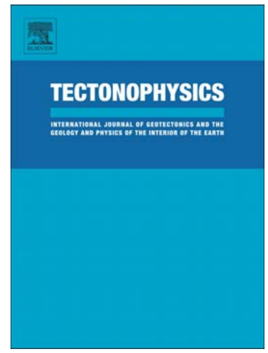
Accepted Manuscript



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PII: S0040-1951(16)30049-X
DOI: doi: 10.1016/j.tecto.2016.04.009
Reference: TECTO 127045

To appear in: *Tectonophysics*

Received date: 22 November 2014
Revised date: 10 March 2016
Accepted date: 3 April 2016

Tectonic evolution of the North Patagonian Andes (41°-44° S) through recognition of syntectonic strata

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Abstract

The North Patagonian fold-thrust belt (41º-44º S) is characterized by a low topography, reduced crustal thickness and a broad lateral development determined by a broken foreland system in the retroarc zone. This particular structural system has not been fully addressed in terms of the age and mechanisms that built this orogenic segment. Here, new field and seismic evidence of syntectonic strata constrain the timing of the main deformational stages, evaluating the prevailing crustal regime for the different mountain domains through time. Growth strata and progressive unconformities, controlled by extensional or compressive structures, were recognized in volcanic and sedimentary rocks from the cordilleran to the extra-Andean domain. These data were used to construct a balanced cross section, whose deep structure was investigated through a thermomechanical model that characterizes the upper plate rheology. Our results indicate two main compressive stages, interrupted by an extensional relaxation period. The first contractional stage in the mid-Cretaceous inverted Jurassic-Lower Cretaceous half graben systems, reactivating the western Cañadón Asfalto rift border ~500 km away from the trench, at a time of arc foreland expansion. For this stage, available thermochronological data reveal forearc cooling episodes, and global tectonic reconstructions indicate mid ocean ridge collisions against the western edge of an upper plate with rapid trenchward displacement. Widespread synextensional volcanism is recognized throughout the Paleogene during plate reorganization; retroarc Paleocene-Eocene flare up activity is interpreted as product of a slab rollback, and fore-to-retroarc Oligocene slab/asthenospheric derived products as an expression of enhanced extension. The second stage of mountain growth occurred in Miocene time associated with Nazca Plate subduction, reaching nearly the same amplitude than the first compressive stage. Extensional weakening of the upper plate predating the described contractional stages appears as a necessary condition for abnormal lateral propagation of deformation.

Key words: *North Patagonia, fold-thrust belt, syntectonic strata, Andean orogenesis*

Introduction

In ocean-continent subduction systems, deformation is transferred from the forearc to the retroarc zone, forcing the upper plate to create new crustal detachments for the tectonic transport of deformed rocks (Cook and Varsek, 1994; Lamb, 2006). Orogenic growth is associated with plates and mantle dynamics (e.g., Schellart et al., 2007; O´Driscoll et al., 2009; Faccena et al., 2013), and with the lithospheric configuration of the upper plate, whose heterogeneities can act as mechanical boundaries for the mountain belt development and extension (e. g., Ziegler et al., 1998; Cloetingh et al., 2008).

The Andes constitute the largest mountain chain in ocean-continent subduction systems, associated with a continuous subduction of a series of oceanic plates beneath South America since the Early Mesozoic. Andean orogenesis has acted in a non-uniform way across the continental margin, producing a segmented mountain chain along its strike (Gansser, 1973; Jordan et al., 1983; Mpodozis and Ramos, 1989; Kley et al., 1999; Tassara and Yáñez, 2003).

In segments characterized by high shortenings and significant crustal thickening, such as the Altiplano-Puna region of the Central Andes, extensional lithospheric relaxation periods have been observed to interrupt orogenic growth (McQuarrie et al., 2005; Oncken et al, 2006; Winocur et al, 2014; DeCelles et al., 2015). These processes locally led to delamination of the lower crust creating a thermally supported plateau (Kay et al., 1994; Garzione et al., 2006). However, delamination in the Southern Andes has also been linked to asthenospheric influx related to slab steepening settings (e.g., Ramos et al., 2014).

Particularly, the Andean margin in North Patagonia located between ~41º -44º S (Figure 1) posses a continuous geological record since the earliest Andean evolutionary stages in the Early Mesozoic, with some particularities evidenced by: i) A broad Late Triassic-Early Jurassic rifting associated with the Gondwana break-up and subduction on the Pacific margin (Pankhurst et al., 2000; Rapela et al., 2005; Suárez and Márquez, 2007; Vásquez et al., 2011); ii) Middle to Upper Jurassic SW-directed magmatic migration associated with an extensional stage (Cañadón Asfalto Basin, Figure 1; Uliana and Biddle, 1987; Fígari, 2005; Mpodozis and Ramos, 2008); iii) expansion of the contractional deformation toward the foreland through the Late Cretaceous and Cenozoic (Suárez and De La Cruz, 2001; Suárez et al., 2010a; Folguera and Ramos, 2011), and iv) Cretaceous and Neogene ocean ridge collisions determined from global reconstructions (Cande and Leslie, 1986; Seton et al., 2012).

The North Patagonian fold-thrust belt has low topography (<2,000 m) and reduced crustal thicknesses, although with a striking amplitude of nearly 500 km, with a series of minor mountain chains annexed to the Andean foothills with altitudes in the order of 1,000-1,500 m (Figure 1). These frontal mountain systems have been grouped in the “Patagonian Broken Foreland”, with a main constructional stage recently constrained to the Miocene (Bilmes et al., 2013; Figure 1). However, this foreland section shows a complex evolution with some outstanding characteristics such as a Paleocene to Eocene flare up magmatic event (Aragón et al., 2011, 2013) and widespread asthenospheric volcanism in the Oligocene-early Miocene (Muñoz et al., 2000; Kay et al., 2007).

This study analyses the tectonic evolution of this Andean segment, on the eastern Andean slope between 42°-44° S, through recognition of the structure and associated synorogenic sedimentation and volcanism. In order to visualize the structure at a crustal scale, a balanced cross section was constructed, using as a deep constrain a thermomechanical model to determine potential decollement depths. Then, an evolutionary model is proposed that reconciles structural development, magmatic evolution and basin mechanisms within a plate-kinematics scenario, linking timing of deformation in the retroarc zone with available thermochronological data on the western Andes.

Tectonic setting

Since the late Oligocene, the North Patagonian Andes are associated with the subduction of the Nazca Plate beneath South America (Figure 1) (e.g., Pardo-Casas and Molnar, 1987; Lonsdale, 2005). The triple junction defined between the Nazca, Antarctic and South American Plates has migrated since 14 Ma from south to north to its present position at 46.5° S (Cande and Leslie, 1986; Tebbens and Cande, 1997). The obliquity in plate convergence and collision of the Chile Ridge resulted in a strain partitioned regime, whose parallel-to-the-margin component is accommodated by the Liquiñe-Ofqui Fault Zone (LOFZ), associated with the emplacement of the volcanic arc (Cembrano et al., 1996; Lavenu and Cembrano, 1999).

Figure 1

The North Patagonian fold-thrust belt (41 - 44ºS) is separated into a series of morphostructural units characterized by distinctive geology and structure: A Coastal Cordillera, a nearly submerged Central Valley, the North Patagonian Andes and a wide broken foreland system (Figure 2). The Coastal Cordillera is a low elevation morphostructure that extends parallel to the trench for more than 3,000 km, separated from the North Patagonian Andes to the east by an elongated depression known as the Central Valley. This feature submerges coincidently with the interruption of the Pacific coast line and the Coastal Cordillera at the Chiloé Island (Figure 1).

The North Patagonian Andes constitute a narrow belt with approximate width of 100 km and maximum altitudes of 2,200 m, supported by a ~ 32 km thick crust (Tassara and Echaurren, 2012), implying that Neogene shortenings have been considerably lower than in the Central Andes to the north (Ramos et al., 2004; Oncken et al., 2006). At these latitudes, the North Patagonian and Deseado Massifs constitute the continental platform in the retroarc zone (Figure 1) (Harrington, 1962; Frutos and Tobar, 1975), being their tectonic origin an ongoing discussion (e.g., Pankhurst et al., 2014; Ramos and Naipauer, 2014). These are separated by the E-trending San Jorge Gulf Basin, a Mesozoic rift developed next to the Atlantic passive margin (Figure 1). East of the North Patagonian Andes, a series of ~N-NW low mountain ranges comprises a vast area of more than 300 km known as the “Patagonian Broken Foreland”, including the western edge of the Cañadón Asfalto Basin (Figure 1).

Geology of the North Patagonian fold- thrust belt

The remnants of the Coastal Cordillera (Chiloé Island and Chonos Archipiélago, Figure 2) and isolated islands in the Central Valley are composed of Paleozoic and Upper Triassic high P-T metamorphic rocks (e.g., Forsythe, 1982; Godoy et al., 1984; Fortey et al., 1992; Duhart et al., 2009). These are intruded by Eocene plutonic rocks and uncomformably overlain by Oligocene to Miocene volcano-sedimentary rocks (Coastal Magmatic Belt; Muñoz et al., 2000; Duhart et al., 2001) (Figure 2).

To the east, the North Patagonian Andes are constituted by calc-alkaline suites of the North Patagonian Batholith (Figures 2 and 3), formed episodically from Late Jurassic to Miocene time, with a main late Early-Late Cretaceous pulse of formation (see Pankhurst et al., 1999 for a synthesis). Contemporaneous volcanism is represented by the Middle-Late Jurassic Ibáñez-Lago La Plata Formations and the late Early Cretaceous Divisadero Group. The Ibáñez-Lago La Plata Formations are interpreted as a subduction-derived volcanism in the Andean margin of Patagonia, extending from ~41° S to southernmost South America, while the Divisadero Group corresponds to Aptian-Albian arc activity, extending from the main Andes toward the broken foreland system from ~41-46° S (e.g., Haller and Lapido, 1982; Ramos et al., 1982; Rapela and Kay, 1988; Parada et al., 2007). Between these magmatic units, Neocomian sedimentary sequences of the Coyhaique Group were deposited, composed of shallow marine and delta facies in an intra-arc basin (Toqui-Tres Lagunas, Katterfeld and Apeleg Formations: Skarmeta, 1976; Thiele et al., 1978; Aguirre-Urreta and Ramos, 1981; Covacevich et al., 1994; De la Cruz et al., 1996; Bell and Suárez, 1997; Suárez et al., 2009a) (Figure 3).

The broken foreland system exposes Carboniferous–Lower Permian marine sediments, grouped in the Tepuel Group (Figure 2) (Ramos, 2008; Pagani and Taboada, 2010), intruded by Triassic-Lower Jurassic calc-alkaline plutons of the Central Patagonian Batholith (201-223 Ma) (Von Gossen, 2003; Zaffarana et al., 2012a). In this zone, Liassic marine and continental deposits accumulated in graben-like depocenters (Suárez and Márquez, 2007) are associated with I-type mafic suites in a NNW-transverse belt (Subcordilleran Batholith 187-178 Ma; Gordon and Ort, 1993; Page and Page, 1999; Rapela et al., 2005, 2008) (Figure 3). A SW shift in magmatism from the Atlantic coast to the Pacific subduction zone occurred under an extensional regime coincident with the early opening of the Cañadón Asfalto Basin (Figari and Courtade, 1993; Figari, 2005). This basin hosts the Early-Middle Jurassic Lonco Trapial Formation, characterized by both crustal and mantle-derived geochemical signatures (Zaffarana and Somoza, 2012; Cúneo et al., 2013; Zaffarana et al., 2014), and the Middle-Upper Jurassic sedimentary sequences of the Cañadón Asfalto and Cañadón Calcáreo Formations (Volkheimer et al., 2009).

Figure 2

Jurassic sequences are uncomformably overlain by lacustrine, fluvial and volcaniclastic deposits of the late Early – Late Cretaceous Chubut Group, locally separated in Los Adobes and Cerro Barcino Formations (Codignotto et al., 1978) (Figure 2). Los Adobes Formation has a maximum U/Pb age of ~109 Ma (Navarro et al., 2015), while in the Deseado Massif to the south, equivalent facies yielded slightly older U/Pb ages of ~118-114 Ma (Césari et al., 2011; Pérez Loinaze et al., 2013). More recently, Suárez et al., (2014) dated the base of the Cerro Barcino Formation in ~ 97 Ma, indicating a 10-15 My period of sedimentation for the Chubut Group. These continental successions have been recently associated with synorogenic sedimentation in surface and seismic sections, related to the development of the broken foreland system in central Patagonia (Gianni et al., 2015; Navarrete et al., 2015).

In the central broken foreland system, the Don Juan Formation, an Upper Cretaceous arc-related unit, equivalent to the younger terms of the Divisadero Group to the west (K/Ar age of 91±3 Ma, Franchi and Page, 1980; Silva Nieto and Márquez, 2005), is unconformably covered by Upper Cretaceous within-plate basalts of the Tres Picos Prieto Formation (Figure 2) (K/Ar ages, 80-72 Ma; Franchi and Page, 1980).

In the eastern broken foreland system, uppermost Cretaceous-Paleocene fluvial-estuarine successions associated with an Atlantic transgression (Paso del Sapo and Lefipán Formations) were accumulated in a NW- embayment of the Cañadón Asfalto Basin, with a NE sediment supply from the North Patagonian Massif area (Lesta and Ferello, 1972). The marine facies of the Lefipán Formation have been correlated with the Salamanca Formation to the south in the San Jorge Gulf Basin (Figure 1; Fitzgerald et al., 1990; Homovc et al., 1995; Homovc and Constantini, 2001), dated by Clyde et al. (2014) in ~ 67 Ma (Ar-Ar).

Paleocene-Eocene ignimbritic successions associated with felsic volcanic rocks of the Huitrera Formation cover vast areas of the broken foreland system, locally with caldera-type activity (Figure 2) (Pilcaniyeu Belt by Rapela et al. 1988; Mazzoni et al., 1991; Aragón and Mazzoni, 1997; Wilf et al., 2010; Aragón et al., 2011). After this event, the Ventana Formation (El Maitén Belt by Rapela et al. 1988) (Figure 2), composed of intermediate volcanic rocks that range from 34 to 21 Ma (Bechis et al., 2012), extended through the transition zone between the broken foreland system and North Patagonian Andes for > 250 km.

Figure 3

Magmatism in the distal retroarc zone, on the eastern North Patagonian Massif, intensified at ~ 27-22 Ma, when a major volcanic field formed ("Meseta de Somuncura"; Kay et al., 2007). These mafic sequences have a complex geochemical signature that has led to contrasting hypotheses about their origin: from a slab detachment in the downgoing Farallon Plate (Muñoz et al., 2000), a mantle upwelling above the subducting plate (de Ignacio et al., 2001), an asthenospheric melting due to the foundering of a mafic crustal root (Remesal et al., 2012), a slab window associated with the detachment of the subducting Aluk Plate (Aragón et al., 2013) and a plume-like mantle upwelling interacting with slab-derived components (Kay et al., 2007).

The Ñirihuau fold- thrust belt developed in association with an lower to middle Miocene foreland basin filled by continental and marine deposits of the Ñirihuau and Collón Curá Formations (Giacosa et al., 2005; Bechis and Cristallini, 2006; Ramos et al., 2011; Orts et al., 2012; Bechis et al., 2014; Huyghe et al., 2015) (Figure 2). Late Miocene basaltic lava flows of the El Mirador Formation cover these deformed sections in the central broken foreland system exhibiting a milder contractional deformation (Volkheimer, 1964; Turner, 1982). After these, small plateaus of Pliocene mafic scoria (Epulef Formation) sealed contractional deformation in the retroarc zone (Figure 2) (Rabassa, 1975; Ravazzoli and Sesana, 1977; Massaferro et al., 2014) (Figure 2).

Field work and syntectonic strata

A Western Domain (Figure 2 and DS1) comprehends the transition from a high North Patagonian Andes formed by a series of east-vergent thrusts that imbricate rocks of the North Patagonian Batholith to a series of lower N-trending ranges of the western broken foreland system, characterized by doubly vergent thrusts and broad folds in Mesozoic and Cenozoic strata.

In the westernmost analyzed sector, in the Situación Range (Figure 4A), wedge-like depocenters hosting volcanic rocks of the Lago La Plata Formation, interpreted as evidence of syn-extensional activity, are unconformably covered by the Divisadero Group. An unconformity relation is also recognized in the Pirámides Range between neocomian sedimentary sequences of the Coyhaique Group below the Divisadero Group (Echaurren et al., 2014).

To the east in the Rivadavia Range, a broad anticline cored by Mesozoic sequences is uncomformably covered by the late Oligocene-early Miocene Ventana Formation with wedge-like geometries associated with inverted normal faults, evidencing synrift geometries that controlled the volcanic activity (Figure 4B). On the eastern flank of the Rivadavia Range (Percey River; Figure 4C), the Ñirihuau Formation presents progressive unconformities, interpreted as syn contractional deposits coetaneous to its uplift by a west-vergent thrust.

Figure 4

To the east, a doubly-vergent anticline of the Esquel and Nahuel Pan ranges is cored by Paleozoic-Lower Jurassic rocks showing a deeper exhumation level. Here, schists of the Esquel Formation are unconformably covered by Triassic volcanic rocks of the Choiyoi Group (252±10 Ma K-Ar age; Vattuone and Latorre, 2004) and intruded by Lower Jurassic granitoids of the Subcordilleran Batholith. On its eastern slope, coarse-grained conglomerates and sandstones of the Early Jurassic Piltriquitrón Formation are thrust over the Lago La Plata Formation.

On the eastern part of this Western Domain, a series of lower basement structures such as Mogote, Chenque and Tecka ranges exposes Paleozoic magmatic and metasedimentary rocks at their cores, uncomformably covered by Cenozoic strata (Figure 2). Contractional structures affecting the Miocene sections in the Cañadon Grande area (Figure 5 and S1) are associated with progressive uncomformities on the backlimbs of anticlines associated with thrusts. A late neotectonic reactivation of some structures is inferred by thrusting of non-consolidated Quaternary deposits (Figure 5).

Figure 5

The Eastern Domain (Figure 2 and DS2) is characterized by lower mean altitudes, with N-trending backthrusts progressively covered by Cenozoic volcanism of the Pilcaniyeu Belt and Mirador Formation. On the east, the NW-trending western edge of the Cañadón Asfalto Basin is inverted through the Taquetrén thrust, exhuming Late Paleozoic rocks. Between the Languiñeo and Tecka ranges (Figure 2), Upper Cretaceous granitoids (~90-75 Ma; Turner [1982]) and contemporaneous to andesitic-dacitic volcanism of the Don Juan Formation (~ 91 Ma K-Ar, Franchi and Page [1980]) are intruding and unconformably covering Paleozoic and Jurassic rocks (Figure 2).

Through the Chubut River Middle Valley (Figure 2), short-amplitude folding is affecting Lower Jurassic to Miocene rocks. Here, the Early Jurassic Lonco Trapial Formation lies unconformably beneath Upper Cretaceous-lower Paleocene sedimentary sequences of the Paso del Sapo – Lefipán Formations that are deformed in tight folds developed on the limbs of the main basement structures. Uncomformably, the Huitrera Formation (Pilcaniyeu Belt, ~ 57 – 43 Ma) lies upon with a smoother deformation, indicating a Cretaceous to Paleocene contractional event.

Synextensional depocenters associated with normal faults in volcano-sedimentary strata of the Huitrera Formation (Figure 6) indicate an extensional relaxation stage in Paleocene to Eocene time. This is in accordance with the within-plate signature determined for these volcanic rocks (Rapela et al., 1988; Aragón et al., 2011).

Figure 6

In the easternmost part, the NW- Taquetrén thrust delineates the western inverted edge of the Cañadón Asfalto Basin, uplifting Paleozoic rocks (U/Pb 314 ±2 Ma, Pankhurst et al. [2006]) that are partially covered by Lower to Upper Jurassic volcano-sedimentary sequences (Zaffarana and Somoza, 2012; Cúneo et al., 2013). Along this structural trend, the Miocene Collón Curá Formation had shown growth strata indicating deposition coeval with contractional deformation (Bilmes et al., 2013). However, in the hanging wall of the Taquetrén thrust (Gorro Frigio area; Figure S2), the base of the Chubut Group represented by the Los Adobes Formation shows progressive unconformities that indicate an older syntectonic activity corresponding to the lateEarly Cretaceous. A seismic line in this area (Figure 2 and 7B) shows extensional structures affecting the Paleozoic basement, controlling a series of Middle to Upper Jurassic depocenters at depth (Lonco Trapial, Las Leoneras and Cañadón Asfalto formations) that thickens toward the halfgraben structure of the Taquetrén thrust. A drastic change in the depocenter structural arrangement can be seen on the overlying basal Chubut Group (Los Adobes Formation), evidencing a change in the tectonic regime. Seismic reflectors corresponding to this unit are onlapping against tight folds associated with the Taquetrén thrust, and sediments are thickened away from the hinge. These evidences indicate that the inversion of the Jurassic extensional structures started contemporaneously with the deposition of the lower Chubut Group in late Early Cretaceous time. See Ranalli et al. (2011) for borehole data and stratigraphic correlation.

Figure 7

Additionally, in the footwall of the Taquetrén thrust, a fan of west-growing strata and progressive unconformities in the Late Cretaceous Paso del Sapo Formation (Figure 8A, B) indicate a younger reactivation. A tuffaceous intercalation in medium-grained sandstones of this unit yielded a 83.1 ±1.6 Ma age (U-Pb; Figure 8A), implying a Campanian compressive reactivation of the Taquetrén thrust (see Data Supplementary for dating details). Older detrital zircon populations of 99 and 117 Ma respectively are interpreted as sourced from the erosion of the Chubut group exposed at the backlimb of the fault, implying an ongoing cannibalization of the wedge top zone during foreland sedimentation.

On the other hand, Paleozoic ages are interpreted as coming directly from the basement exposed at the core of the hanging wall of the Taquetrén thrust, implying a relatively deep exhumation already by the Late Cretaceous. This episode of deformation is likely prolonged to Danian times due to the syntectonic character of the Lefipán Formation that shows progressive uncomformities in the footwall of the Taquetrén thrust, where mid Jurassic Lonco Trapial volcanic rocks were thrust on top of these sequences (Figure 8C).

Figure 8

Integrating geology with geophysical data into a balanced cross section

In order to visualize the crustal structure of the studied segment, we integrated the described field geology with independent geophysical information and constructed a balanced cross section.

Thermomechanical model

Compositional layering of the upper plate and the thermal regime of the subduction system determines the rheological properties of the lithosphere, whose thermomechanical structure allows identifying brittle-ductile transitions. Here, crustal decollements can nucleate and act as master fault-systems for the propagation of deformation on the middle/upper crust. We used a preexisting 3D density model with its upgraded geometry (Tassara et al., 2006; Tassara and Echaurren, 2012), produced by forward modeling the gravity field of EGM2008 (Pavlis et al., 2008), to build a thermomechanical 2D cross-section of the North Patagonian fold-thrust belt.

Temperature distribution inside the upper plate was computed assuming that heat is partially created inside the crust via radioactive production and conducted upwards from a thermal boundary layer (Turcotte and Schubert, 2002). The thermal boundary layer above the intersection between the subducted slab and the lithosphere-asthenosphere boundary (LAB) is defined by the geometry of the latter with a temperature of 1,350ºC, following the approach of Maule et al. (2005) and Tesauro et al. (2009). To the west of the LAB-slab intersection, we take the slab upper surface as the thermal boundary layer and assign a depth-dependent temperature to this surface based on the analytical formulation of Molnar and England (1990) and Lamb (2006) that take into consideration the thermal age of the slab, frictional heat and advection due to the movement of the slab toward the mantle. For further details of the model strategy see Tassara and Morales (2013).

Using the concept of the yield strength envelope (Burov and Diament, 1995; Tesauro et al., 2009) we combine the compositional and thermal models to predict the thermomechanical behavior of the lithosphere. Assuming a given tectonic stress of 200 MPa loading the lithosphere (the average tectonic stress available in Andean-type margins to produce deformation following Coblentz and Richardson 1996) we can compute the predicted present location of rigid (elastic) sheets of lithosphere above ductile (viscous) sections. The resulting geometry of these transitions was used as possible decollements into the cross-section for the present-day configuration on the margin.

In Figure 9A, strength values obtained are represented in a 3D block diagram. Yield strength envelopes were plotted for three columns (I, II and III on bottom of Figure 9A), illustrating the weakening in lithospheric structure toward the eastern foreland. Thus, the forearc posses a strongly coupled lithospheric structure, characterized by low heat flux, mainly due to proximity with the cold subducting slab. As seen in Column I, the Western Domain is characterized by a ~ 22 km thick rigid middle-upper crust, where brittle behavior rocks are stacked by the contractional structures that uplift basement sheets. Yield strength envelopes of the Eastern Domain (Columns II and III) indicate that the configuration of the middle-upper crust is disrupted by an intra-crustal discontinuity, defining a thin layer (~3 km thick) of ductile behavior at ~7 km depth that thickens (~8 km) toward the east beneath the Cañadón Asfalto Basin. The lower crust is a relatively uniform layer (~10 km thick) above the Moho with ductile, high viscosity, mechanical properties, while the lithospheric mantle is divided into a rigid upper layer (44-48 km depth) and a viscous, ductile layer at its base.

Building the structural cross section

The construction of the balanced cross section (Figure 9B) was performed using the Move® software using surface geology (Figures DS1 and DS2) as a general constrain for the basement depth and, at a lesser extent, gravity and aeromagnetic data (Figures DS3 and DS4). Thick-skinned structures were modeled using the flexural slip unfold algorithm. (Kane et al., 1997; Griffiths et al., 2002) that constitutes a useful tool for balance and restore fold-thrust belts, especially those related to tectonic inversion and also with strata with lateral thickness variations.

Figure 9

Different structural styles were recognized through the analyzed domains: In the Western Domain, an east-vergent thrust system is developed across the North Patagonian Andes and central broken foreland system, while in the Eastern Domain, doubly vergent contractional structures with lower wave-lenghts (~5 km) control the deformation. In the latter domain, the structural style is interrupted by the Taquetrén thrust that defines to the east (western Cañadón Asfalto Basin) an open-folded system with long wave-lenghts (~15-20 km). This segmentation has allowed selecting determined brittle-ductile transitions from the predictive thermomechanical model described for each segment that could have controlled the depth of the associated master fault. In particular, for the Western Domain, the ~22 km-depth brittle-ductile transition is selected as the decollement above which east-vergent thrusts are nucleated, while for the central sector two decollements are selected, one at ~ 7 km associated with the shallow brittle-ductile transition, and a deeper decollement east of the Taquetrén thrust front. This is consistent with surface geology, which shows thick-skinned deformation on thrusts of the North Patagonian Batholith and inverted Mesozoic hemigraben systems (Western Domain) and thin-skinned deformation recognized in the Chubut

River Middle Valley (Eastern Domain). We interpret that both decollements would be connected through a ramp structure in the transition of the defined domains (Figure 9A).

With all these considerations, shortening magnitudes do not surpass 11 km in a 217.65 km length section, representing only a 3.78% of the initial length. This is considered a minimum shortening since important sectors of the profile are obliterated by Cenozoic strata that have not absorbed older contractional stages. The geometry of the deeper decollement defines a gentle east-vergent ramp-flat structure, similar to the orogenic architecture described for Central Chile and Argentina (e.g., Farías et al., 2010; Giambiagi et al., 2014).

Discussion: Andean tectonic evolution of North Patagonia

We have described syncompressional and synextensional sequences associated with the growth/extensional relaxation stages of the North Patagonian fold-thrust belt, integrating field geology and structural, geochronological, geophysical and petrological information. Absolute overriding plate and convergence velocity rates between South America and a series of Pacific plates calculated since 170 Myr (Maloney et al., 2013) show a good correlation with the stages indicated. This model is based on a plate kinematic global model that reconstructs the plate configurations in the Mesozoic and Cenozoic (Seton et al., 2012). An evolutionary model is proposed in this work that reconciles these observations with plate kinematics from the Jurassic to the present, which is schematically represented in Figures 10 and 11.

Extensional regime and lithospheric weakening

In Jurassic-Early Cretaceous time an extensional regime affected the upper plate in North Patagonia associated with within-plate and arc magmatism. During Gondwana break-up, the Karoo-Ferrar Large Igneous Province emplaced in the proto-Atlantic margin predating the Chon Aike magmatic event, a major silicic outburst in Patagonia and the Antarctic Peninsula (187 – 178 Ma, Kay et al., 1989; Feraud et al., 1999; Pankhurst et al., 1998; Jourdan et al., 2005), leaving a refractory crust due to the extensive crustal melting (Pankhurst and Rapela, 1995; Riley et al., 2001). Then, the magmatic locus migrated toward the Pacific margin, in association with I-type suites of the Subcordilleran Batholith on a thin-weakened crust (Gordon and Ort, 1993; Page and Page, 1999; Rapela et al., 2005), and mixed crust-mantle signature volcanism of the Lonco Trapial Formation (Zaffarana and Somoza, 2012; Zaffarana et al., 2014). A synextensional character of the Jurassic volcanism is evidenced in wedge-like geometries identified in the North Patagonian Andes at the analyzed latitudes in this work (Figure 4A and 7B).

This trenchward retraction of the magmatic activity since Early Jurassic has been related to high rates of slab rollback (Rapela et al., 2005; Mpodozis and Ramos, 2008) and the thermal effects of Karoo-Ferrar plume (Suárez and Márquez, 2007). In the Middle-Upper Jurassic, magmatism settled in the Pacific margin, represented by the North Patagonian Batholith and the Ibáñez- Lago La Plata Formations, whose distribution shows a rather stable arc magmatic axis through a ~40-50 Myr period (Pankhurst et al., 2003; Suárez et al., 2009a). During this stage, arc and retroarc subsidence in the Austral and Cañadón Asfalto basins was most likely controlled by the eastward movement of South America, determining negative trench-normal absolute velocities (Figure 10 A).

Cretaceous orogenic growth

The late Early Cretaceous compressive stage recognized in this study is also recognized throughout most of the Andean margin (e.g., Cobbold et al., 2007), and coincides with South Atlantic opening and a period of sea floor global spreading acceleration (Larson and Ladd, 1973; Eagles, 2007). According to Seton et al. (2012), at this time (~125 Ma) the break-up of the Phoenix (Aluk) Plate into the Chasca-Catequil Plates, produced the subduction of a mid-ocean ridge at the studied latitudes. The absolute motion of South America changed to the west during this stage, provoking a significant increase in the trench-normal convergence (Figure 10 B). Available thermochronological data in the forearc region (Figure 2) imply that exhumation was produced at this time at slow rates affecting broad areas of the Paleozoic crystalline basement (Thomson et al., 2001). Contemporaneously, volcanic activity of the Divisadero Group exhibits an eastward expansion at ~118 Ma, from the North Patagonian Andes to the foothills (Suárez and De La Cruz, 2001), following basin closure of the Coyhaique Group (e.g., Suárez et al., 2009a, 2010b), evidenced in the innermost sectors of the fold-thrust belt by an angular unconformity (Figure 4A). Then the orogenic wedge propagated to the east, at least 500 km from the trench, inverting the Cañadón Asfalto Basin, where syntectonic strata of the Chubut Group indicate a late Early Cretaceous deformation (Figure 7B).

After this contractional event, in Late Cretaceous times (~100-80 Ma), the major stage of emplacement of the North Patagonian Batholith occurred, in a period of high convergence, when the highest westward velocities of South America were achieved (Somoza and Zaffarana, 2008). Fission-track ages indicate that in this period, the forearc region exhumed from depths of at least 10-12 km (Duhart and Adriasola, 2008). Even though magmatic suites of the North Patagonian Batholith are mainly concentrated in the North Patagonian Andes, satellite plutonic and volcanic units reached the foreland after 90 Ma (see location in Figure 2, S2 and S4), evidencing a ~150 km eastward expansion of the magmatic activity (Figure 10C). These eastern bodies are calc-alkaline intermediate-to-acid volcanic rocks of the Don Juan Formation (K-Ar age of 91±3 Ma; Franchi and Page, 1980) and I-type, calc-alkaline, basic-to-acid plutonic suites of the Lago Aleusco area (López de Luchi et al., 1992). Radiometric K-Ar ages of ~90-75 Ma of this plutonism (Turner, 1982) indicate a temporal association with retroarc deformation, described in this work in the Taquetrén thrust front, where the synorogenic Paso del Sapo Formation has yielded a ~83 Ma age (Figure 8A).

At the end of this period of magmatic expansion, the Maastrichtian- early Paleocene synorogenic Lefipán Formation deposited in an Atlantic embayment next to the eastern Andean front (Scasso et al., 2012), probably due to the flexure of the lithosphere under the proximal orogenic load (Ruiz et al., 2005) (Figure 10 C).

According to the model of Seton et al (2012), the extinct Chasca-Catequil Ridge was replaced by the NW-trending Farallon-Antarctica Ridge at ~85 Ma that started to be subducted beneath the margin at these latitudes. Contemporaneously, the basaltic plateau of the Tres Picos Prieto Formation with ages between ~80-70 Ma and characterized by mixed subduction and within plate magmatic sources was emplaced in the retroarc zone (Franchi and Page, 1980; Zaffarana et al., 2012b). A slab-window origin was proposed for these back arc mafic units as a product of ridge subduction (and equivalents Morro Negro-Alto Rio Senguer basalts; see Demant et al., 2007; Gianni et al., 2015). Then, a drop in trench-normal plate convergence occurred simultaneously to ridge subduction, presumably in association with a reduction in slab pull forces after the development of the slab window, postdating the rapid development of the fold-thrust belt during the Cretaceous (Figure 10D).

Eastward magmatic migration, subsequent arc waning, contemporaneous subduction of mid-odean ridges and enhanced retroarc deformation, point to a stage when dynamics in the subduction system seems to have changed dramatically. Isotopic values from the North Patagonian Batholith at these latitudes shows nearly no participation of crustal-derived materials (Pankhurst et al., 1992; 1999), precluding arc migration due to subduction erosion (von Huene and School, 1991). Therefore, a shallow slab configuration could be an alternative to explain rapid expansion of retroarc deformation and magmatism and the subsequent magmatic gap/waning, as earlier proposed by Suárez et al. (2010a) for the segment between 45° and 49°S. This could have been favored by subduction of young lithosphere in a high-convergence regime, during two consecutive mid-ocean ridge collisions (Chasca/ Catequil and Farallon/Antarctic in Figure 10B-D; Gianni et al. 2015).

Figure 10

Extensional relaxation interrupting Andean orogenesis

In the Paleocene-Eocene, tectonic reconstructions indicate that the Farallon and South American plates converged at a high obliquity (e.g. Pardo-Casas and Molnar, 1987; Somoza, 1998; Somoza and Ghidella, 2012). During this period, magmatic activity took place in the central broken foreland system concentrated in the Pilcaniyeu Belt, a voluminous bimodal volcanic plateau (Aragón and Mazzoni, 1997; Aragón et al., 2011). Field evidence show the synextensional character of these sections (Figure 6), which is compatible with chemical data that indicate an asthenospheric source for the rhyolitic ignimbrites associated with caldera-type volcanism, characterized by anomalous low contents of Sr and nearly no crustal assimilation (Aragón et al., 2011). We interpret the bimodal character of the Pilcaniyeu Belt as related to retroarc extension and mantle decompression, associated with progressive slab rollback (Muñoz et al., 2000; Aragón et al., 2011) (Figure 11A). Eocene plutonic suites in the Chiloé and Chonos region would account for an increasing steepening of the Farallon Plate during this stage (see Figure 2).

In the late Oligocene, magmatic activity emplaced more or less synchronously from the forearc (Coastal Magmatic Belt) to the retroarc zones (El Maitén Belt and Somún Curá volcanic field; Muñoz et al., 2000) coeval with absence of arc activity. In this broad magmatic system, the Coastal Magmatic Belt and intra- to retroarc El Maitén Belt have chemical signatures that reflect the combination of an asthenospheric OIB-type sources and a mantle contaminated with slab-derived fluids (Muñoz et al., 2000; Kay et al., 2007). This can be explained by a rollback of the Farallon Plate that would have enhanced a thermal weakening of the upper plate and crustal stretching (Kay and Rapela, 1988), reflected in the synrift wedge-like geometries of the Ventana Formation described in this work (Figure 4B). This extensional setting would have controlled the volcanic activity and interrupted temporarily the development of the fold-thrust belt (Figure 11B). The Somún Curá volcanic field in the retroarc zone, whose chemical signature has been interpreted as coming from a deeper asthenospheric, plume-like mantle upwelling (Kay et al., 2007), is explained in a context of nearly stable absolute velocity of South America at this time (Figure 11B) (Kay and Copeland, 2006; Kay et al., 2007). Crustal thinning and thermal softening could have acted as a rheological pre-requisite for following development of contractional deformation (e.g., Thompson et al., 2001; Cloetingh et al., 2012), as proposed by Fosdick et al. (2011) as an important control for the fold-thrust belt development in Austral Patagonian Andes.

Contractional reactivation of the fold-thrust belt

At the end of the Oligocene, the breakup of the Farallon Plate and subsequent eastward subduction of the Nazca Plate at ~23 Ma (Lonsdale, 2005) determined a significant increase in relative convergence (Figure 11 A-B). At these earliest stages, generalized subsidence led to Atlantic and Pacific marine transgressions in several depocenters of Northern Patagonia (Encinas et al., 2013, 2014; Bechis et al., 2014).

Through the 19-16 Ma time period, these sections corresponding to the Río Foyel Group-Ñirihuau Formation show growth strata in contractional structures as described in this and previous works (Figure 4C) (Orts et al., 2012). This indicates the development of an incipient foreland basin in the western broken foreland system (Figure 11C). Synorogenic strata in the late Miocene Collón Cura Formation dated in the interval ~16-11 Ma (Bilmes et al., 2013; Ramos et al., 2015) are displaced to the east respect to the Ñirihuau depocenters, (Figure 2) constraining the last activity of the Taquetrén thrust front in the easternmost study area, as proposed by Costa et al. (1996) (Figure

11D). This eastward progression of the fold-thrust belt in Miocene times reached the Cretaceous-early Paleocene deformational front, showing the mechanical control that preexisting structures exerted on the new ones. Neotectonic contractional deformation has been described in the Cañadón Grande area in association with Neogene thrusts (Figures 5 and 11D).

Figure 11

Conclusions

Two compressive stages affected the North Patagonian fold-thrust belt. The first in late Early Cretaceous-early Paleocene times and the second since the middle Miocene. The former is characterized by coupled forearc exhumation, known from thermochronological data, with foreland expansion of deformation and magmatism in the retroarc, determined from growth strata. Subduction of two oceanic ridges, together with a fast trenchward displacement of South America in late Early-Late Cretaceous time, could have determined a shallow subduction configuration, explaining this spatiotemporal arrangement of contractional deformation with arc expansion.

Paleocene to Eocene flare up magmatism, whose products were accumulated in synextensional depocenters, was followed by highly voluminous mantle-derived Oligocene mafic eruptions associated with an enhanced extension. These magmatic events separated the two compressional stages, interrupting temporally orogenic development.

Late Cretaceous and Miocene contractional structures are mechanically controlled by Jurassic-Early Cretaceous and late Paleocene to Oligocene extensional structures, suggesting that extensional weakening of the upper plate exerted a strong control in localizing subsequent contractional deformation. The structural cross section suggests that the North Patagonian fold-thrust belt was developed by lateral incorporation of sectors of the foreland zone involving minimum crustal thickening.

Acknowledgments

This study was financed by PIP 11220110100506, UBACYT 20020110100019, PICT-2012-1490 and Proyecto Fondecyt 1110914. We are very grateful for careful reviews, comments and suggestions from Brian Horton. We also acknowledge S. Kay and two anonymous reviewers whose reviews greatly enriched earlier versions of this article, and Editor Hans Thybo. Midland Valley is acknowledged for 2D Move academic licenses. Thanks to Víctor Ramos for fruitful comments and Jeremías Likerman, Miguel Ramos, Jonathan Tobal and Lucía Sagripanti for discussion. Thanks to Parques Nacionales in Los Alerces for granting access and hospitality, and Macarena Henkel and Francisco Rusconi for field assistance. The reader is referred to the Data Supplementary in the online version of the article for additional geophysical information constraining the cross section, detailed field maps and analytical methods of zircons dating. This is the R-XXX contribution of the Instituto de Estudios Andinos "Don Pablo Groeber".

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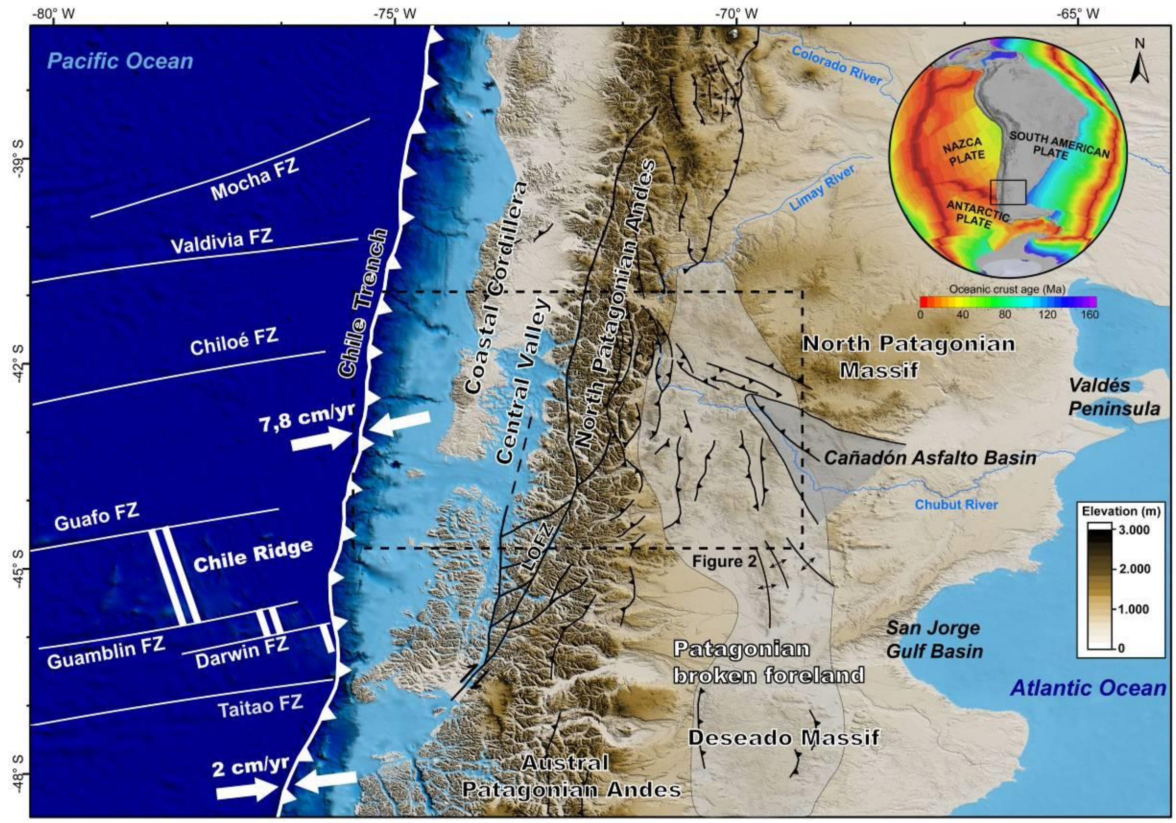
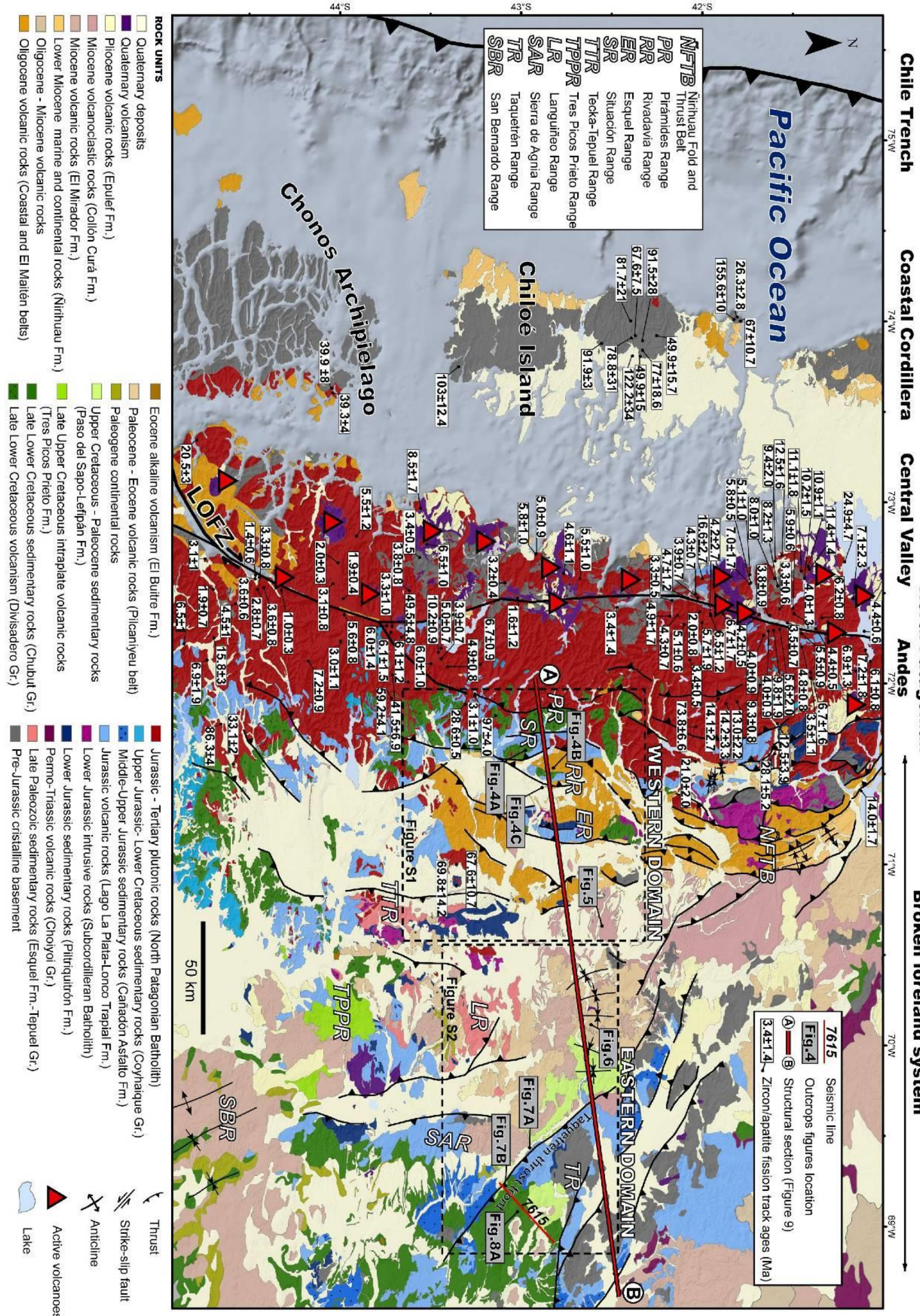


Figure 1. *Present tectonic setting of the North Patagonian fold and thrust belt. The North Patagonian Andes are structurally controlled by the Liquiñe-Ofqui fault zone (LOFZ), where neotectonic deformation occurs. Note the development of a broken foreland system across central Patagonia that extends nearly 500 km from the trench. DEM corresponds to Shuttle Radar Topographic Mission from NASA.*



Chile Trench
Coastal Cordillera
Central Valley
North Patagonian Andes
Broken foreland system
Pacific Ocean
Chiloé Island
Chonos Archipielago
ÑFTB Ñirihuau Fold and Thrust Belt
PR Pirámides Range
RR Rivadavia Range
ER Esquel Range
SR Situación Range
TTR Tecka-Tepuel Range
TPPR Tres Picos Prieto Range
LR Languiñeo Range
SAR Sierra de Agnia Range
TR Taquetrén Range
SBR San Bernardo Range
WESTERN DOMAIN
EASTERN DOMAIN
LOFZ
Figure S1
Figure S2
50 km
7615 Seismic line
Fig.4 Outcrops figures location
A — B Structural section (Figure 9)
3.4±1.4 Zircon/apatite fission track ages (Ma)
Thrust
Strike-slip fault
Anticline
Active volcanoes
Lake
ROCK UNITS
Quaternary deposits
Quaternary volcanism
Pliocene volcanic rocks (Epulef Fm.)
Miocene volcanoclastic rocks (Collón Curá Fm.)
Miocene volcanic rocks (El Mirador Fm.)
Lower Miocene marine and continental rocks (Ñirihuau Fm.)
Oligocene - Miocene volcanic rocks
Oligocene volcanic rocks (Coastal and El Maitén belts)
Eocene alkaline volcanism (El Buitre Fm.)
Paleocene - Eocene volcanic rocks (Pilcaniyeu belt)
Paleogene continental rocks
Upper Cretaceous - Paleocene sedimentary rocks (Paso del Sapo-Lefipán Fm.)
Late Upper Cretaceous intraplate volcanic rocks (Tres Picos Prieto Fm.)
Late Lower Cretaceous sedimentary rocks (Chubut Gr.)
Late Lower Cretaceous volcanism (Divisadero Gr.)
Jurassic - Tertiary plutonic rocks (North Patagonian Batholith)
Upper Jurassic- Lower Cretaceous sedimentary rocks (Coyhaique Gr.)
Middle-Upper Jurassic sedimentary rocks (Cañadón Asfalto Fm.)
Jurassic volcanic rocks (Lago La Plata-Lonco Trapial Fm.)
Lower Jurassic intrusive rocks (Subcordilleran Batholith)
Lower Jurassic sedimentary rocks (Piltriquitrón Fm.)
Permo-Triassic volcanic rocks (Choiyoi Gr.)
Late Paleozoic sedimentary rocks (Esquel Fm.-Tepuel Gr.)
Pre-Jurassic cristalline basement

Figure 2.*Geology of the study area from Turner (1982), Lizuaín et al. (1995), SERNAGEOMIN (2003), Silva Nieto and Márquez (2005) and own data. A series of morphostructural units with distinctive geology and structure has been defined from west to east: The Coastal Cordillera separated by the submerged Central Valley from the North Patagonian Andes, and a series of mountain ranges that define a broken foreland system (see text for further details). Red triangles indicate the present arc front. Fission track ages are taken from Adriasola et al. (2006), Duhart and Adriasola (2008) and Thomson (2010 and references therein).*

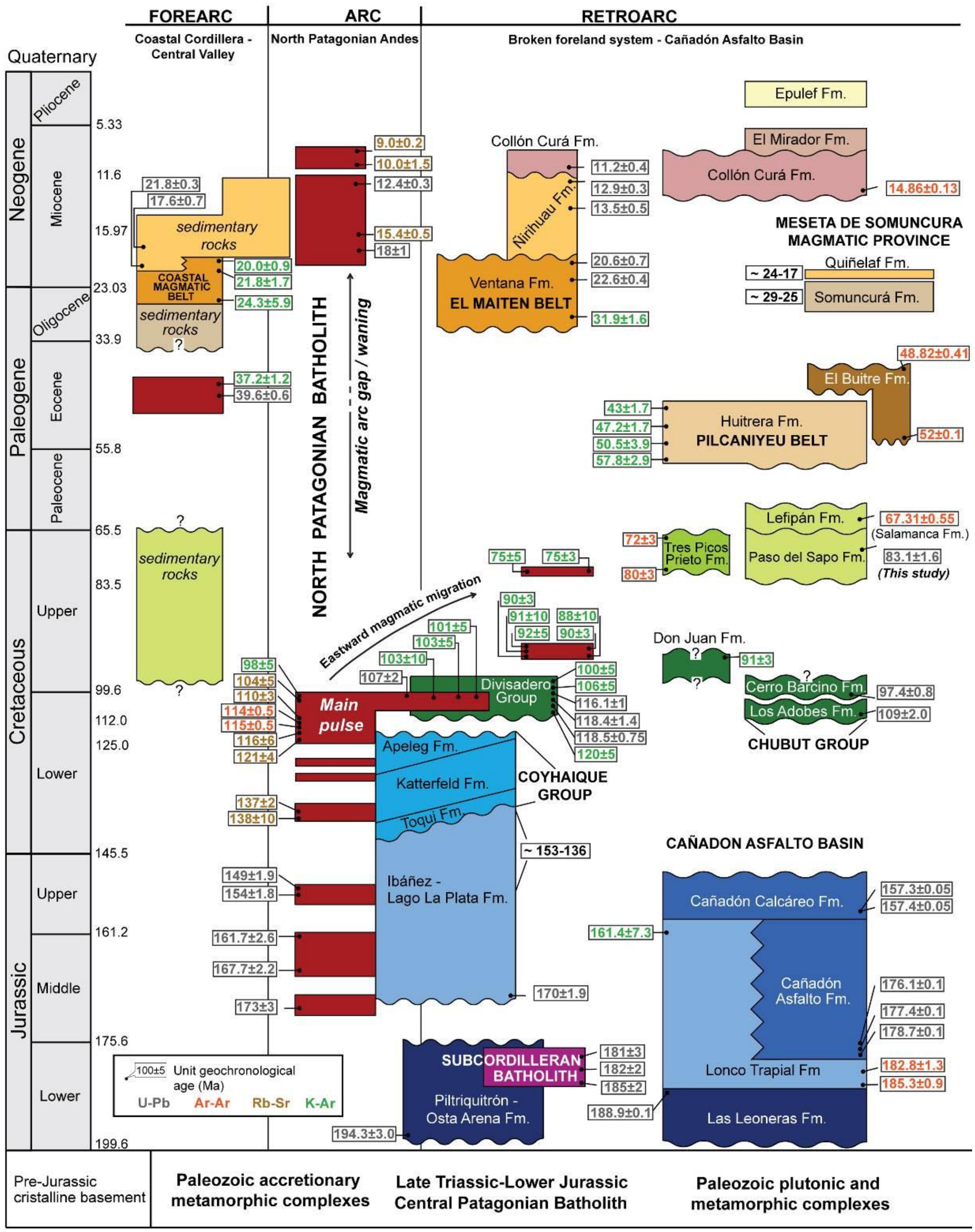


Figure 3. *Stratigraphic chart of the North Patagonian fold and thrust belt. See Data Supplementary for radiometric dataset sources.*

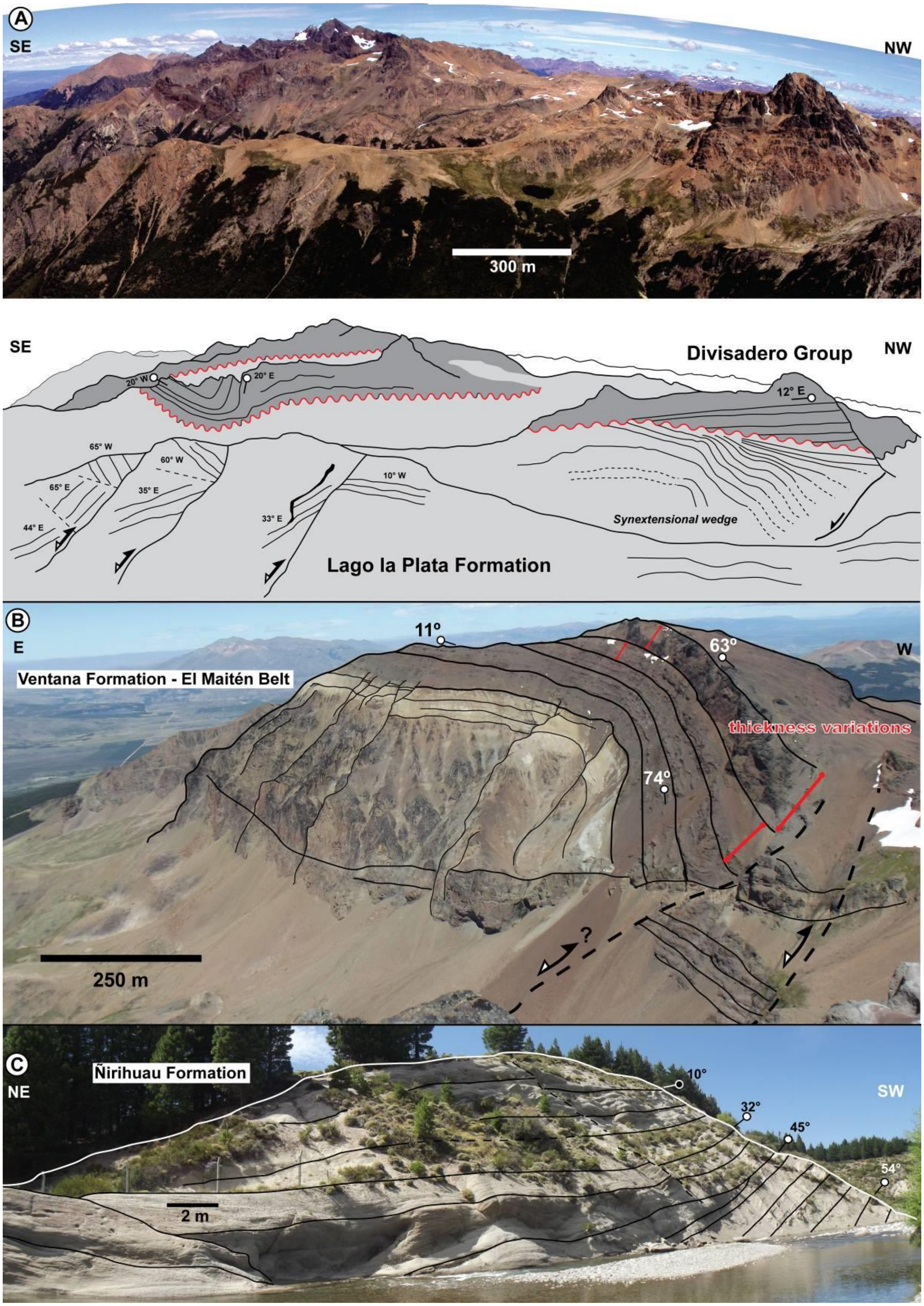

A
SE
NW
300 m
SE
Divisadero Group
NW
20° W
20° E
12° E
65° W
60° W
65° E
35° E
10° W
44° E
33° E
Synextensional wedge
Lago la Plata Formation
B
E
11°
63°
W
Ventana Formation - El Maitén Belt
thickness variations
74°
?
250 m
C
Ñirihuau Formation
NE
10°
SW
32°
45°
54°
2 m

Figure 4. *A) Partially inverted wedge-like depocenters of Mid to Late Jurassic sections of the Lago La Plata Formation and pre-Aptian contractional structures in the Situación Range, unconformably covered by Early Cretaceous volcanic rocks (Divisadero Group). B) Late Oligocene-early Miocene Ventana Formation in the Rivadavia Range with wedge-like geometries associated with high-angle normal faults. C) Early Miocene fluvial deposits and tuffs of the Ñirihuau Formation on the eastern slope of the Rivadavia Range in the Percey valley, showing progressive unconformities. See location on Figure 2.*

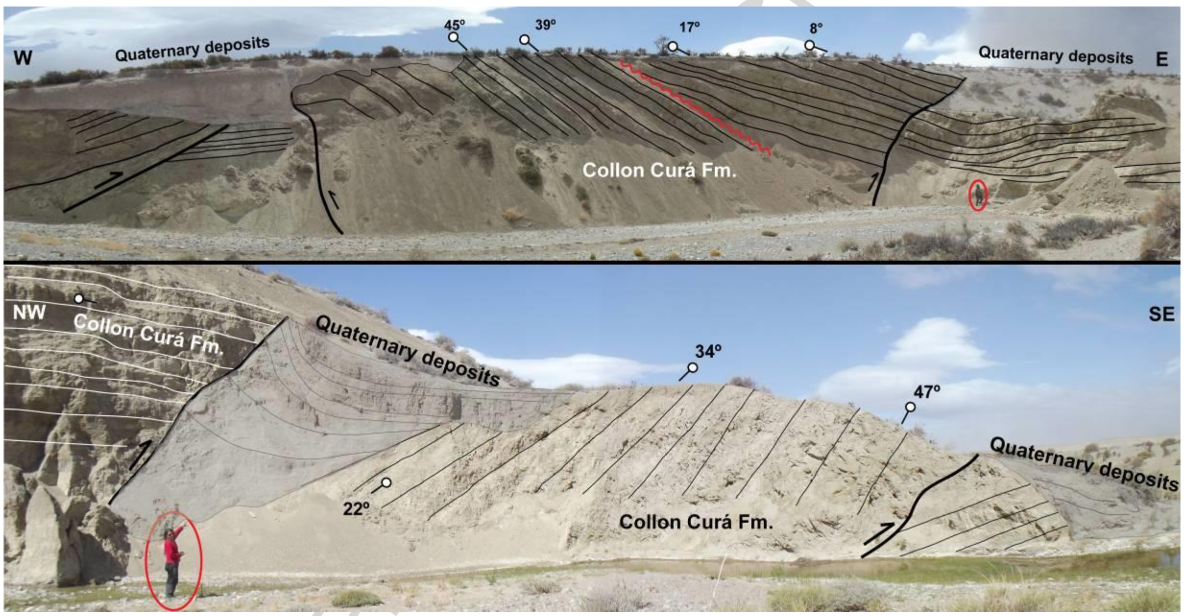


Figure 5. *Syn-contractional Miocene sections of the Collon Curá Formation in the Cañadón Grande area east of Mogotes Range (see location in Figure 2). Note that Quaternary deposits are affected by reactivation of Neogene contractional structures. The red ellipse indicates a person as a scale.*

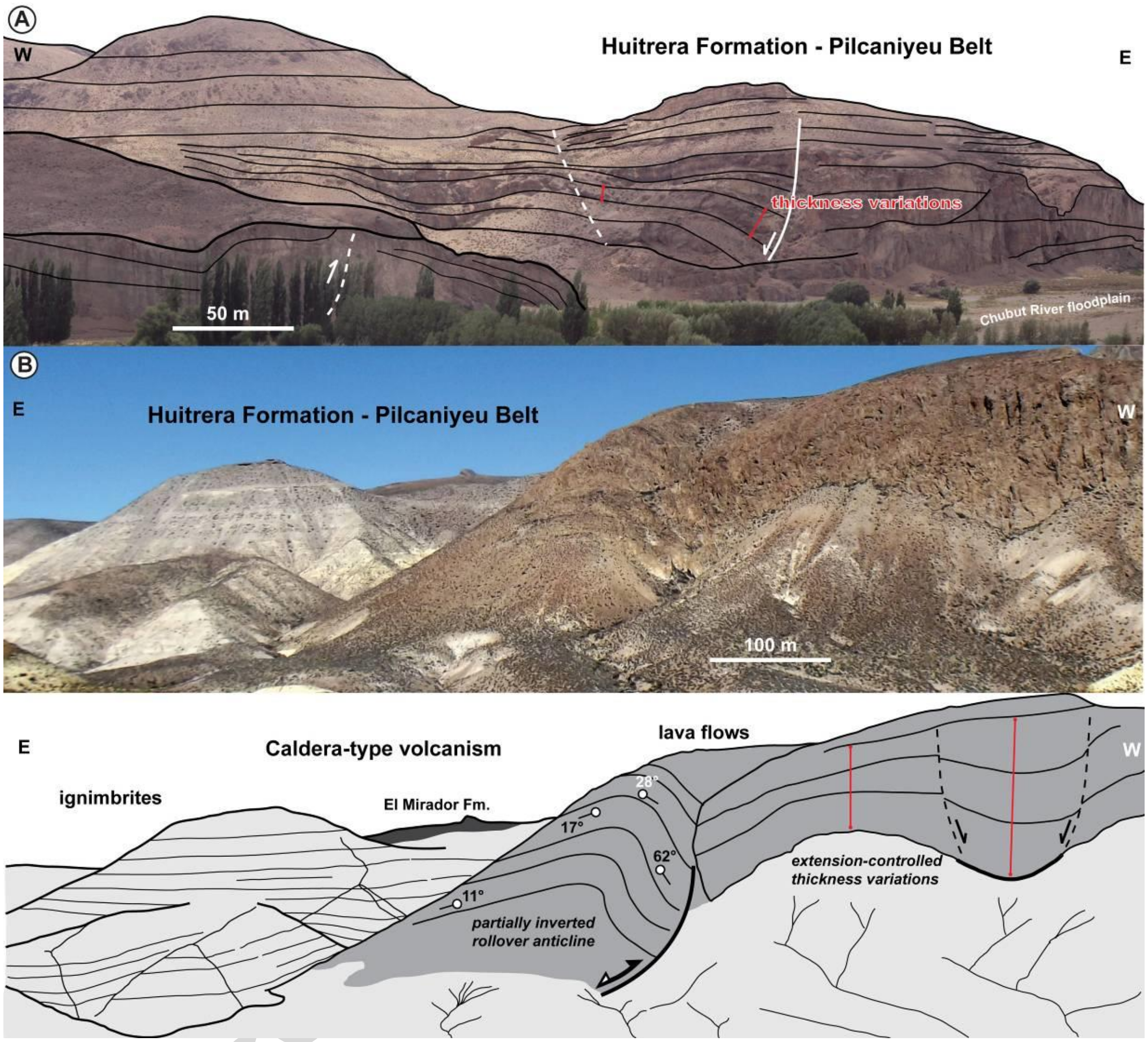


Figure 6. *Paleocene-Eocene volcanic sections outcropping in the Chubut River Middle Valley, corresponding to the Huitrera Formation. See location in Figure 2. A) Wedge-like depocenter in a Huitrera Formation outcrop. B) Inversion of Paleocene to Eocene extensional structures. Note a partially inverted rollover and thickness variations in Paleocene to Eocene strata.*

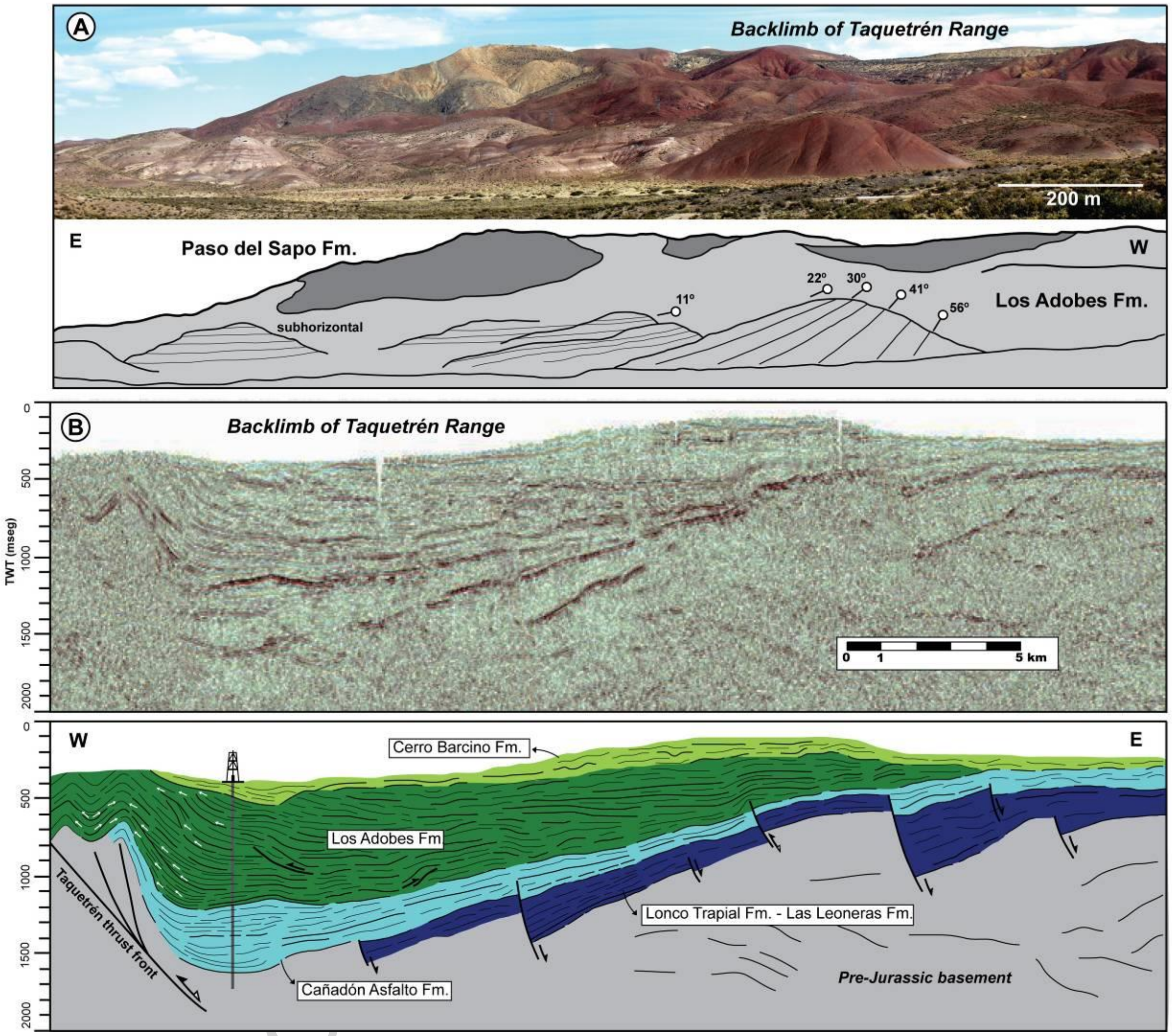


Figure 7. *A) A fan of growth strata at the base of the Chubut Group (Los Adobes Formation) in the hanging wall of the Taquetrén thrust. B) Seismic line 7615 in two-way-travel time (mseg), across the western edge of the Cañadón Asfalto Basin across to the Taquetrén thrust (see location in Figure 2). A main NW- half graben was inverted during the deposition of the basal Chubut Group (Los Adobes Fm.), indicated by onlapping of seismic reflectors (white arrows) against the folded sedimentary packages.*

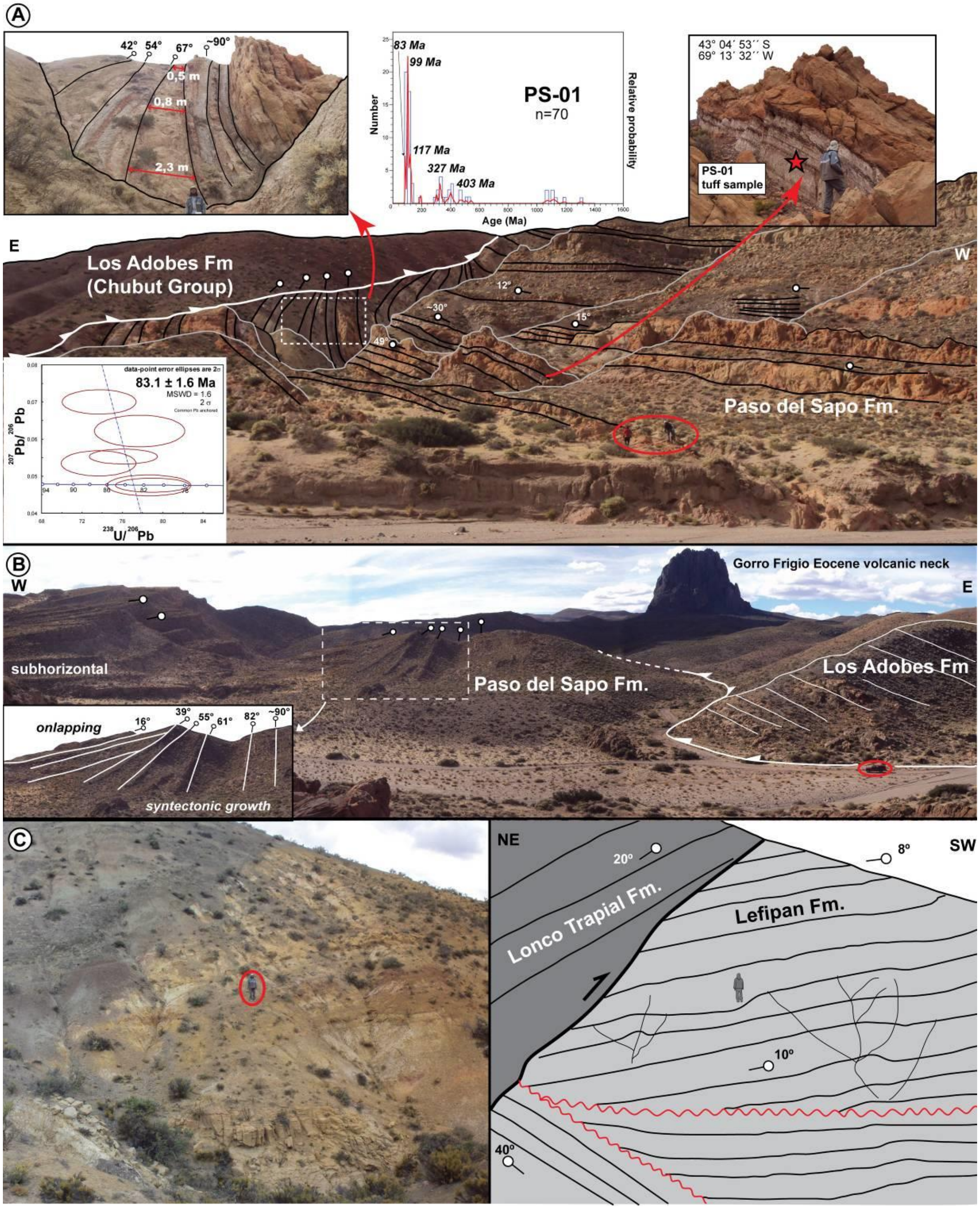


Figure 8. *Synorogenic sedimentary units associated with the Taquetrén thrust. A) West-growing fan of strata in the Paso del Sapo Fm. that opens against the thrust front, from completely overturned to almost horizontal. A tuff level intercalated in the sedimentary sequence yielded an U/Pb age of 83.1 ± 1.6 Ma interpreted as the maximum age of the deposit. Older peaks of 99 and 117 Ma are interpreted as fed from the erosion of the Chubut Group implying an ongoing cannibalization of the wedge-top zone during foreland sedimentation. Red ellipse indicates a person for scale. B) North-view of the same section. C) Shallow marine strata of the*

Maastrichtian to Danian Lefipán Formation, with progressive unconformities, beneath Jurassic volcanics of the Lonco Trapial Formation thrust on top of them.

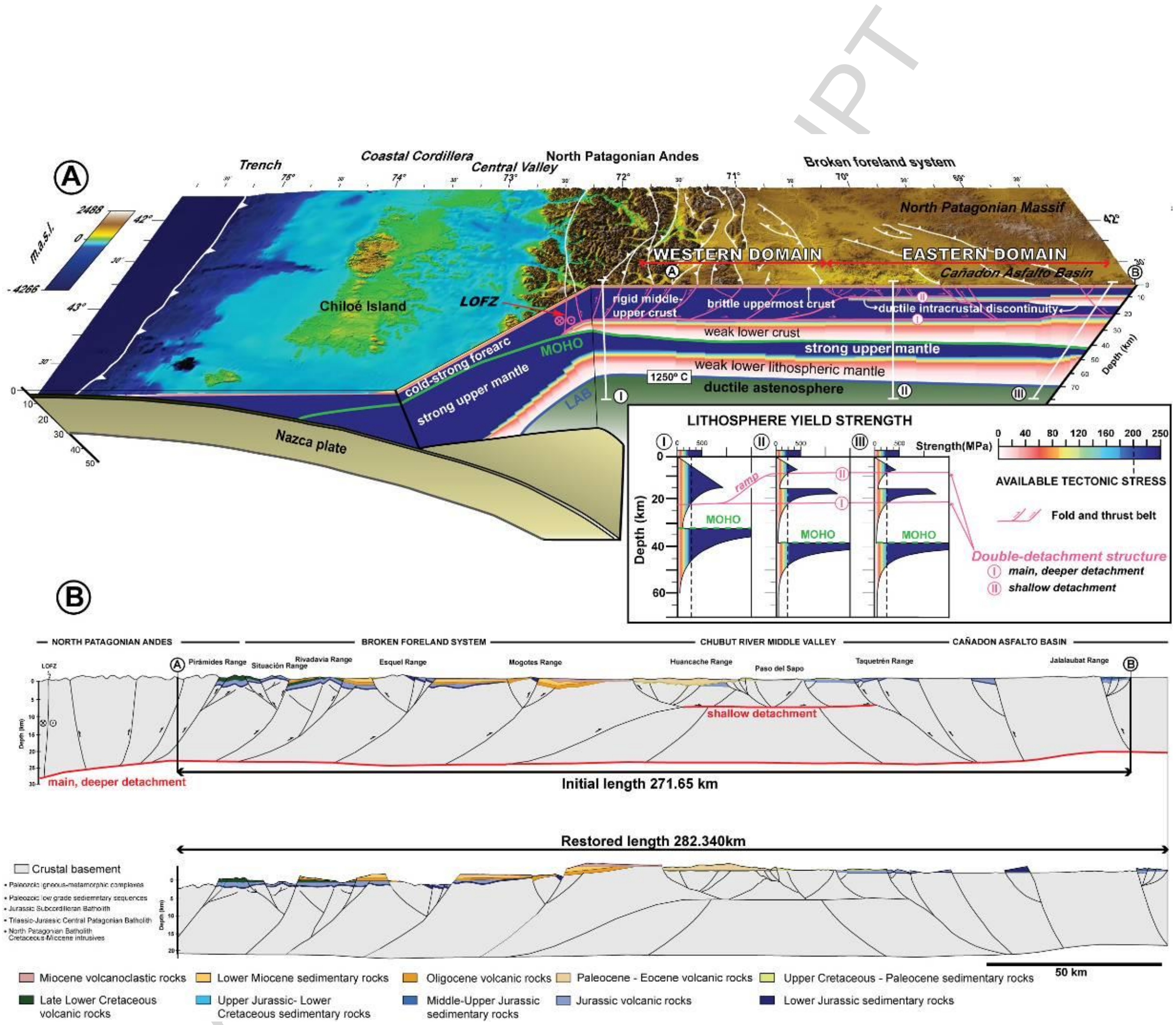


Figure 9. *A) Block diagram with a DEM draped on top. Slab and lithospheric geometries from Tassara and Echaurren (2012). To the right-bottom, yield strength envelopes representing lithospheric strength based on a thermomechanical model. Strong transitions in the strength values are interpreted as brittle-ductile transitions over which the crust is deformed (see text for further details). B) Balanced structural cross profile and restored section that yielded a total shortening of 10.69 km equivalent to a 3.78 % of the initial length whose deeper structure is based on the thermomechanical model.*

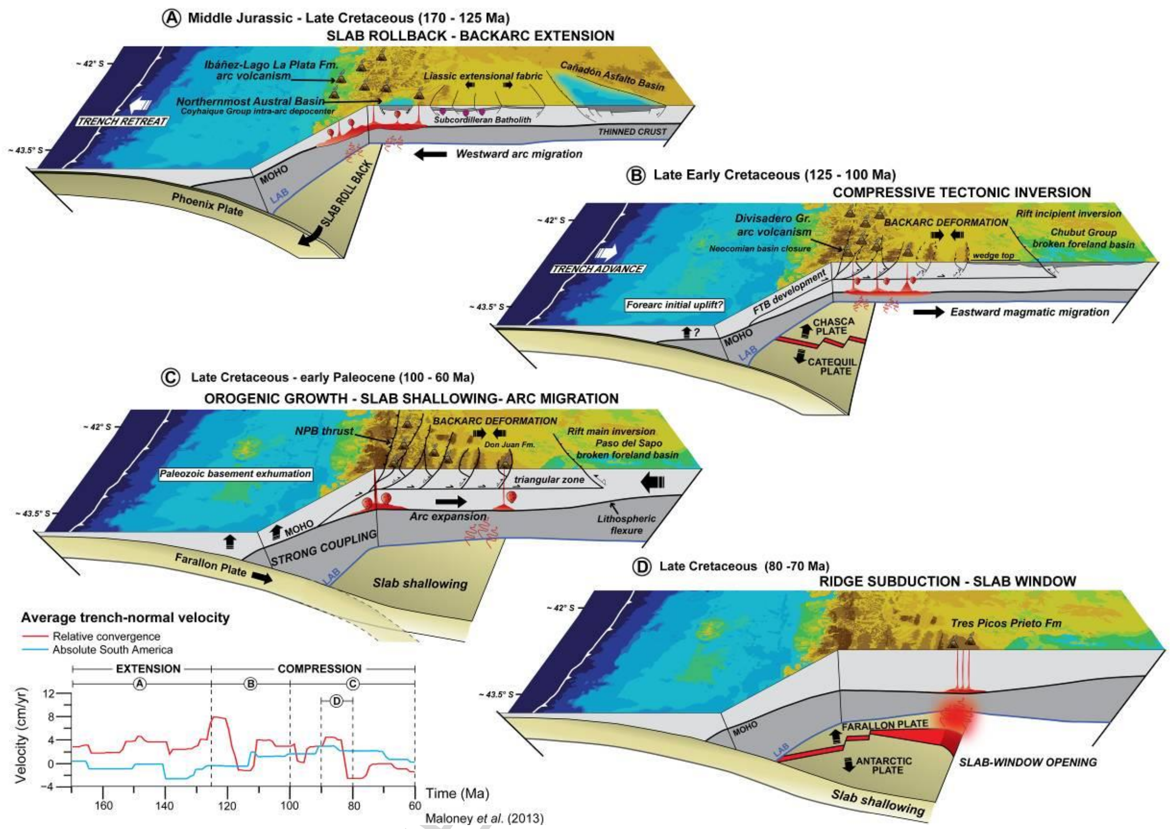


Figure 10. *Schematic representation of the tectonic evolution of the North Patagonian fold and thrust belt from the Jurassic to the Early Paleocene. See Discussion for details.*

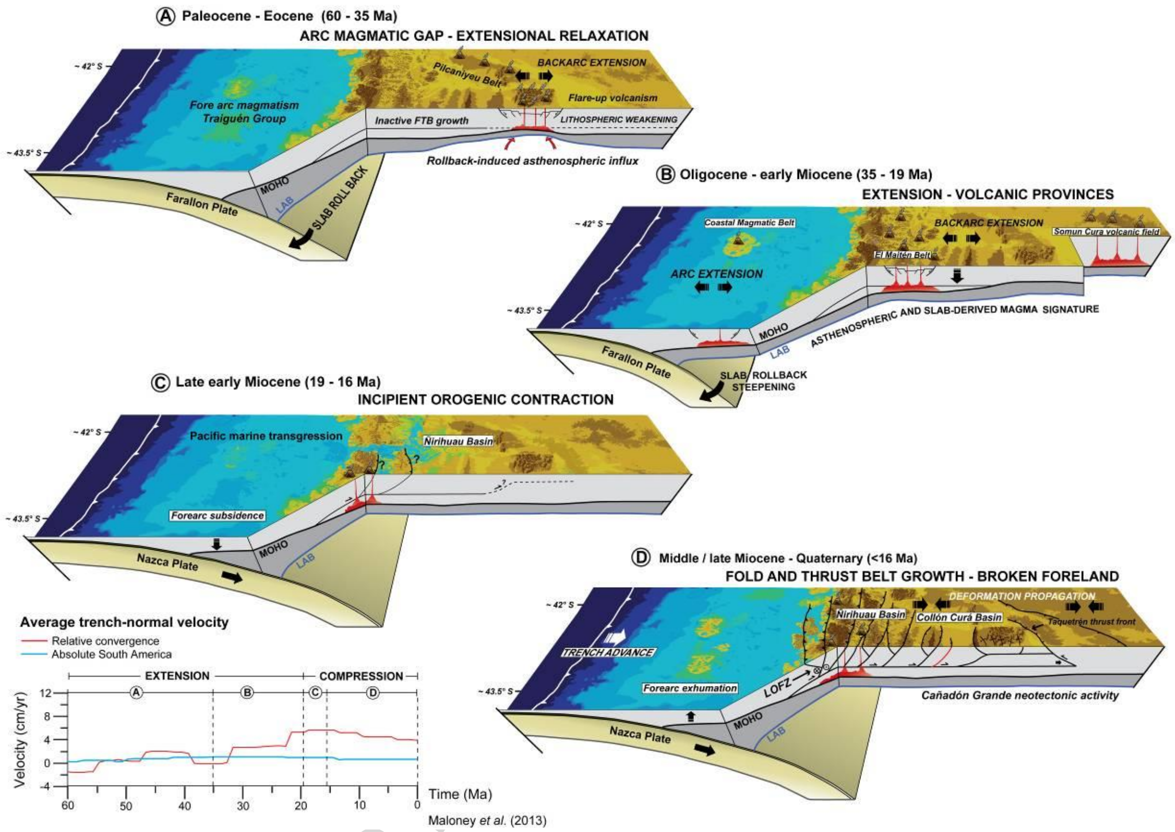
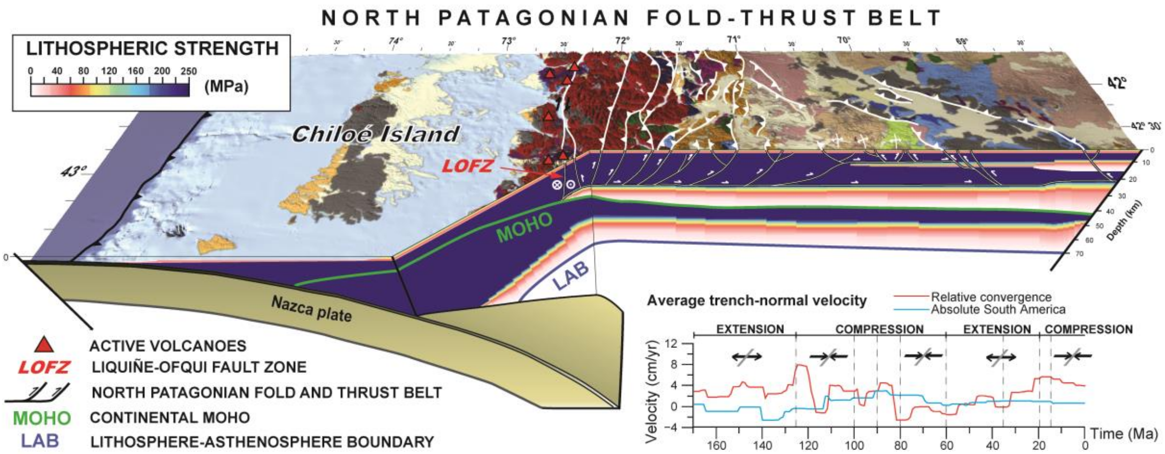


Figure 11. *Schematic representation of the tectonic evolution of the North Patagonian fold and thrust belt from the Paleocene to the present. See Discussion for details.*



Graphical Abstract

Highlights

- The Andes of Northern Patagonia have an abnormal retroarc lateral development
- New field and seismic syntectonic strata constrain timing of deformation
- Forearc exhumation stages known from thermochronology correlate with our data
- Thermomechanical modeling was performed to analyze deep structure
- Two stages of orogenic growth are interrupted by an extensional relaxation period