Tectonic Evolution of the Northern Patagonian Andes (40°S)

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Abstract This chapter is focused on the tectonic evolution of the North Patagonian Andes comprised between 38° and 40°S. Field recognition of main structures allowed establishing a structural control for the main sedimentary packages that coexisted with Andean development. These structures affect Miocene strata at the eastern deformational front, indicating a last stage of development, although cooling ages suggest a Mid to Late Cretaceous exhumation of the Paleozoic basement exposed at the westernmost sector. Synextensional deposits of late Oligocene age imply an interruption of Andean constructional mechanisms at these latitudes. Finally, seismic tomographies at these latitudes show an area of relatively low seismic velocities in the orogenic front area, separated from the arc front zone. Computed elastic thicknesses from gravity data show a good correlation with these areas with abnormal heat flow associated with retroarc stretching and magmatic emplacement in the last 5–2 Ma.

Keywords North Patagonian Andes · Late Oligocene and Pliocene to Quaternary retroarc extension

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1 Introduction

The transitional zone from the arc to the western retroarc at the Villarrica-Lanín volcanoes latitudes is considered a key area to recognize the main constructional stages that shaped the North Patagonian Andes and their mechanisms (Fig. 1). This area has been recently related to a tearing of the Nazca Plate as suggested by a strong segmentation of the subducted slab (Fig. 2) (Pesicek et al. 2012). Based on this work, around 5 Ma ago at ~39–40°S a steeper nearly vertical subduction zone was replaced by a ~30°E subduction zone that led to the present configuration (Bohm et al. 2002; Lüth et al. 2004).

This segment has few structural and tectonic analyses due to a difficult access, a rather homogeneous stratigraphy and no hydrocarbon interest. This chapter analyzes depocenter geometry through field and gravimetric data that were incorporated into the fold and thrust belt. Additionally, it gives general constraints about timing of inversion of those depocenters into the orogenic wedge over the Argentinian slope of the Andes. The retroarc zone at these latitudes is characterized by the superposition of different sedimentary prisms, corresponding to the Late Triassic, late Oligocene–early Miocene, late Miocene, and Quaternary basins. Understanding the geometry of these basins and their relation to the Andean formation are the main objectives of this chapter.

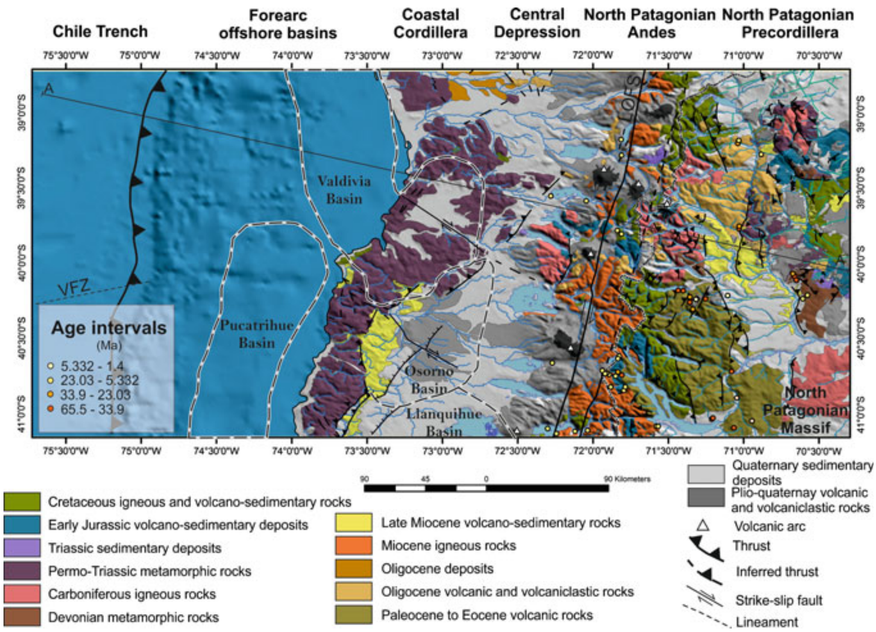

Fig. 1 Simplified geological map between the 39° and 41°S with the main structures of the western-intra and back-arc zones. The A–A′ line shows the structural profile depicted in Fig. 2a. *Color dots* indicate available Cenozoic ages for the intra- and retroarc volcanic rocks

2 Geological Setting

North Patagonian Andean evolution is initially linked to the subduction of the Farallón (previously to 26 Ma) and then the Nazca plates (Cande and Leslie 1986). During the Paleogene, the Farallón Plate subducted obliquely northward, up to its breakup into the Cocos and Nazca Plates (Pardo-Casas and Molnar 1987). This provoked the present relative convergence velocity of 8 cm/a in the N78ºE direction (Somoza 1998). This mild obliquity of the convergence since 26 Ma was associated with a certain degree of strain partitioning of the upper plate, with a major dextral strike-slip N-trending fault zone, known as the Liquiñe-Ofqui Fault system (Fig. 1) that runs through the axial North Patagonian Andes for over 1000 km from 39º 30′ to 47°S (Hervé 1976; Forsythe and Nelson 1985; Cembrano and Lara 2009; Thomson 2002).

The North Patagonian Andes can be divided into a series of morphostructural systems (Figs. 2, 3) (Diraison et al. 1998; García Morabito and Ramos 2012; Giacosa et al. 2005). These systems exhumed a variety of units that range from the Paleozoic, characterized by plutonic and metamorphic rocks (see Thomson and Hervé 2002, for a synthesis) to Cenozoic volcano-sedimentary rocks (Jordan et al. 2001; Radic et al. 2002). In an offshore forearc position between ∼38 and 40ºS, the Valdivia basin (González 1989) has concentrated subsidence in Cretaceous, Eocene, and Miocene times (Fig. 1). To the east, the Coastal Cordillera was interpreted as a Late Carboniferous accretionary prism intruded by Neopaleozoic plutonic rocks (Munizaga et al. 1988; Thomson and Hervé 2002) that extend along the Chilean coast. The eastern sector of this Coastal Cordillera is partly covered by Miocene volcanic and sedimentary units (Vergara and Munizaga 1974) corresponding to a series of depocenters such as the Osorno and Llanquihue basins (Fig. 1). These have been gathered in the Central Depression, corresponding to a 1000-km-long low zone located in the forearc region (Lavenu and Cembrano 1999). These depocenters are exhumed along the Liquiñe-Ofqui Fault system in the eastern limit of the Central Depression, where they are incorporated in the North Patagonian Andes.

The drainage divide area corresponding to the political boundary between Argentina and Chile is constituted by the Patagonian Andes (Fig. 1). A series of stratovolcanoes rises over this structural relief up to 1500 m, among which the Villarrica, Quetrupillán, and Lanín are the most prominent. These volcanic centers are aligned together with monogenic Quaternary volcanic fields through NE and W–NW structures (Lavenu and Cembrano 1999; Lara 2004). Here, the Paleozoic basement is exposed at the eastern-frontal sector by a series of thrusts and backthrusts (Turner 1965; García Morabito and Ramos 2012). Cretaceous plutonic rocks are exposed in batholiths (Pankhurst et al. 1992, 1999) exhumed by structures mainly rooted at the Chilean slope. In this magmatic suite, the Liquiñe-Ofqui Fault system controlled the emplacement of younger Miocene plutons that are along the axial part of the Patagonian Andes (Fig. 2a) (Munizaga et al. 1988; Hervé 1976, 1984; Hervé et al. 1979).

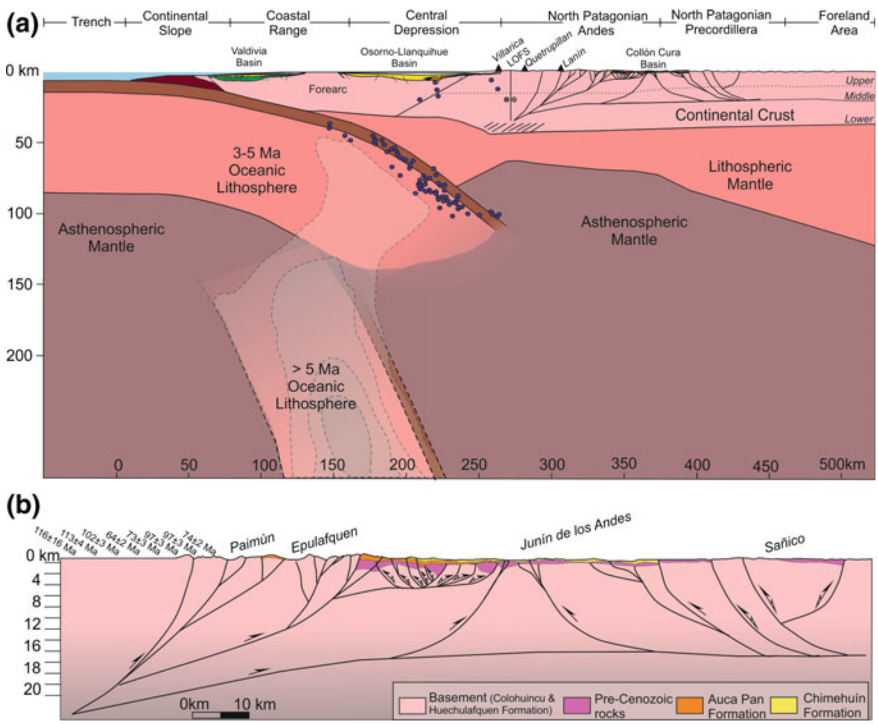

Fig. 2 **a** Lithospheric cross section across the southern Andes at 39–40°S (see Fig. 1 -A to A′- for location in map view). Lower crustal geometry is based on the density model of Tašárová (2007). Crustal and interplate seismicity are based on Dzierma et al. (2012). Superimposed tomography contours of Pesicek et al. (2012) were interpreted as a detached subducted slab at ~5–3 Ma. Forearc structure is based on González (1989), while retroarc structure is based on data of this work. **b** Balanced cross section on the eastern slope of the Andes from the drainage divide area to the foreland zone across Junín de los Andes town. Note three distinctive areas, two where the basement is exposed, and an intermediate where it is covered by Cenozoic sections. Basement depth beneath main sedimentary depocenters was calculated from a gravity model. Note two opposite verging structural systems interfering at Junín de los Andes longitude

North of 39ºS, these rocks are covered by the late Oligocene to early Miocene Cura Mallín Basin composed of volcanic and volcaniclastic rocks locally interfingered with lacustrine and delta deposits (Suárez and Emparan 1995, 1997). This is an intra-arc basin formed during the late Oligocene–early Miocene— extensional stage that affected vast portions of the North Patagonian Andes (Suárez and Emparan 1995; Muñoz et al. 2000; Jordan et al. 2001; Burns et al. 2006; Melnick et al. 2006; Radic et al. 2002; Radic 2010). The Cura Mallín Basin is composed of a series of diachronous depocenters that span from 27 to 16 Ma along the axial zone and western Andean slope (Suárez and Emparan 1997; Radic et al. 2002; Burns et al. 2006). Locally, over the eastern Andean slope, Franzese et al. (2011) described a relatively contemporaneous Aluminé depocenter, composed of

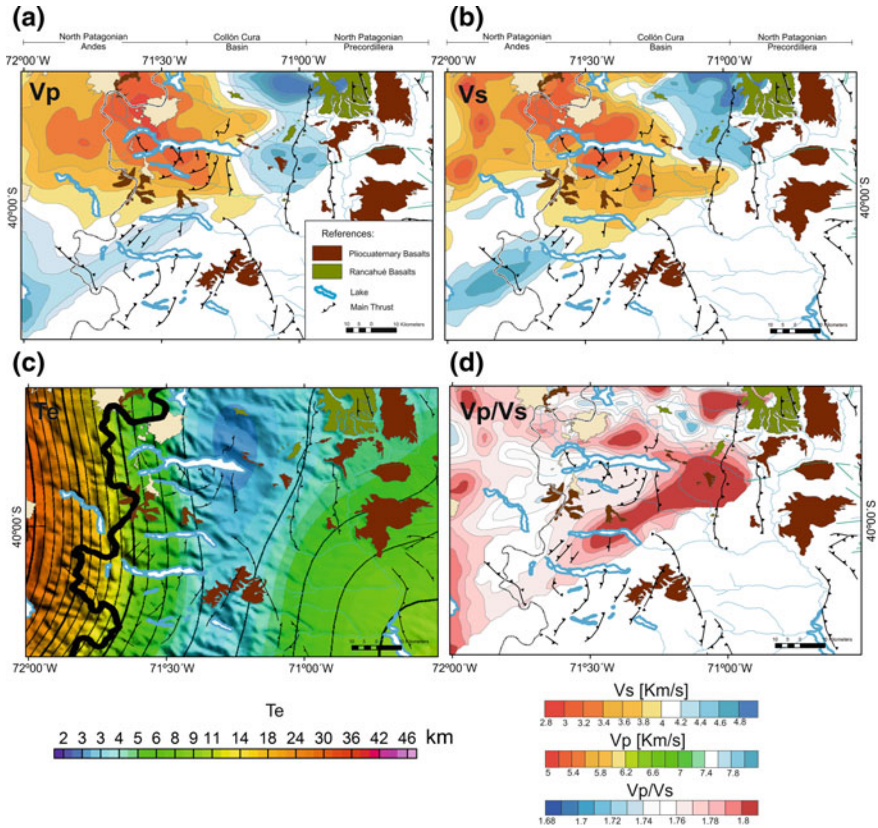

Fig. 3 Seismic velocity structure of the retroarc area at 39–40°S. **a** Vp anomalies at 10 km in depth; **b** Vs anomalies at 10 km in depth; **d** Vp/Vs anomalies at 10 km in depth (Dzierma et al. 2012). Note the spatial correlation that exists between arc and retroarc volcanic centers and related lava fields and seismic low-velocity zones. In particular, note a low-velocity anomaly associated with the volcanic arc particularly pronounced beneath the Villarrica, Quetrupillán, and Lanín Volcanoes. **c** Elastic thicknesses (Te) computed from gravity data that show lower values at the sites of low Vp and Vs

thick clastic deposits derived from the erosion of the crystalline basement, volcanic, volcaniclastic, and epiclastic rocks.

The Collón Cura Basin, to the east of the Patagonian Andes, separates an area of inverted Paleogene depocenters from the North Patagonian Precordillera. The Collón Cura Formation, the main unit filling this basin, was dated by Mazzoni and Benvenuto (1990) in the Río Collón Curá in 15–11 Ma. These are tuffs, ignimbrites, and reworked fluvial deposits, included in the Chimehuín Formation that agglutinates the Collón Cura Formation and the overlying Río Negro Formation of Pliocene age (Turner 1965; Cucchi and Leanza 2005). Spalletti and Dalla Salda (1996) had interpreted this basin as a pull-apart depocenter, based on its geometry and some sedimentary considerations. Contrastingly, Ramos and Cortés (1984) showed that these sedimentary sections were formed by synorogenic deposits, related to the eastward migration of the orogenic front. Similarly, Giacosa et al. (2005) proposed a foreland basin for the origin of these sedimentary successions. More recently, Ramos et al. (2011), García Morabito et al. (2011), and García Morabito and Ramos (2012) described at these latitudes progressive unconformities in the wedge top of the fold and thrust belt, associated with Neogene contractional structures.

An isolated depocenter north of the Collón Cura Basin accommodates a succession of late Oligocene to Miocene rocks. The volcanic rocks of the Auca Pan Formation (Turner 1965, 1973) constitute the dominant exposures of this structural depression, described as the Auca Pan depocenter. These magmatic rocks of the Auca Pan Formation were dated in 29.6 ± 1.2 Ma (K/Ar age, Ramos et al. 2014).

To the east, the North Patagonian Precordillera system is divided into two particular sectors; a western part where mainly Neogene deposits are openly folded and an eastern sector where Triassic depocenters are partly inverted (Franzese and Spalletti 2001; García Morabito et al. 2011; D'Elia et al. 2012). This system has been described as a thick-skinned west-vergent structural belt (García Morabito et al. 2011) that is segmented by NE and W–NW extensional faults that are selectively inverted (D'Elia et al. 2012). The inverted Sañicó depocenter is the southernmost expression of the Precordillera. Its volcano-sedimentary filling corresponds to the Late Triassic Precuyano and Early Jurassic Cuyano cycles (Gulisano et al. 1984; Gulisano 1993) that constitute the syn-rift constituted during the Pangea breakup at these latitudes.

3 Upper Crustal Structure

A structural transect has been performed across the North Patagonian Andes and the North Patagonian Precordillera region identifying and analyzing in detail the following domains (Fig. 2b): (i) a western sector formed by east-verging thrusts and limited amounts of backthrusts that exhume the Paleozoic basement. This sector has thick-skinned faults that to the east determine a basement wedge. The eastward boundary of this system is the Piedras Paradas fault, which uplifts the basement over the late Oligocene Auca Pan Formation. (ii) To the east, a system with a shallower decollement is associated with folds with characteristic short wavelength amplitude that to the east become more open. The geometry determined of the main depocenters is concordant with the described surficial faults interpreted as inverted normal faults that bound the main sedimentary thicknesses. This intermediate sector shows a series of halfgraben features limited to the east by a deeper east-verging N-thrust near the Junín de los Andes valley. (iii) The eastern system is dominated by west-verging thick-skinned faults that characterize the North Patagonian Precordillera. The westernmost fault through this system is the Media Luna fault that determines a triangular zone together with the previous east-verging fault array with a decollement inferred at 15 km depth. The easternmost structures exhume the Sañicó depocenter exposing Late Triassic syn-rift sections.

This section was constrained by gravity data that allowed computing sedimentary infills at the intermediate region from the gravity density model identifying sections up to 3000 m in thickness. Calculated sedimentary depocenter geometries were introduced in the structural section, where 700 m corresponds to the maximum thickness of the Auca Pan Formation and 500 m for the Chimehuín Formation (Cucchi and Leanza 2005). An additional, not outcropping, sedimentary section needs to be added in depth that is considered corresponding to Mesozoic deposits buried beneath Cenozoic piles based on their direct exposure on the eastern analyzed zone (Fig. 2b).

4 Lower Crustal Structure

Dzierma et al. (2012) calculated Vp and Vs anomalies as deviations from a 1D background velocity model, shown in a series of horizontal sections at 10, 30, and 50 km deep, respectively. Along these, a low velocity anomaly at lower crustal and upper mantle levels is particularly pronounced beneath the Villarrica, Quetrupillán and Lanín Volcanoes. These authors regarded this to either an expression of a melt reservoir from which these volcanoes are fed or to a reduced mantle wedge density due to volatile addition from a highly serpentinizated subducted slab. This area lies at the crossing point between the Liquiñe-Ofqui Fault system and the extrapolation of the Valdivia fracture zone in the Nazca plate that are considered natural paths for fluids coming from the subducted slab.

Elastic thicknesses (Te) computed from gravity data show low values in an elongated area parallel to the Andean front, east of the Lanín volcano (Ramos et al. 2014). Te values at the arc front are relatively higher than in the described anomalous area, which is not consistent with Vp and Vs anomalies determined by Dzierma et al. (2012). However, seismic data are mostly missing at the southeast studied area, enabling direct comparison between both datasets. Finally, around the Lanín volcano area, there seems to be a consistency between low Vp and Vs values and low elastic thicknesses (Fig. 3).

5 Discussion

The fold and thrust belt between 39º and 40ºS is dominated by the inversion of previous normal faults that produced in the western analyzed area east-verging structures and in the east west-vergent faults that exposed the Neopaleozoic basement. These two systems interfere at the central part where younger successions of late Oligocene to Miocene age are differentially preserved. In the eastern section, Triassic–Jurassic extension affected the present foreland area concentrated in the

Sañicó and the Piedra del Aguila depocenters and the series of eastern depocenters that constitute the Huincul system. In the western section, the Auca Pan depocenter concentrates the Oligocene to early Miocene sedimentary record that could have a Triassic section beneath, as it is inferred from gravity data.

Contractional deformation is thought to have acted in two different stages, beginning in the Late Cretaceous (Fig. 4), as it is indicated by available cooling K/Ar ages in Neopaleozoic rocks (García Morabito and Ramos 2011). This deformational stage affected the whole Andes at these latitudes, from the Coastal Cordillera, through the Patagonian Andes and the North Patagonian Precordillera (Burns et al. 2006; García Morabito and Ramos 2012; Thomson 2002). Coetaneous to this process, the arc expanded from the western Chilean Andean slope to the retroarc zone (Ramos and Folguera 2005). This eastern volcanic front rested over the Argentinean side of the Andes until the early Eocene (Llambías and Rapela 1984, 1989; Franchini et al. 2003), when it retracted to the west (Fig. 4). After this, late Oligocene to early Miocene extensional Auca Pan (≤29 Ma)–Rancahue (≤26 Ma)–Cura Mallín (≤17 Ma) series of depocenters were developed at the western retroarc area with a volcanic front located over the Chilean Andean side (Suárez and Emparan 1995; Jordan et al. 2001; Radic et al. 2002; Franzese et al. 2011; García Morabito and Ramos 2012). These sections have been emplaced under low-pressure conditions associated with a normal crust as it is indicated by geochemical data (Ramos et al. 2014, and see references therein).

A second contractional event affected the area in late Miocene times, reactivating the Patagonian Andean and the North Patagonian Precordilleran systems. This is evidenced by deformation affecting late Miocene sedimentary sections. During this time, the arc retracted at the intra-arc Liquiñe-Ofqui fault system (Fig. 4).

Pliocene to Quaternary times is characterized by important volumes of basaltic plateaus that were emplaced at the retroarc area (Fig. 4). Low Vp and Vs anomalies would indicate a heated middle crust partly coincident with computed low elastic thicknesses.

As indicated, seismic tomographies allow inferring the presence of a subducted steeper older slab beneath the present subduction zone (Figs. 2, 4) (Pesicek et al. 2012). This has been considered an evidence of a slab tearing associated with the steepening of the subduction zone at these latitudes some 5–3 Ma ago (Fig. 4). This is potentially related to the upwelling of hot asthenospheric mantle, and thermal anomalies in the middle crust described by Dzierma et al. (2012), related low Te values, and retroarc volcanic eruptions.

Expansions and narrowings of the volcanic arc at the studied latitudes showed to be contemporaneous to the described contractional and extensional stages; while the subduction of the Valdivia transform fault and the strong tearing that the Nazca plate exhibits would explain the present seismic velocity structure of the crust.

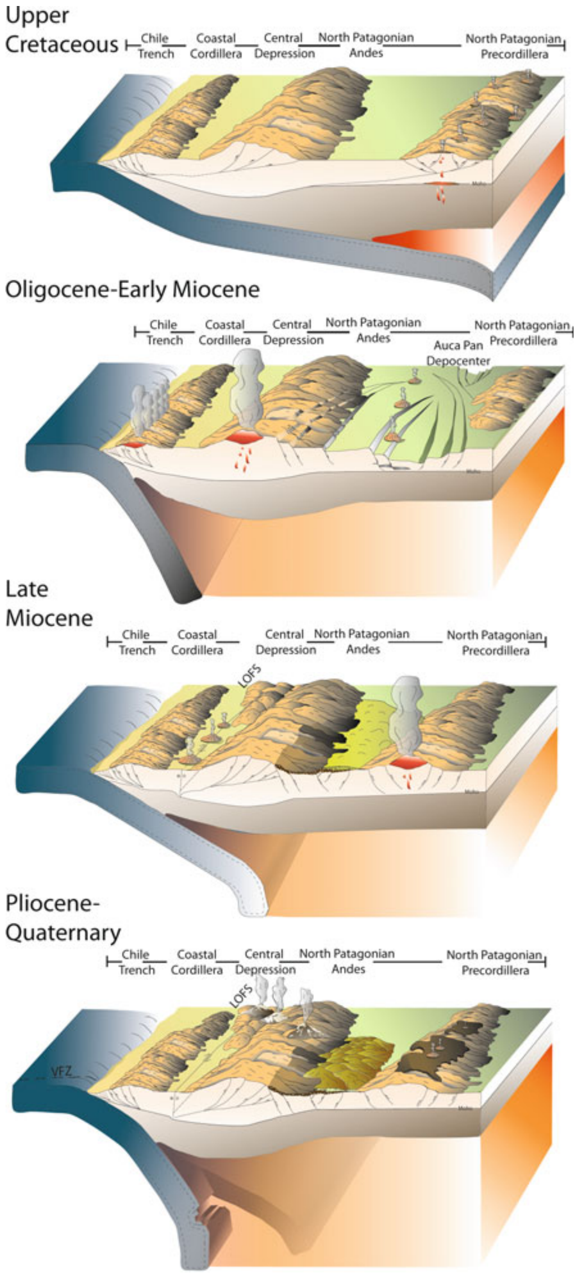

Fig. 4 Schematic block diagrams summarizing the evolution of the North Patagonian Andes since the latest Cretaceous to Pliocene–Quaternary times nearby the 40ºS (see text for further details)

6 Conclusions

The present chapter exemplifies how the North Patagonian Andes are characterized by a long and complex deformational history. Three different sectors have been described with characteristic behaviors. These sectors have been uplifted by the inversion of previous extensional structures from the Triassic–Jurassic and the Oligocene times. During this evolution, two main extensional periods occurred, first during the Triassic–Jurassic associated with Pangea breakup and then during Oligocene times. Contractional stages have taken place during the Late Cretaceous and the upper Miocene, respectively, affecting vast proportions of the fold and thrust belt. The first stage is determined at these latitudes mainly from K/Ar ages, interpreted as cooling ages, while the youngest by the age of sedimentary and volcanic sections deformed at the Andean front.

Recently, released seismic tomographies show the present geometry of the subduction system at these latitudes where slab detachment processes are described. This slab detachment would have given place to the injection of an asthenospheric inflow under this segment of the North Patagonian Andes. Thermal conditions revealed by low Vp and Vs velocities and Te values, together with the occurrence of less than 5 My mafic rocks at the retroarc zone, could be linked to this particular environment.

Oscillations of the subducted slab through time inferred by the arc behavior coincide with the deformational regimes that affected the North Patagonian Andes.

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