by progressive angular unconformities in a clastic succession of Early Jurassic age (see detrital zircon analyses section related to this). Middle Jurassic volcanic rocks are covering the underlying successions showing half-graben geometries as well. These are unconformably overlain by late Early Cretaceous volcanic rocks of the Divisadero Formation, dated at 101 ± 10 Ma at this locality [*Lizuaín*, 1987]. This entire package is in tectonic contact with Jurassic to Cretaceous granitoids corresponding to the North Patagonian Batholith dated by *Gordon and Ort* [1993] at this site.

are observed as the predominant rocks [*Gordon and Ort*, 1993; *Rapela et al.*, 2005; *Hervé et al.*, 2007b] (Figure 4). Jurassic rocks are thick marine, volcanic, and volcaniclastic successions up to ~2,000 m thick [*Miró*, 1967; *Lizuaín*, 1980]. These strata appear as roof pendants or are lying in tectonic contact with the plutonic rocks of the Cordilleran Batholith, as well as thrust over Tertiary units at the eastern edge of the main Andes. In this domain these rocks show a sparse distribution, through a NNW depocenter, from Cerro Piltriquitrón in the Precordilleran system to the east toward the inner parts of the main Andes (Figure 4). The age of these sequences was assigned to the Jurassic based on their paleontological content (see *Lizuaín*, 1980) and intrusive relationships with Early Cretaceous granitoids that yielded a minimum age [*González Díaz and Lizuaín*, 1984; *Giacosa et al.*, 2001].

[15] Particularly, west of the Cerro Plataforma area, in the Cerro Pico Solo eastern slope, an isolated outcrop composed of Jurassic volcano-sedimentary rocks has been identified in this study (Figure 5). These sedimentary packages are separated by an angular unconformity from the overlying Early Cretaceous volcanic lavas and breccias of the Divisadero Group (Figure 5). These rocks consist of a cyclical succession of limestone beds, quartz-feldspar sandstones, conglomeratic sandstones, and volcanic breccias (Figure 6). Similar successions that crop out further north were studied by *Spalletti et al.* [2010] who obtained U-Pb SHRIMP ages from a tuff of 191.7 ± 2.8 Ma, interbedded in mudstones, siltstones and coarse to pebbly sandstones of Piedra del Aguila Formation. This succession, identified at the Pico Solo locality, is thrust over 100 ± 3 and 72 ± 2 Ma granitoids by two reverse faults N60°W and N-S oriented [*Lizuaín*, 1979; *Gordon and Ort*, 1993]. The lower sedimentary succession exhibits a complex internal architecture that we interpreted as a synrift wedge (Figure 5). These strata thicken toward the N-S-oriented subvertical fault that thrusts the Early Jurassic successions over Cretaceous granitoids. This is interpreted as an inverted normal fault, where progressive angular unconformities accommodated synextensional sedimentation. A sample from the base of this succession was collected from a coarse-grained sandstone strata for U-Pb (LA-ICP-MS; analyses conducted at Washington State University) geochronology on detrital

Figure 4. Geological map of the study area located in the North Patagonian fold and thrust belt and southern portion of the late Oligocene to middle Miocene Ñirihuau and Collón Curá basins. Geology is based on new mapping and adaptation of previous works in the area [*Petersen and González Bonorino*, 1947; *Volkheimer*, 1973; *González Bonorino*, 1979; *Volkheimer and Lage*, 1981; *Lage*, 1982; *Lizuaín*, 1983; *Giacosa and Heredia*, 2004b]. Note three clear domains: the main Andes in the western part, and to the east the Precordilleran system and the foreland area. The main Andes are characterized by Jurassic to Cretaceous granitoids [*Hervé et al.*, 2007b; *Castro et al.*, 2011] intruding Mesozoic volcaniclastic successions [*Skármeta and Charrier*, 1976; *Ramos*, 1982; *Suárez and de la Cruz*, 2001; *Suárez et al.*, 2009] and localized Neogene sequences. The Precordilleran system is formed by Paleozoic sequences [*Pankhurst et al.*, 2006; *Varela et al.*, 2005], intruded by Early Jurassic granitoids [*Gordon and Ort*, 1993], unconformably covered by Middle Jurassic to Cretaceous and Tertiary successions [*Lizuaín*, 1987; *Rapela et al.*, 1988]. Available radiometric ages of igneous and volcanic units are also displayed [*González Díaz*, 1982; *Lizuaín*, 1983; *Rapela et al.*, 1988; *Cazau et al.*, 1989; *Mazzoni et al.*, 1991; *Gordon and Ort*, 1993]. Locations of 2D seismic reflection profiles, borehole data, and the present structural cross sections A-A′ (Figure 15) and B-B′ (Figure 16) are depicted.

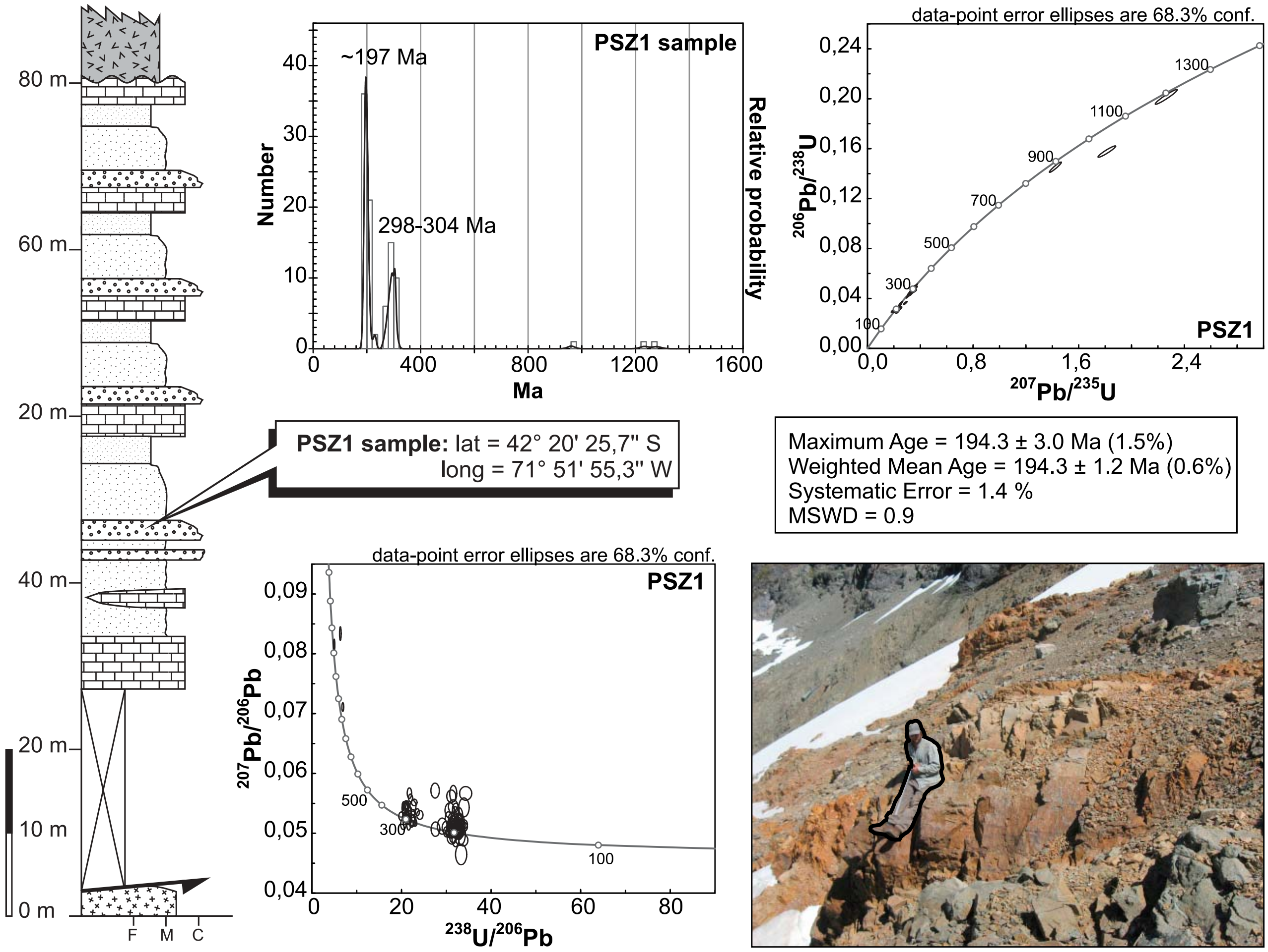


Figure 6. Age distribution curves and histograms depicting detrital zircon U-Pb ages and concordia diagrams depicting $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ data for zircon grains corresponding to the coarse sandstone of Early Jurassic syngrowth strata depicted in Figure 5 (sample PSZ1). Lower right corner shows an outcrop in the sample area of limestones and interbedded sandstones (person for scale). Note a younger population of 194.3 ± 3.0 Ma age assigned to the maximum sedimentation age. Note also an important 298–304 Ma population represented in the region by a metamorphic source exposed to the north in the Main North Patagonian Andes and to the east in the western Precordilleran region [*Basei et al.*, 1999] (see Figure 4).

zircons (Figure 6) (see auxiliary material for complete data set and methodology details).[1]

[16] The U/Pb ages obtained for this succession are shown in Figure 6. The youngest peak of 197 Ma is considered the maximum sedimentation age for these deposits. This age is fairly similar to that obtained by *Spalletti et al.* [2010] in correlative strata to the north. Older populations are centered around 298–304 Ma, which implies a Late Paleozoic source that could be located along the axis of the main North Patagonian Cordillera (Figure 2) as well as in the Precordilleran region (Figures 2, 4 and 7).

[17] These rocks are unconformably overlain by andesites and rhyolitic ignimbrites of the Divisadero Group (Figure 5) that have been dated as 101 ± 10 Ma by *Lizuaín* [1987] at the adjacent arroyo Villegas locality and as 108 ± 2 Ma at the Cholila locality by *Rapela et al.* [1988] (Figure 4).

[18] To the east, the Cerro Plataforma (Figure 4) is formed by a basal section of Late Cretaceous granitoids [*Gordon and Ort*, 1993] that locally intrude volcanic strata of the Divisadero Group. These rocks are unconformably covered by 450 m of early middle Miocene marine clastic and volcanic rocks (Figure 8b) whose age was initially inferred based on their paleontological content [*Lizuaín*, 1979; *Griffin et al.*, 2002]. The uppermost volcanic succession (Figure 8b) was subsequently dated by *Lizuaín* [1983] as 15 Ma (K/Ar), indicating a minimum age for the lower sedimentary deposits. The volcanic succession also crops out west of the Plataforma area in the Cerro Premolar, where they are strongly deformed (Figure 8a). Neogene strata are preserved in syncline cores (Figure 8). The thickest column is preserved in the Cerro Plataforma at the syncline axis and western flank (Figures 9a and 9b), narrowing toward its eastern flank. Onlap relationships can be observed at both flanks, implying ongoing contraction at the time of sedimentation (Figures 9c–9f). Therefore, this narrowing is

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/tc/2011tc003084. Other auxiliary material files are in the HTML. doi:10.1029/2011TC003084.

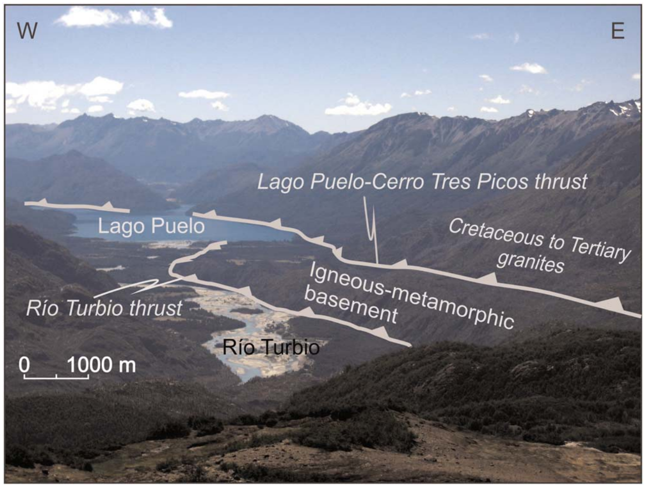


Figure 7. Backthrusts in the Lago Puelo-Cerro Plataforma area that are uplifting the Paleozoic basement and Cretaceous to Cenozoic granites of the Cerro Tres Picos (see Figure 4 for location).

interpreted as related to syncline development at the time of sedimentation. Maximum sedimentary thicknesses have been found next to the Cerro Pico Solo thrust that uplifts Mesozoic successions to the west (Figure 9). This is here interpreted as a Neogene thrust front associated with a frontal foredeep that was later cannibalized.

[19] The Miocene marine succession at the Cerro Plataforma consists of 300 m of fossiliferous sandstones, siltstones, and minor conglomerates that form two parasequences in an overall coarsening-upward arrangement. The succession from base to top comprises (Figure 10): i) A basal interval 50 m thick of massive and through-cross bedded coarse to very coarse sandstones and minor conglomerates. Facies characteristic of this interval were deposited during the initial stage of the marine transgression in the area and are typical of the upper shoreface [*Clifton*, 2006]. ii) This interval is followed by a 30 m thick succession of dark siltstones and very fine sandstones with fossils of planktic foraminifers, gastropods, and echinoderms. This facies is characteristic of the shelf and was deposited during a relative sea level rise [*Clifton*, 2006]. iii) A partially covered interval with interbedded siltstones and sandstones that probably represent inner shelf-lower shoreface transitional deposits crop out locally. iv) A 70 m thick interval of coarse- to medium-grained sandstones with large-scale cross-bedding with sets showing different orientations. Undetermined burrows were observed at the top of the succession. These facies represent upper shoreface deposits [*Clifton*, 2006]. Molds of marine macrofossils are abundant in the upper part of this interval. They were studied by *Griffin et al.* [2002] who correlated them with faunas of the Monte León and Chenque Formations that crop out along the eastern coast of Patagonia and were deposited by an Atlantic marine transgression. v) A partially covered interval follows. It consists of an incomplete succession of fine- to medium-grained fossiliferous sandstones, siltstones, and fine-grained sandstones with convolute and parallel lamination, and coarse-grained sandstones that pass upwardly to cross-bedded pebble conglomerates with volcanic clasts. vi) Overlying the conglomerates, a 170 m thick volcano-sedimentary succession follows. It consists of centimeter to meter thick strata of crystalline and lithic tuffs, andesitic lava flows, and minor sandstones (Figures 9c and 9d). This volcanic succession was dated by *Lizuaín* [1983] at 15 Ma. The marine and volcano-sedimentary successions are conformable. These sequences are cut by basaltic feeder dykes that radiate from moderate size intrusives that constitute the last subvolcanic pulses in the area.

[20] U/Pb ages have been obtained for two locations along the clastic succession of Cerro Plataforma (Figure 10). The lower sample (CPL) corresponds to the second identified sand package. The ages obtained at this level show three main peaks, two corresponding to an Early Cretaceous source, and an older one to the Late Paleozoic (Figure 11). The last has a mean peak around 304 Ma, coincident with the one recorded in Early Jurassic clastics immediately to the west (Figure 6). This implies a common source from the Early Jurassic to Neogene times that could be both a western Andean source as depicted in Figure 2 and an eastern Andean

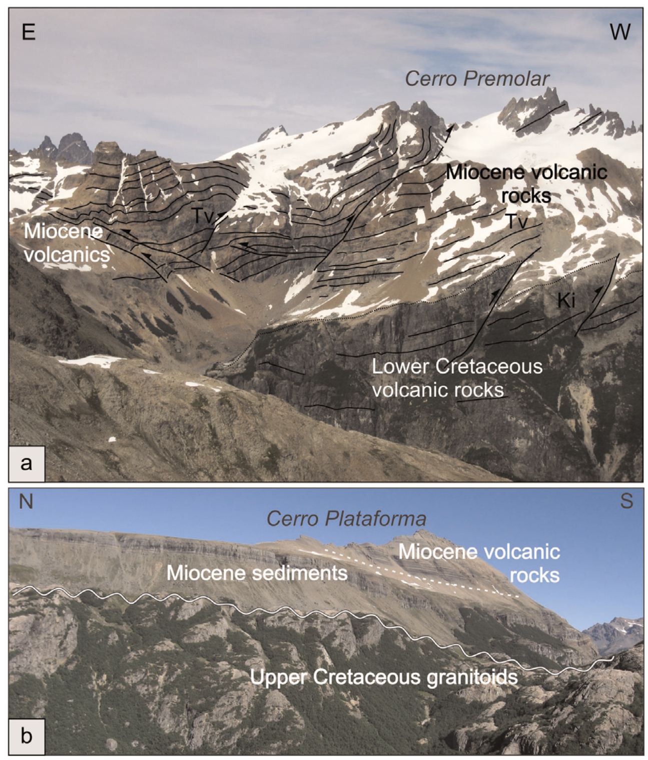


Figure 8. (a) Miocene volcaniclastic rocks lying conformably over late Early Cretaceous rocks of the Divisadero Group. Their age has been determined by K/Ar dating at 15 Ma in the Cerro Plataforma immediately to the west [*Lizuaín*, 1983]. Note the important deformation in the upper units. (b) East of Figure 8a in the west flank of Cerro Plataforma (see Figure 4 for location), these Miocene volcanic rocks conformably overlie marine Cenozoic deposits of the Ñirihuau Formation [*Spalletti*, 1983; *Lizuaín*, 1979], and these are in turn placed over an important erosional surface over Cretaceous granitoids implying a Late Cretaceous-Oligocene episode of exhumation. These Cenozoic deposits constitute the westernmost outcrops of the Ñirihuau basin at these latitudes.

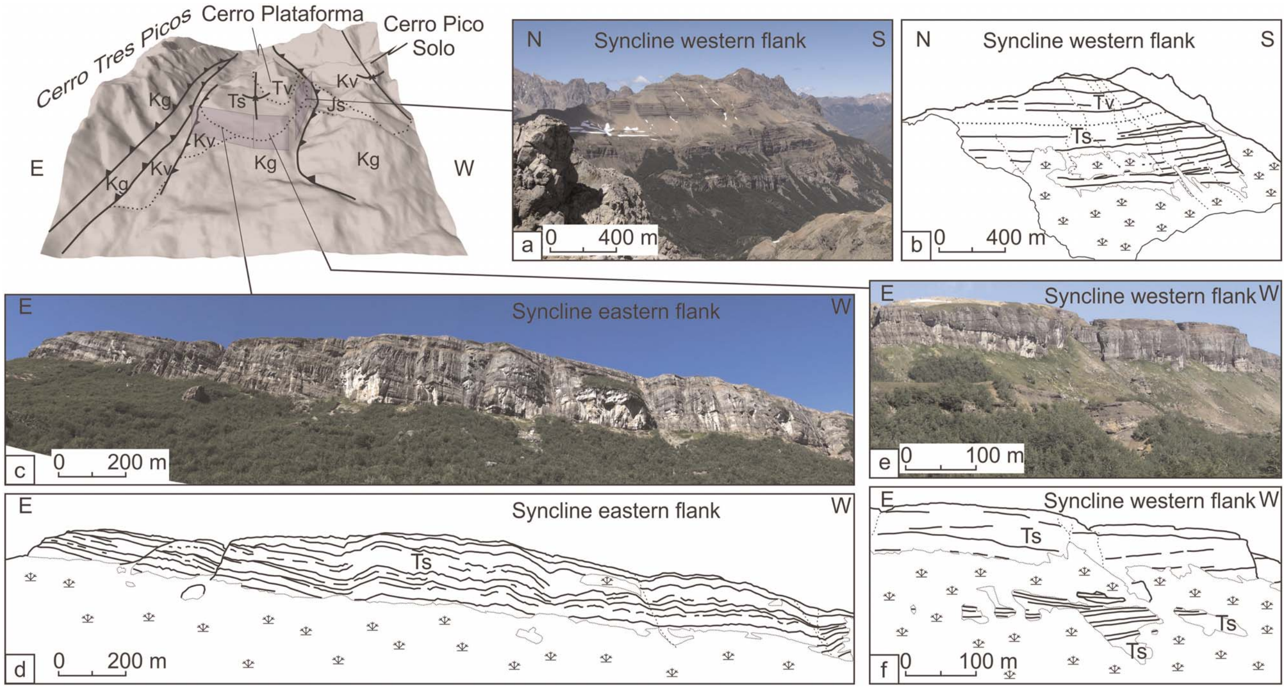


Figure 9. Progressive unconformities as seen in clastic sections of the Ñirihuau Formation, in both limbs of the Cerro Plataforma syncline (see Figure 4 for location) (upper left corner; see Figures 9a–9f for location): (a, b) Southwestern flank seen from the NW where onlap relations are visible underlying Miocene volcaniclastic successions; (c, d) eastern and (e, f) western flanks where thickening of sandstone packages toward the syncline core is described as well as onlap relationships toward the flanks. JS: Early and Middle Jurassic successions; Kg: Cretaceous granitoids; Kv: Divisadero Group; Ts: Ñirihuau Formation; Tv: Miocene volcaniclastic rocks.

source (Figure 7), both sources at a distance shorter than 30 km. The other two sources are centered around 112 and 126 Ma, ages typical of the Divisadero Group exposed immediately to the west and south in the Cerro Pico Solo and Lago Cholila [*Lizuaín*, 1987; *Rapela et al.*, 1988]. The uppermost sample (CPU) was taken from the last sandstone package, just below the conglomeratic level that constitutes the base of the overlying volcanic succession (Figure 10). In this sample, medium age sources show four main peaks, the first three already identified in the lower section plus a new one centered around 18.3 ± 0.6 Ma. This age was obtained through the TuffZirc algorithm from the Isoplot software [*Ludwig*, 2008] applied to a coherent group of nine idiomorphic zircons. This age is taken as the maximum sedimentation age, implying that the base of the marine succession should be slightly older. The other populations are again centered around the Early Cretaceous and Late Carboniferous, inverting the lower sample proportions. This indicates that the Late Carboniferous source diminished, while the Early Cretaceous one rose toward the top, suggesting a progressive cannibalization of the Neogene depocenter and creation of Andean barriers to the sediment supply of the marine incursion.

[21] The Precordilleran region, east of the main Andean domain, comprises four main mountain systems. From north to south: western and eastern El Maitén, Mogotes, Gualjaina, and Leleque ranges (Figure 4). The western El Maitén range is characterized by Paleozoic rocks intruded by Mesozoic granitoids that are unconformably overlain by Jurassic to Tertiary volcanic rocks. The eastern El Maitén range in turn presents a younger cover that overlies a Paleozoic basement. This coverage consists of Oligocene-earliest Miocene volcanics (33–21 Ma) dated by *Cazau et al.* [1989] (see also *Mancini and Serna* [1989], for a compilation). To the south, along the same structural trend, the Mogotes range is characterized by broader Paleozoic exposures covered by Oligocene to Miocene volcanic rocks. The southernmost Precordilleran sector in the study region corresponds to the Leleque range in the west and the Gualjaina range to the east (Figure 4). These systems are characterized by a geology similar to that seen to the north, corresponding to Paleozoic rocks intruded by Early Jurassic granitoids and unconformably covered by Mid Jurassic-Early Cretaceous to Cenozoic volcanic rocks.

[22] The Oligocene to Miocene coverage of volcanic rocks in the Precordilleran region has some peculiar characteristics. These, >1,500 m thick successions, consist of andesites and dacites with lesser amounts of rhyolite and basalts [*Rapela et al.*, 1988]. The complete sequence has been described by *González Bonorino and González Bonorino* [1978] to the north, where the basal section is composed of thick packages of andesites followed by breccias, ignimbrites, and tuffs with minor lenses of clastics. To the south, in the study region, the sequence is more homogeneous, starting with andesites that grade into ignimbrites toward the top [*Ramos et al.*, 2011]. Thicknesses are variable, corresponding to wedge-like geometries such as the ones depicted in Figure 12 found in the Leleque and El Maitén ranges. From these observations, these can be interpreted as synextensional (Figure 12).

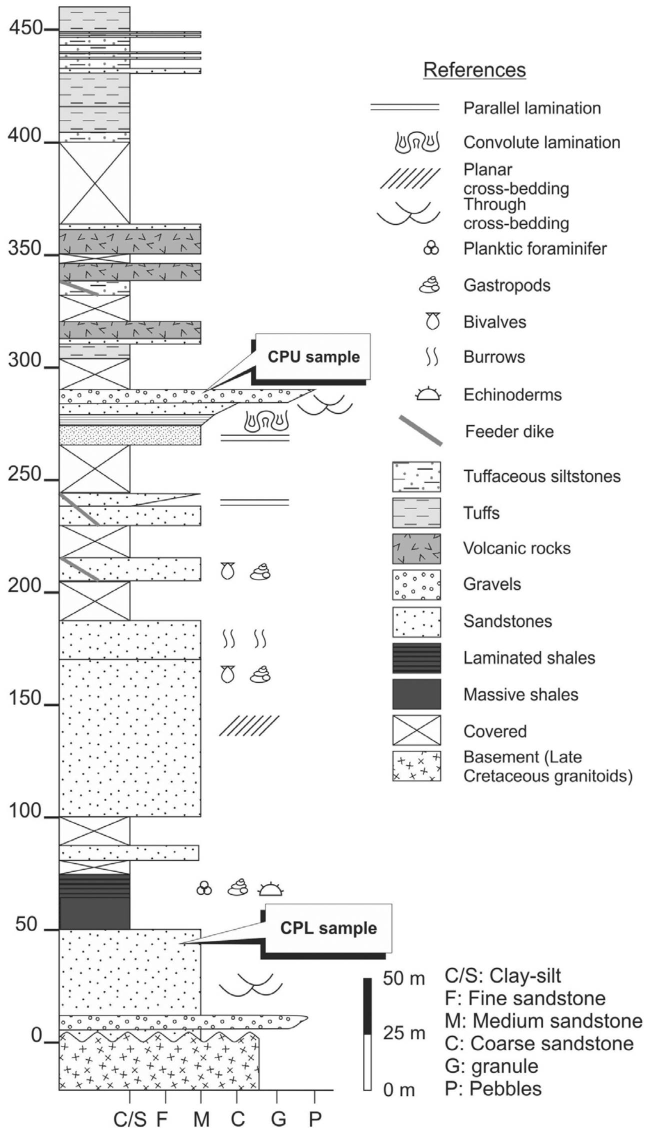


Figure 10. Stratigraphic profile of the sedimentary and volcanic cover of Cerro Plataforma (see Figures 4 and 8). Note that two main sections can be recognized, a lower marine clastic succession and an upper tuffaceous section interfingered with lava flows.

3.2. Geology of the Wedge-Top and Foreland Area

[23] The wedge-top is located between the Precordilleran system and the foreland area (Figure 4). Here, Miocene synorogenic strata were deposited in a broad flat zone next to the Precordilleran eastern slope [*Giacosa et al.*, 2005]. Two different areas where the synorogenic wedge has been differentially cannibalized by the advancing deformation front, can be differentiated north and south of the Chubut river (Figure 4). Whereas the wedge-top area is characterized by up to 2,000 m of Miocene strata of the Ñirihuau and Collón Curá Formations in the northern section [*Giacosa et al.*, 2005], to the south a series of basement uplifts have led to erosion and condensation of the Neogene cover and exposure of the Late Paleozoic rocks.

[24] The Miocene Ñirihuau Formation is exposed east of the El Maitén range and comprises a basal interval of shales, sandstones, and coal deposited in a lacustrine environment. Toward the top of this unit, fluvio-lacustrine and volcaniclastic levels of reworked fluvial deposits and ashfall layers crop out. On top, Gilbert delta lobes have prograded in a lacustrine environment that passes upwardly into a high energy fluvial setting [*Ramos et al.*, 2011]. *Cazau et al.* [1989] obtained an age of 21 Ma for the Ñirihuau Formation in a locality north of the study area. The lower section has received different formal designations, corresponding to equivalents of the Ñirihuau and Ñorquinco Formations, and constitutes a partial age equivalent to the strata described in the main North Patagonian cordillera (Cerro Plataforma), although it differs in its paleoenvironment.

[25] The upper successions are denominated as the Collón Curá Formation and have been dated by *Cazau et al.* [1989] and *Mazzoni and Benvenuto* [1990] at 16–11 Ma. These are tuffs, fluvial, and lacustrine deposits locally interfingered with ignimbrites. These two sections show particular internal geometries next to the Precordilleran emergent front (Figure 4) that are interpreted as progressive angular unconformities. These are found from the lower segments of the Ñirihuau Formations to the lower segments of the Collón Curá Formation (Figure 13) [*Ramos et al.*, 2011].

[26] These progressive unconformities have also been identified in seismic sections that were recorded across the wedge-top area at the eastern slope of the El Maitén range (Figure 14). Here one seismic line tied to borehole data allows identification of the two mentioned sedimentary packages at depth beneath Pleistocene glaciofluvial deposits. Over the eastern buried flank of the El Maitén range, formed by basement east-verging structures, there is a series of thin-skinned back thrusts. These are associated with growing structures at their back limbs that show progressive unconformities in the Collón Curá Formation. To the east along this line, progressive unconformities are interpreted in the lower segments of the Ñirihuau Formation in the frontal limb of an identified west-vergent antiform (Figure 14).

4. Shortening Mechanisms Along the Fold and Thrust Belt

[27] In order to evaluate the different mechanisms involved in the deformation of the described units two regional structural cross sections have been constructed (Figures 15 and 16) using field data at the hinterland zone plus seismic and borehole data in the wedge-top area (Figure 4). The northernmost section (A-A′, Figure 15; see Figure 4 for location) is constructed from the main North Patagonian cordillera, in the Hielo Azul range to the foreland zone, east of the arroyo Fita-Michi in a W-E direction, while the southernmost section (B-B′, Figure 16; see Figure 4 for location) is more oblique, going from the Cerro Pico Solo in the main North Patagonian cordillera to the town of Gualjaina (Figure 4). This last orientation was chosen to highlight the NE-SW oriented structures at the Precordilleran region in the Leleque range.

[28] Thus, the two structural cross sections are characterized by broad antiforms that can only be explained by thick-skinned deformation. Furthermore, the main North

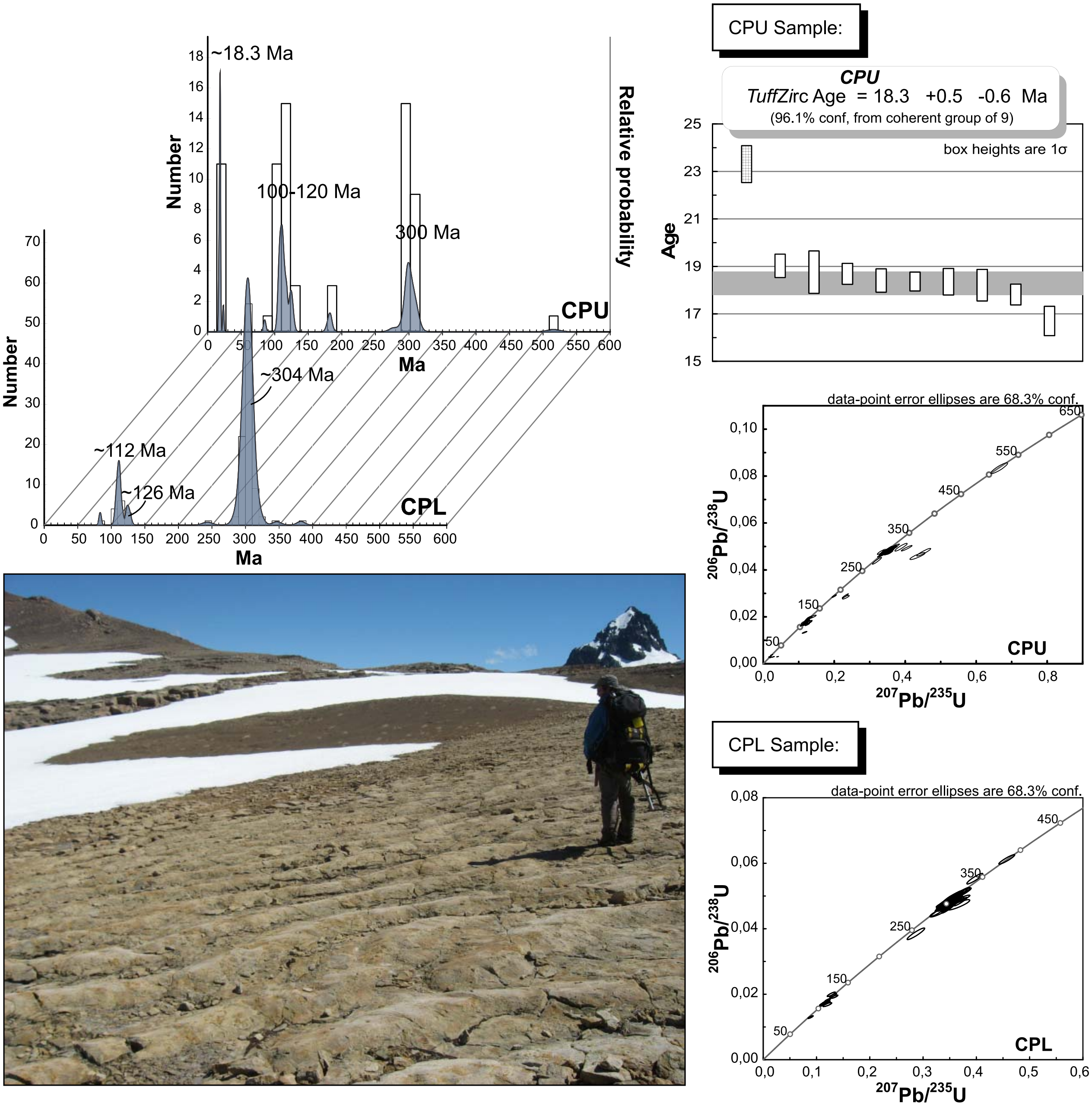


Figure 11. U/Pb detrital zircon ages for the marine strata at Cerro Plataforma (see Figure 4 for location). Two localities have been sampled (see Figure 10 for location in a stratigraphic column). Histograms corresponding to basal levels denote a double polarity source characterized by two main populations, a 304 Ma peak described for the Early Jurassic successions in the area (Figure 5) that is fed mainly from the Precordilleran system, and a late Early Cretaceous source corresponding to the Divisadero Group in the Main Andes to the west. Even though a double polarity exists, the eastern source predominates. Upper levels are characterized by an inhibited 304 Ma source and a relatively increased late Early Cretaceous source denoting a predominance of the Main Andean source, in contrast to the lower section. This can be interpreted as a cannibalization of the Tertiary depocenter due to the advancing deformational front. Note also a younger peak at 18.3 Ma interpreted as the maximum sedimentation age for this unit. Upper right corner shows how this value was obtained through a TuffZirc algorithm [*Ludwig*, 2008] applied to a group of nine coherent idiomorphic zircons.

Patagonian Cordillera has a predominant east-vergent structure, whereas the Precordilleran system is a double wedge-vergent thrust system. The wedge-top zone shows different degrees of cannibalization and compartmentalization.

[29] The hinterland zone along the structural cross sections was constructed tying structural data to a topographic profile, determining main structural domains marked by structures and dip changes. Main geometries at this sector

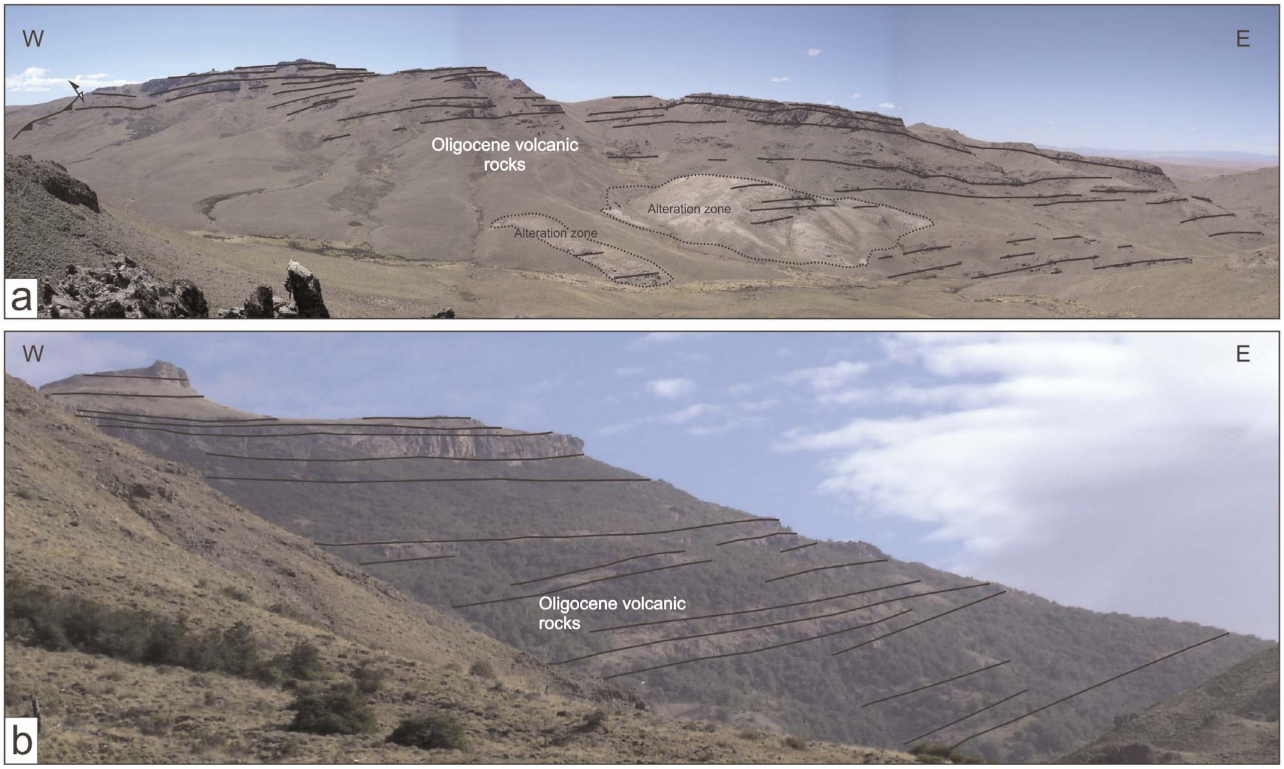


Figure 12. Angular unconformities observed in the Precordillera region in wedge-like volcanic packages: (a) Cordillera de Leleque area and (b) El Maitén Belt location dated at 33–21 Ma (see Figure 4 for location) [*Rapela et al.*, 1988; *Mancini and Serna*, 1989].

were defined from our own data plus previous observations of *Giacosa and Heredia* [2004b] and *Tobal et al.* [2012]. At the wedge-top area the cross section is based on new data, field work by *Ramos et al.* [2011], and seismic and borehole information (Figure 14). The seismic line AR4A-107C was depth converted using velocity intervals coming from the Horqueta.X-1 well log. Once this conversion was performed, a narrow depocenter was defined between two prominent structures with opposite vergency. Well log data show that this depocenter is formed by the superposition of Oligocene to Miocene strata and a thin Quaternary cover of less than 300 m.

[30] Development of the structural profiles was done taking into account thicknesses from field observations at the hinterland zone, combined with previous measurements in the foreland area [*Cazau*, 1980] and depth-converted 2D seismic lines and well-log data. These cross sections were balanced using 2D Move ® software (Midland Valley Ltd.). Their geometry was adjusted through forward and reverse modeling techniques applying flow parallel flow for most of the basement-involved structures. A reverse modeling using the trishear algorithm was done for the wedge-top area to restore the fan of blind faults related to synorogenic sedimentation. The depth to decollement along these sections was in general defined as an average of the different fits from reverse modeling. These consisted in restoring the observed structures over a supposed regional decollement using normal parameters for the specific algorithm of deformation.

[31] The northernmost section (Figure 4) is formed by east-verging structures at the main North Patagonian Cordillera, locally interrupted by a back thrust that folds Early Jurassic sequences in a cannibalized triangular structure (Figure 15). These structures are interpreted as Jurassic inverted normal faults because of the identification of wedge-like geometries of Early and Middle Jurassic age (Figure 4), following the earlier proposal of *Giacosa and Heredia* [2004b]. To the east, the El Bolsón subbasin constitutes the westernmost depocenter of the Miocene foreland basin [*Encinas et al.*, 2011]. This depocenter constitutes another triangular zone transported at the flat top of a deep wedge that inserts beneath the Precordilleran region (Figure 15). This last feature is a doubly vergent system with a deeper exhumed western domain where Late Paleozoic metamorphic and igneous rocks and Early Jurassic volcano-sedimentary sequences are intruded by Jurassic to Cretaceous granitoids. In contrast, the east vergent eastern domain is characterized by late Oligocene to early Miocene volcanic rocks of the Ventana Formation exhumed in the El Maitén range. This structure is dismembered by a fan of east verging blind thrusts and two backthrusts that affect early Miocene clastic successions of the Ñirihuau Formation. The basal part of the overlying Collón Curá Formation presents growth strata developed at the wedge-top of the foreland basin (Figures 13 and 14). The foreland basin to the east is partially cannibalized by a west-vergent basement uplift that condenses the Ñirihuau and Collón Curá Formations over its

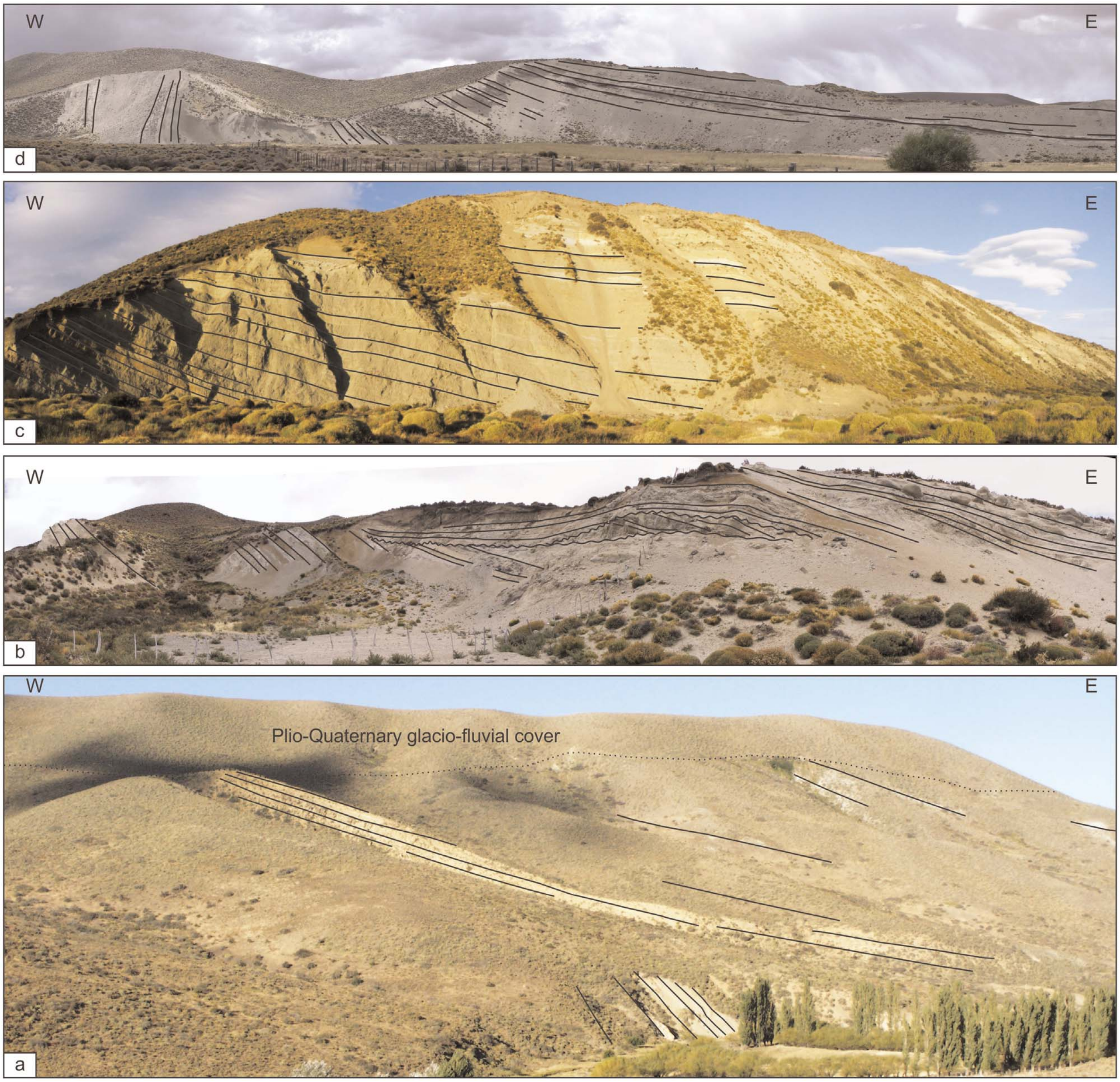


Figure 13. Progressive and regional unconformities corresponding to growth strata (Figures 13a, 13b, and 13c: Ñirihuau Formation; Figure 13d: Collón Curá Formation) at the backlimbs of main structures in the eastern slope of the El Maitén Belt (see Figure 4 for location): (a) Lower section of the early Miocene lacustrine Ñirihuau Formation; (b) Pyroclastic and siliciclastic segments in the mid part of the Ñirihuau Formation showing progressive unconformities; (c) deltaic successions in the upper part of the Ñirihuau Formation with progressive unconformities; (d) basal part of the fluvial Collón Curá Formation of late Miocene age [*Cazau et al.*, 1989; *Mazzoni and Benvenuto*, 1990] showing progressive unconformities.

axial zone. This structure coincides with a regional structure that is uplifting the western North Patagonian Massif as a fan of basement backthrusts, interpreted as pre late Miocene in age [*Coira et al.*, 1975]. Total shortening absorbed through this entire section in pre- and Miocene times is 17 km.

[32] The southernmost section (Figure 4) is also characterized by long-wavelength structures controlled by basement ramps with a predominant east-vergence (Figure 16). In the main North Patagonian Cordillera the level of exhumation is deeper than in the Precordilleran region to the east. Here, Early Cretaceous andesitic rocks [*Lizuaín*, 1987; *Rapela et al.*, 1988] and Middle to Early Jurassic strata (Figure 5) have been uplifted by an east verging fan of basement thrusts that is interrupted by the Tres Picos back thrust system that exposes up to the Upper Paleozoic basement (Lago Puelo-Tres Picos thrust; see Figure 7) [*Petersen and González Bonorino*, 1947].

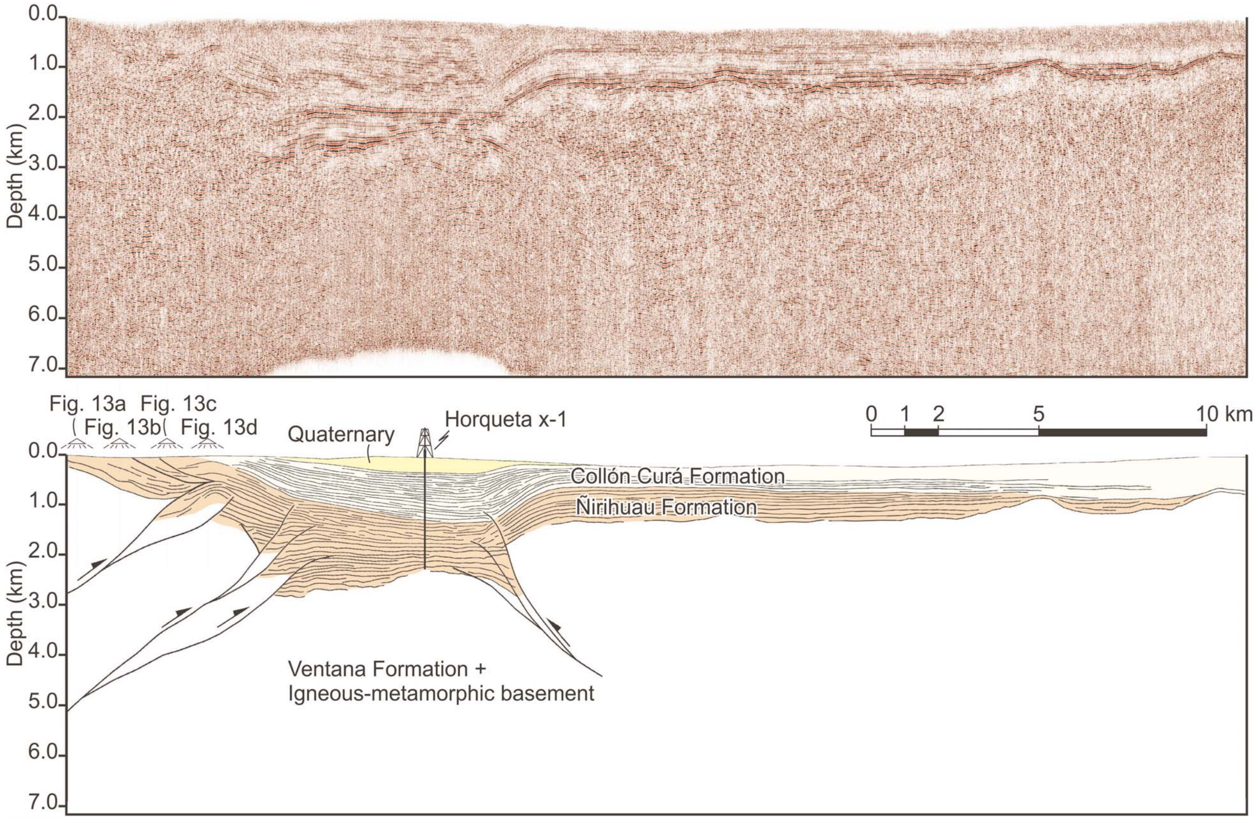


Figure 14. The 2D reflection seismic profile located in the eastern slope of the El Maitén Belt and foreland area, converted to depth using interval velocities provided by borehole data (see Figure 4 for location). Below, corresponding interpretation where a triangle zone is defined hosting synorogenic deposits of the Ñirihuau and Collón Curá basins. Their synorogenic character is defined by onlap reflectors toward the edges of the main depocenter. Note the blind fan of structures corresponding to the eastern El Maitén Belt deforming proximal strata, interpreted as the orogenic front. Note also to the east a greater structure that regionally exhumes the foreland area, interpreted as a broken foreland region beyond the emergent orogenic front. This structure is interpreted to have been active at the time of foreland sedimentation due to the condensation of the Ñirihuau strata and onlap relationships of upper Collón Curá reflectors.

To the west, at the innermost section, the Patagonian batholith is thrust over Cretaceous volcanic successions [*Lizuaín*, 1987; *Gordon and Ort*, 1993]. Basement structures are interpreted as in the previous case as Jurassic inverted normal faults based on wedge-like geometries that characterize the Jurassic succession (Figure 5). A Miocene clastic to volcanic depocenter is shifted over a basement ramp and highly deformed (Figure 8) as a small piggyback basin in this system, indicating a Neogene reactivation of this fan of thrusts. Its maximum age is pre-Miocene based on an angular unconformity between Early Cretaceous volcanic and granitoids and Miocene strata (Figure 8b). The Precordilleran area (Figure 16) is characterized by the occurrence of widespread Oligocene deposits of the Ventana Formation [*Rapela et al.*, 1988]. Field evidence (Figure 12) shows that these depocenters are synextensional in origin. Moreover, orogenic topography has been created by their inversion, producing broad synclines and dismembered antiforms. To the east, an early to late Miocene depocenter is

Figure 15. (a) Balanced cross section on the eastern slope of the Andes from the drainage divide area to the foreland zone across the El Maitén Belt (see Figure 4 for location; A-A′). Note that an inner domain corresponding to the main North Patagonian Cordillera up to the El Bolsón sub-basin (see Figures 3 and 4 for regional location), is formed by two main structures: an out of sequence thrust that exhumed the Patagonian Batholith over older Mesozoic strata, and a frontal thrust that uplifts Mesozoic rocks over Tertiary ones. To the east these deposits hosted in the El Bolsón sub-basin are folded by two blind basement faults. The Precordilleran system is dominated in the west by a back thrust fan that exhumes Paleozoic and Mesozoic rocks, and in the east by east-verging thrusts associated frontally with Miocene synorogenic strata of the Ñirihuau and Collón Curá Formations. Finally, the foreland area is characterized by onlap of synorogenic strata controlled by blind basement structures that break the foreland area. (b) Restored section that has yielded 17 km of shortening at these latitudes.

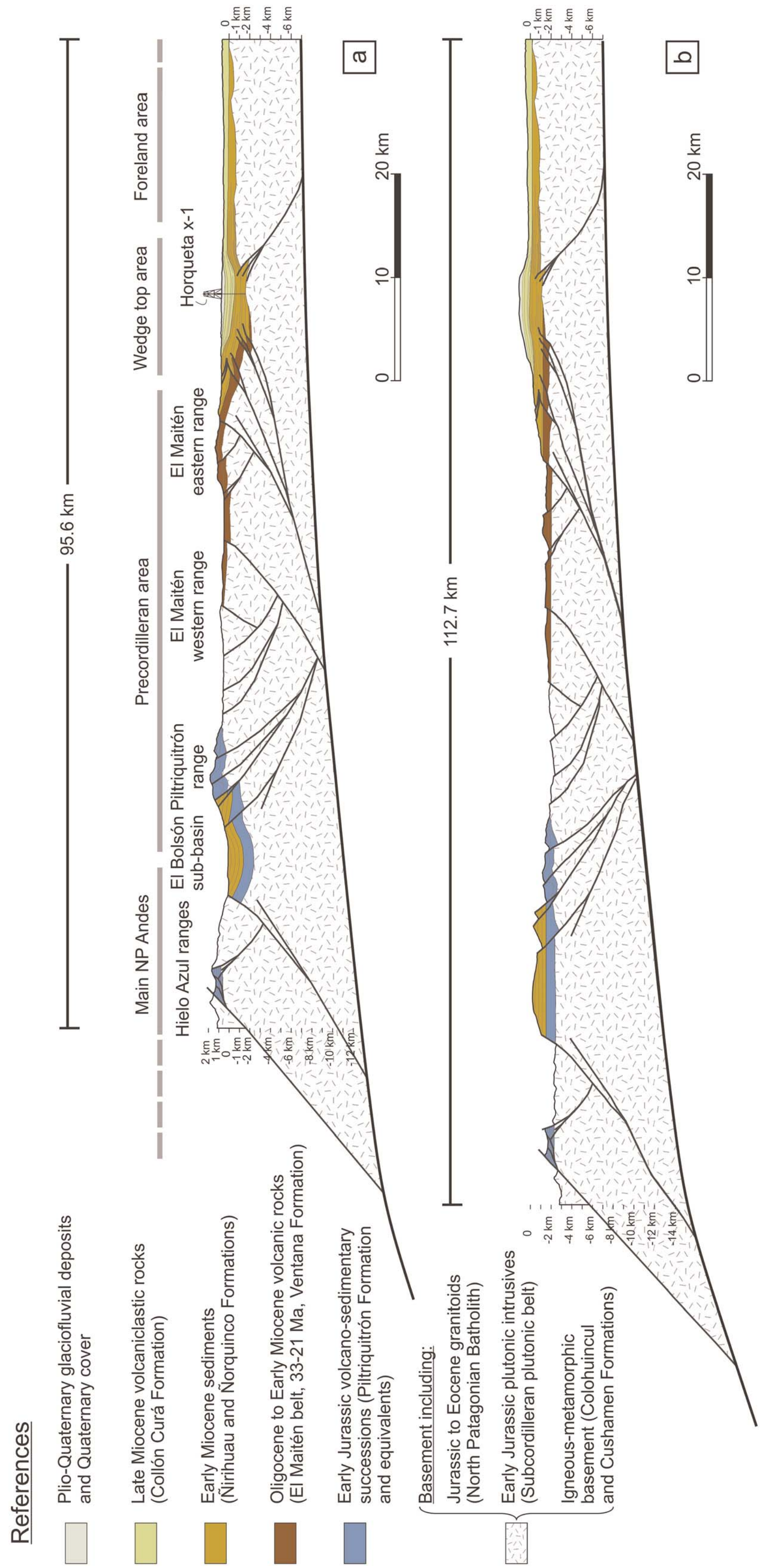
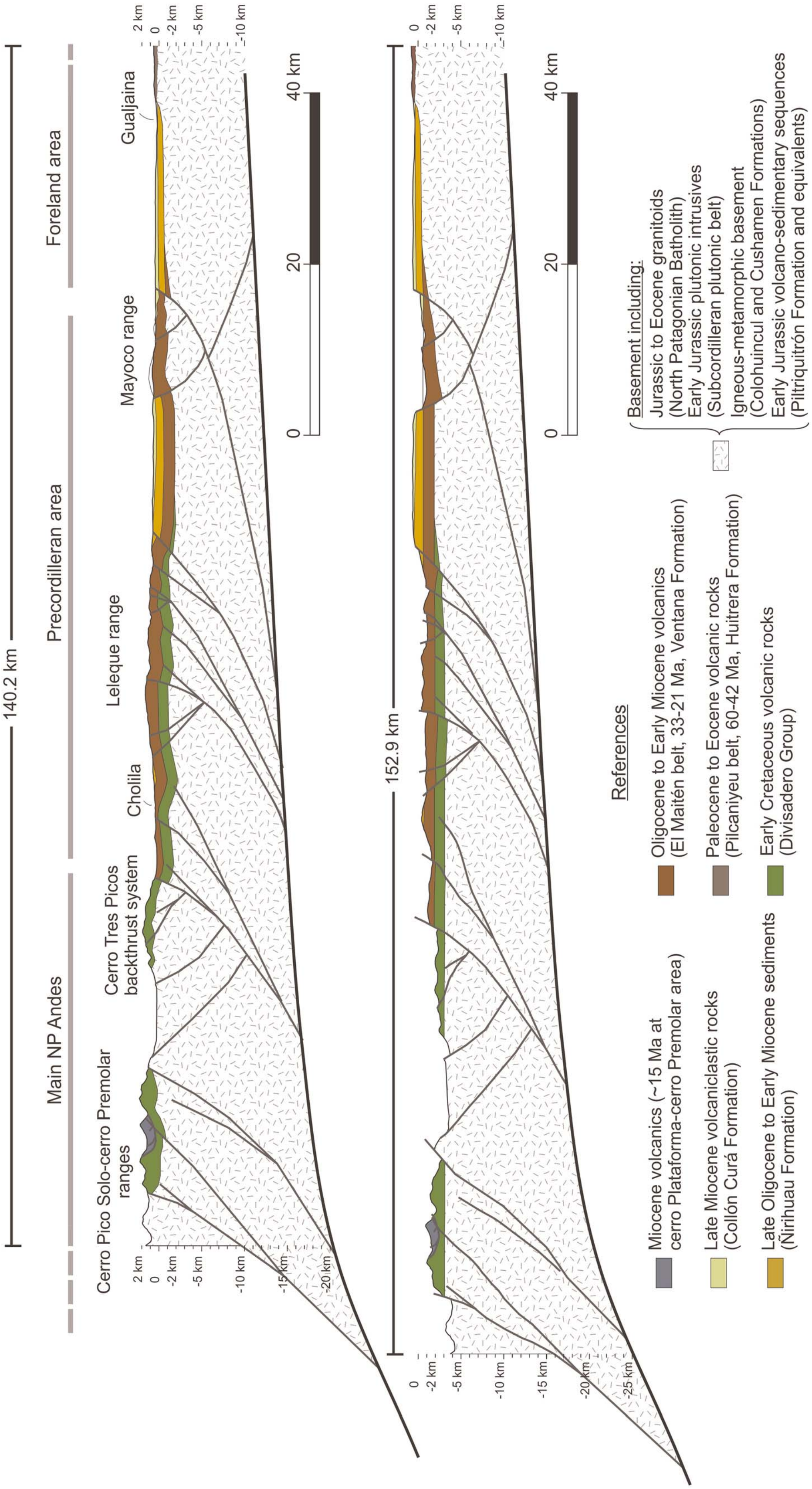

References
Plio-Quaternary glaciofluvial deposits and Quaternary cover
Late Miocene volcaniclastic rocks (Collón Curá Formation)
Early Miocene sediments (Ñirihuau and Ñorquinco Formations)
Oligocene to Early Miocene volcanic rocks (El Maitén belt, 33-21 Ma, Ventana Formation)
Early Jurassic volcano-sedimentary successions (Piltriquitrón Formation and equivalents)
Basement including:
Jurassic to Eocene granitoids (North Patagonian Batholith)
Early Jurassic plutonic intrusives (Subcordilleran plutonic belt)
Igneous-metamorphic basement (Colohuincul and Cushamen Formations)
95.6 km
Main NP Andes
Precordilleran area
Wedge top area
Foreland area
Hielo Azul ranges
El Bolsón sub-basin
Piltriquitrón range
El Maitén western range
El Maitén eastern range
Horqueta x-1
a
0
10
20 km
112.7 km
b

Figure 15



140.2 km
152.9 km
Main NP Andes
Precordilleran area
Foreland area
Cerro Pico Solo-cerro Premolar ranges
Cerro Tres Picos backthrust system
Cholila
Leleque range
Mayoco range
Gualjaina
0
20
40 km
References
Miocene volcanics (~15 Ma at cerro Plataforma-cerro Premolar area)
Late Miocene volcaniclastic rocks (Collón Curá Formation)
Late Oligocene to Early Miocene sediments (Ñirihuau Formation)
Oligocene to Early Miocene volcanics (El Maitén belt, 33-21 Ma, Ventana Formation)
Paleocene to Eocene volcanic rocks (Pilcaniyeu belt, 60-42 Ma, Huitrera Formation)
Early Cretaceous volcanic rocks (Divisadero Group)
Basement including:
Jurassic to Eocene granitoids (North Patagonian Batholith)
Early Jurassic plutonic intrusives (Subcordilleran plutonic belt)
Igneous-metamorphic basement (Colohuincul and Cushamen Formations)
Early Jurassic volcano-sedimentary sequences (Piltriquitrón Formation and equivalents)

Figure 16

developed, where in contrast to the northern case, neither seismic nor borehole data exist to constrain its internal geometry. Finally, a west vergent structure cut by a later east vergent thrust (Mayoco range; Figure 16) cannibalized the outer foreland basin exposing Oligocene successions that lie on top of the Upper Paleozoic basement [*Lage*, 1982]. In contrast to the northern section, where a thick synorogenic wedge is developed, this foreland structure compartmentalized the foreland basin.

[33] Finally, considering that most of the contractional structure has been created in Miocene times along the analyzed transects, at least east of the Cerro Plataforma area, due to the fact that this region was below sea level at 18.3 Ma, an estimated shortening rate of 23.4 mm/yr is achieved. This is considering a time period of 7.3 Ma, corresponding to the lapse of synorogenic sedimentation in the area, estimated in this study from 18.3 Ma for the top of the Cerro Plataforma sequence to 11 Ma for the top of the Collón Curá Formation. This is an approximate assumption taking into account that basal levels of the synorogenic strata at Cerro Plataforma area were not dated. According to this calculated rate, Miocene shortening rates at these latitudes would have been larger than GPS horizontal displacements, bracketed between 16 mm/yr at 37°S and 5.7 mm/yr at 45.5°S, particularly when considering that they mostly represent elastic deformation [*Kendrick et al.*, 1999].

5. Discussion: Tectonomagmatic Evolution of the North Patagonian Andes

[34] From the above described data some uncertainties on the structure and tectonic evolution of the North Patagonian Andes can be addressed. Only 12 to 17 km of shortening have been absorbed by thick-skinned structures from the Main North Patagonian Cordillera to the Precordilleran region mostly in Miocene times. This implies that the inferred shortening gradient that had been determined for the southern central Andes can be extrapolated into the Patagonian Andes [*Kley and Monaldi*, 1998]. While the fold and thrust belt absorbed ~170 km of shortening at 30°S, ~90 km at 33°S and ~40 km at 35°S, it falls abruptly at 42°S to 17–12 km.

[35] In the main North Patagonian Cordillera, contractional structures are the result of the tectonic inversion of Early to Middle Jurassic peri-Gondwanic extensional basins. This shortening occurred in two contractional stages; first during a pre-Miocene stage and then in early to late Miocene times. The older contractional event took place during the late Early Cretaceous based on the angular unconformity between Middle Jurassic and late Early Cretaceous volcanic rocks described for the main North Patagonian Cordillera. The last mountain building stage has formed a foreland basin that broadened to the east at the time of the advance of the orogenic front. This basin is dated in this work at its westernmost part at around 18.3 Ma, which is younger than in previous proposals (*Giacosa and Heredia* [2004b], among others). Additionally, this work proves that this basin has been formed in a contractional context evidenced by growth strata described in the field and seismic data. Provenance studies demonstrate that the main Andes were constructed at the time of deposition.

[36] Between the two contractional stages an extensional phase affected the orogenic wedge, leading to the deposition of thick volumes of volcanic rocks during the Oligocene. Extensional structures formed during this period constituted the heterogeneities that were contractionally re-activated in Miocene times, creating the Precordilleran system.

[37] The 60 to 23 Ma time period corresponds to a magmatic period in the North Patagonian retroarc zone that has some outstanding characteristics, as summarized earlier by *Rapela et al.* [1988] (Figure 17a). Two magmatic belts with anomalous retroarc positions differ in age and composition. While the easternmost one (Pilcaniyeu magmatic belt) has a Latest Cretaceous to Eocene age and a bimodal composition, the westernmost one (El Maitén magmatic belt) is characterized by tholeiitic affinities and Oligocene ages (Figure 17a). The latter belt has wedge-like geometries typical of synrift series. Based on seismic information, *Mancini and Serna* [1989] proposed that extension continued during the deposition of the lower part of the Ñirihuau Formation (Figure 17a). This spatiotemporal magmatic pattern is interpreted as a magmatic westward migration achieved approximately in the 45–35 Ma period [*Rapela et al.*, 1988]. The area of retroarc extension is limited to the zone presently occupied by the eastern Precordilleran system that results from the inversion of these Oligocene normal structures, as described in previous sections. To the west, in the forearc region on the western slope of the Andes, Oligocene basins share the here-proposed mechanism described for the El Maitén magmatic belt: *Hervé et al.* [1995], based on geochemical data, inferred an extensional intraarc setting for the Oligocene Traiguén basin (44°–46°S), while *Muñoz et al.* [2000], based on similar criteria, identified a partly contemporaneous coastal basalt plateau as related to asthenospheric influx favored in an extensional setting (40°–44°S) (Figure 17a).

[38] Late Miocene granitoids form a plutonic belt east of the present volcanic arc over the western slope of the Andes and east of the Coastal magmatic belt described by *Muñoz et al.* [2000] that was considered the late Oligocene arc front (Figures 17b and 17c). Isolated plutons are locally exposed in the eastern slope of the Andes, showing a maximum eastward expansion at 42°S [*González Díaz*, 1982;

Figure 16. (a) Balanced cross section on the eastern slope of the Andes from the drainage divide area to the foreland zone across the Cordillera de Leleque (see Figure 4 for location; B-B′). This section is similar to the one depicted in Figure 15, although it differs in the degree of exhumation of the broken foreland area that becomes deeper. Innermost thrusts are linked to inversion of Early Jurassic synextensional wedges (Figure 4). Note in this area a broader expansion of late Early Cretaceous volcanic rocks in comparison to the northern transect (Figure 15), which is in accordance with important pre-Neogene exhumation at the inner part (Main North Patagonian Cordillera) (see Figure 6). (b) Restored section that has yielded 12.7 km of shortening at these latitudes and shows the pre-inverted geometry corresponding to a series of Oligocene halfgrabens.

Aragón et al., 2012]. These last authors identified the calc-alkaline nature of these eastern bodies, which implies an anomalous eastern expansion of the arc when compared to the present one (Figures 17b and 17c). Early Miocene clastic successions were deposited on the present eastern slope of the Andes, contemporaneously with this arc migration (Figure 17b). These strata were dated at 18.3 Ma (Figure 11) and show synorogenic characteristics as noted above (Figure 9). A bimodal detrital provenance (Figure 17b) implies potential exhumation of the main Andes to the west and the broken foreland area to the east (Figures 11, 15 and 16). Andesitic strata dated at ∼15 Ma (K/Ar; *Lizuaín*, 1983], overlie these marine strata, constraining the contractional stage at the 18–15 Ma interval. This stage had been attributed to ∼1 km uplift of the Patagonian Andes further south [*Blisniuk et al.*, 2005]. This volcanic pile constitutes the southernmost part of the late Miocene arc expansion (Figure 17b). An open late Oligocene-early Miocene depocenter corresponding to the Ñirihuau Formation developed east of the area of the Miocene arc emplacement. Onlapping relationships are identified from field and seismic data (Figures 13 and 14) in growing structures that define the wedge-top area in a narrow foreland basin (Figures 14 and 15). This foreland basin has been differentially cannibalized through the Precordilleran uplift, isolating the El Bolsón sub-basin (∼21 Ma; *Encinas et al.*, 2011] (Figure 15) and forming the orogenic front area to the east through the El Maitén belt and Mayoco uplifts (Figure 16). The latitudinal extent of the foreland sedimentary wedge coincides with the area of late Miocene arc expansion depicted in Figure 17b. Partly correlative Ayacara Formation (∼20 Ma), outcropping over the Pacific coast at these latitudes, has been connected to important subduction erosion based on its sedimentological characteristics and benthic foraminifers [*Encinas et al.*, 2010]. This process is coherent with the here described contraction at the retroarc zone and foreland basin formation. A younger sedimentary prism (the Collón Curá Formation, 16–11 Ma [*Cazau et al.*, 1989; *Mazzoni and Benvenuto*, 1990] is partially superimposed on the early Miocene depocenters, and has been shifted to the east

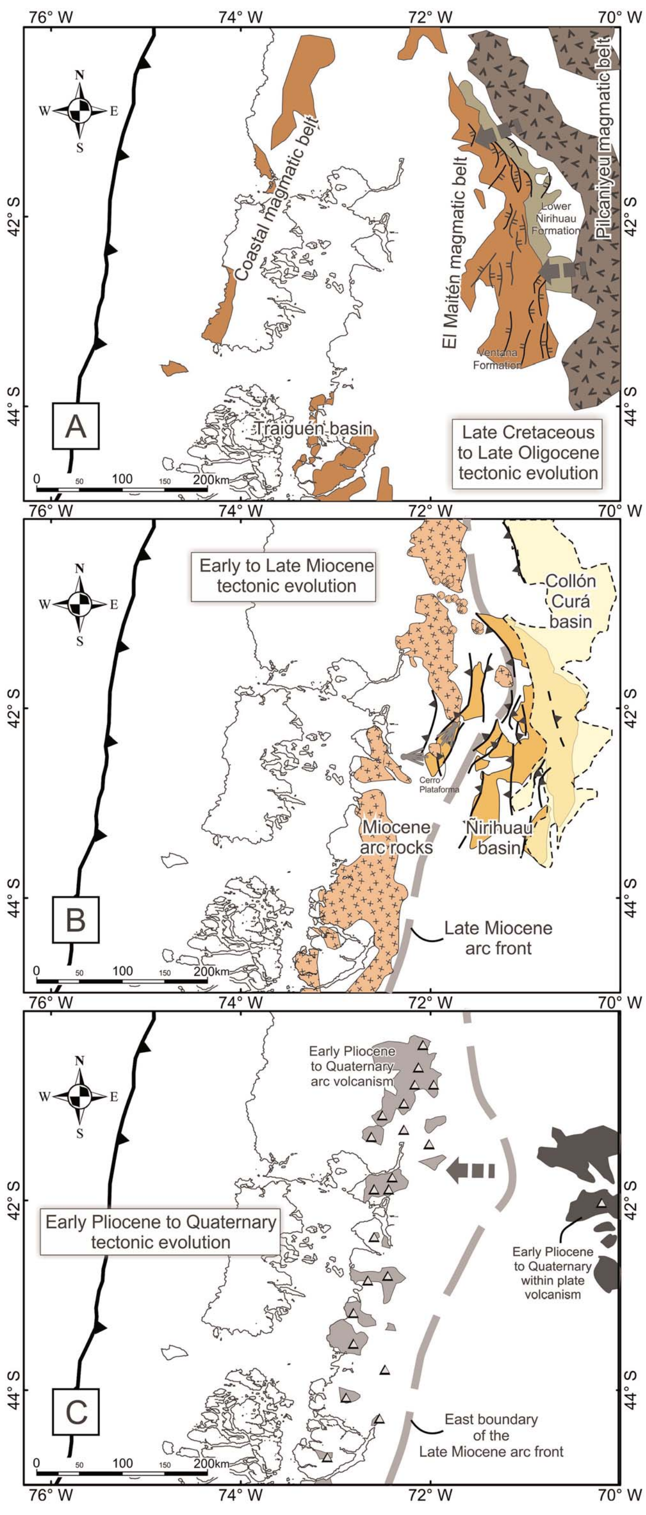


Figure 17. Tectonic sketches of the Northern Patagonian Andes for the last 60 My. (a) Westward retraction of the Paleogene arc after *Rapela et al.* [1988]. Note that a Paleocene arc was established in the present foreland area (Pilcaniyeu belt [*Rapela et al.*, 1988]); in Oligocene times arc rocks were re-established from the orogenic front area to the Coastal zone (Ventana belt [*Rapela et al.*, 1988]; and Coastal magmatic belt [*Muñoz et al.*, 2000]). These last volcanic rocks are associated with synextensional features as depicted in Figure 12. The synextensional character of the basal segments of the upperlying clastic Ñirihuau Formation has been described from seismic information by *Mancini and Serna* [1989], indicating that this period of arc retraction coincides with crustal stretching. (b) Early to late Miocene magmatic-tectonic evolution. Note an arc expansion with a maximum at 42°S with respect to late Oligocene eastern rocks [*González Díaz*, 1982; *Heredia et al.*, 2005] which coexists with contractional deformation dated in this work at 18.3 Ma. Note also widespread development of synorogenic depocenters that are redefined in the foreland area between 20 and 13 Ma. (c) Early Pliocene to Quaternary magmatic and tectonic setting. Within-plate volcanism in the Gastre and Pilcaniyeu regions [*Massaferro et al.*, 2006; *Pécskay et al.*, 2007] is developed at the foreland area coincident latitudinally with the site of former late Miocene arc expansion. Present arc is re-established in the hinterland zone, west of the late Miocene arc.

(Figure 17b). This unit shows progressive unconformities in its lower segments, depicted from field data (Figure 13), as well as condensed and onlap relations observed in seismic data (Figure 14). As in the previous case, the latitudinal extent and maximum foreland development coincide with the area of westward late Miocene arc expansion (Figure 17b). The Miocene uplift of the Precordilleran system and the reactivation of the Late Cretaceous main North Patagonian Cordillera explain the anomalous westward development that the Andean system has reached at these latitudes, coeval with the arc expansion.

[39] In the last 5–2 Ma the arc retracted to its present position along the axial zone of the Andes [*Lara et al.*, 2001], leaving the former late Miocene arc to the east (Figure 17c). Here, the Liquiñe-Ofqui fault zone played an important role focusing magmatism and deformation in the Andean axis, with coeval retreat of the deformation front [*Lavenu and Cembrano*, 1999]. Additionally, the climatic cooling and consequent onset of glaciation played a fundamental role in sites of active deformation [*Thomson et al.*, 2010]. In the foreland area, within-plate volcanic rocks developed between 41 and 43°S [*Massaferro et al.*, 2006; *Pécskay et al.*, 2007], coincidentally with the latitudinal strip of maximum late Miocene arc expansion.

[40] Late Miocene arc expansion coincides with a stage of mountain building and synorogenic basin formation. During this process, the foreland basin was cannibalized and the foreland area was broken. After this, within plate volcanism and arc retraction dominated the scene during the last 5 Ma. Similar processes were described in neighboring regions, such as immediately to the north in the Payenia shallow subduction zone [*Kay et al.*, 2006; *Orts et al.*, 2012; *Spagnuolo et al.*, 2012], and to the south in the Santa Cruz shallow subduction zone [*Espinoza et al.*, 2010; *Ramírez de Arellano et al.*, 2011]. Both examples constitute proposed shallow subduction settings developed in the last 17 Ma, where the arc expanded to the east contemporaneously with the development of the Andes and the generation of foreland basins. In both cases, posterior arc retraction to the trench was associated with injection of within plate basalts in the retroarc zone.

[41] The synorogenic successions grouped in the Ñirihuau and Collón Curá Formations seem to be the direct product of these processes, where the arc and the fold and thrust belt expanded, linked with a shallowing of the subducted slab. At ages less than 5 Ma foreland within plate volcanism may reflect a later steepening of the subducted slab at these latitudes.

6. Concluding Remarks

[42] The North Patagonian Andes between 41°30′ and 43°S have experienced at least two contractional stages: one in the late Early Cretaceous and another in the early to middle Miocene. The latter fragmented the foreland area, and was associated with a relatively high shortening rate of 23.4 mm/yr, while the older phase was restricted to the present hinterland zone. The calculated Miocene shortening rate is higher than modern estimates based on GPS observations. Miocene shortening in the retroarc zone is estimated at only 17–12 km, implying a strong gradient from north to south as inferred in previous works. This contractional stage started at 18.3 Ma and progressed up to 15–11 Ma, based on the presence of angular unconformities in foreland strata. These synorogenic depocenters shifted to the east in this time period, with the westernmost ones cannibalized by the advancing orogenic front. The shortening mechanisms are intimately linked to inversion of extensional systems of both older Early Jurassic age (~197 Ma) in the main Andes and Oligo-Miocene age (32–21 Ma) in the Precordillera. The Miocene contractional stage has led to a broken foreland with foreland basin formation contemporaneous with eastward arc expansion. Based on work in similar neighboring environments, we interpret Miocene contraction as being related to a mild shallowing of the subducted slab that provoked the eastward migration of the asthenospheric wedge and consequent development of brittle-ductile transitions in the foreland area that caused the rapid expansion of the orogenic wedge.

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