Tectonic evolution of the Andean Fold and Thrust Belt of the southern Neuquén Basin, Argentina

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Abstract: The Andean Fold and Thrust belt between 36° and 39°S can be divided in two sectors. The Eastern Sector corresponds to the Agrio Fold and Thrust Belt (FTB) characterized by a major exhumation during the Late Cretaceous, and minor deformation during the late Eocene and Late Miocene. The Western Sector corresponds to the main cordillera and is characterized by a complex evolution that involves periods of out-of-sequence thrusting with respect to the previously deformed outer sector, and pulses of relaxation of the compressive structure. Cretaceous uplift constituted an orogenic wedge that extended to the inner sectors of the Agrio FTB. Eocene compression was mainly concentrated within the Western Sector but may have reactivated the pre-existing structures of the Agrio FTB, such as the Cordillera del Viento. Late Miocene minor compressional deformation occurred in the retro-arc area and extended into the foreland area. This deformation event produced the closure of a short-lived intra-arc basin (Cura Mallín Basin, 25–15 Ma) at the innermost sector of the FTB. The Pliocene and Quaternary, between 37°30′and 39°S, have been periods of relaxation of the inner part of the FTB and fossilization of the Agrio Fold and Thrust Belt.

Localization of episodic late Oligocene–Early Miocene and Pliocene to the present extensional structures in the intra- and inner retro-arc is controlled by pre-existing Jurassic half-grabens related to the formation of the Neuquén Basin. The Jurassic rift seems to be controlled by deep crustal–lithospheric discontinuities derived from a Proterozoic–Palaeozoic history of amalgamation in the area, now deeply buried under multiple episodes of Mesozoic–Tertiary synorogenic and synextensional sedimentation.

Geophysical studies have revealed that the Andes mountain belt is extremely variable in crustal thickness and topography (Introcaso *et al.* 2000). The topography varies between broad amplitudes greater than 700 km measured from the trench, and narrow belts restricted to the inner sectors of the fold and thrust belt. These variations are mainly related to shortening within the Andes (Ramos *et al.* 2004). However, the causes of variable shortening and relief remain open to discussion and include several key factors: (1) shortening of the mantle lithosphere related to overthrusting of the Andes over old cratonic shields (Lyon-Caen *et al.* 1985; Lamb & Hoke 1997; Kley *et al.* 1999); (2) pre-existing anisotropies in the foreland of the orogen pre-dating the Andean orogeny, which differentially deformed under compression (Allmendinger & Gubbels 1996); (3) changes in the lithospheric thermal structure and the consequent development of brittle–ductile transitions that become new detachments where the upper crust yields and is stacked over the foreland (James & Sacks 1999; Ramos *et al.* 2002); and (4) climate (Beaumont *et al.* 1992; Thomson 2002).

At this latitude (37°–39°S), the Andean mountain belt deforms the Mesozoic Neuquén Basin (Fig. 1). The maximum topographic heights are restricted to a narrow band next to the volcanic arc, and the external zone represents a smooth surface where older deformations have taken place during the Late Cretaceous and Palaeogene (Fig. 1) (Zapata *et al.* 1999, 2002). The lack of amplitude and height of the orogenic system, in comparison with neighbour segments to the north, are in accordance with the minimum shortening computed from surface structures and crustal roots (Zapata *et al.* 1999; Ramos *et al.* 2004).

The tectonic evolution of the Andean mountains in the southern portion of the Neuquén Basin reveals certain anomalies to the general

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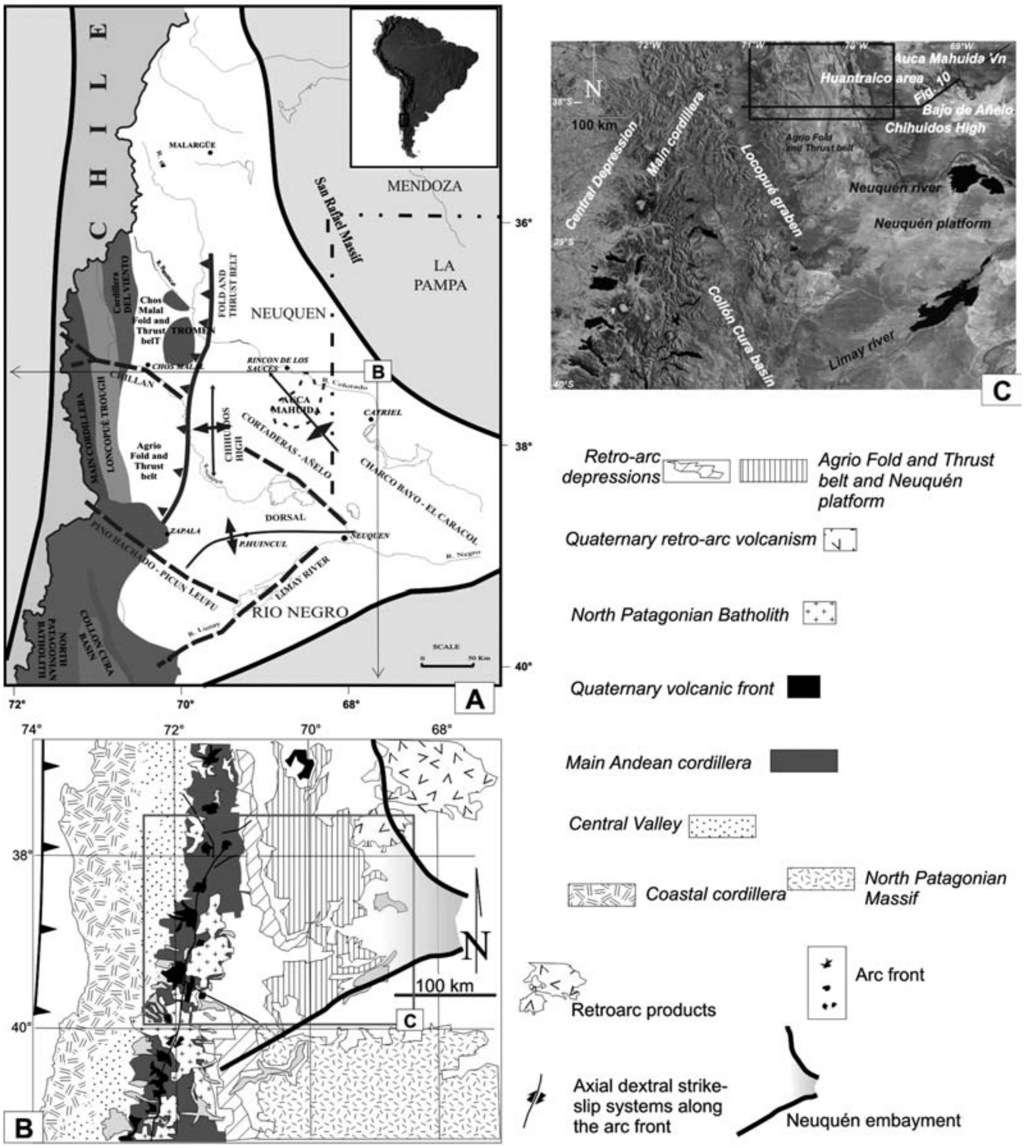

Fig. 1. Regional location map, where main morphostructural units of the Andes between 36° and 40°S are displayed. (**A**) Arc and retro-arc morphostructural units. (**B**) Fore arc to retro-arc systems mentioned throughout the paper. (**C**) Thematic mapper scan of the area occupied by the Neuquén Embayment during the Mesozoic from the western to the eastern side of the present Andean belt. The square represents the area of Figure 5 and the black line indicates the position of the profile in Figure 10.

picture of progressive foreland-propagating deformation in the Andes. These anomalies are characterized by a positive roll-back velocity, since the break-up of southern Gondwana (Ramos 1999*b*), and periods of foreland propagation of thrust sheets alternating with periods of tectonic relaxation, possibly originated from changes in the Wadati–Benioff geometry. However, are these real anomalies from the Andean orogeny point of view or do they exemplify a long-standing process in many segments along the Andean chain that elsewhere have been obscured by younger tectonic imprints? Other subduction-related orogens around the world show that tectonic relaxation in the inner sectors of fold and thrust belts is a common process, and is related to changes in boundary conditions such as oblique convergence between plates, subduction acceleration and roll-back velocity (Pe-Piper *et al.* 1995; Petford & Atherton 1995; Jolivet & Faccenna 2000; Morley 2001; Melnick *et al.* 2003).

The objective of this study is to illustrate the evolution of a particular segment of the Andes, where the presence of certain anomalous features may highlight the evolutionary path of the whole Central Andean system. This segment (37°30′–39°S) is suitable to reveal these anomalous features, particularly along the inner sectors of the fold and thrust belt, due to the oscillatory behaviour of the arc front (Mpodozis & Ramos 1989), in contrast to the rest of the Austral Central Andes (5°–35°S) where the continuous foreland progression of the volcanic arc has obscured parts of the contractional history. This study focuses on the connection of the foreland and hinterland deformation, and assesses the complexity of the process by addressing the questions posed above.

Tectonic framework of the Andean Fold and Thrust Belt

Three morpho-structural units can be identified between 36°15′ and 38°30′S (Figs 1 & 2) from west to east. (1) The main Andean cordillera (71°45′ − 71°W), located at the arc front and at the inner retro-arc area, where mainly Tertiary volcaniclastic sequences are exposed. These ranges, located mostly within the hinterland orogenic region, have experienced a rather complicated evolution where the normal progression of thrusts sheets has been interrupted during periods of orogenic relaxation (Ramos & Folguera 2005). (2) The inner sector of the Agrio Fold and Thrust Belt (FTB) is composed of Jurassic–Lower Cretaceous predominantly marine units of the Neuquén Basin that have been deformed since Late Cretaceous times. (3) The outer sector of the Agrio FTB, where mainly Cretaceous–Miocene rocks occupy an almost peneplaned surface, that was continuously deformed up to the late Miocene (Figs 1 & 2).

The Agrio FTB

The Neuquén Basin Mesozoic deposits are incorporated in both the Inner and the Outer Agrio FTB (Ramos 1977). Documentation of timing of tectonic activity by synorogenic Tertiary volcaniclastic deposits is restricted to a few remnants in narrow intermontane basins (Ramos 1998; Zapata *et al.* 2002) (Figs 3 & 4).

Stratigraphy

The basement of the Mesozoic Neuquén Basin is composed of a thick pile of volcanic sequences

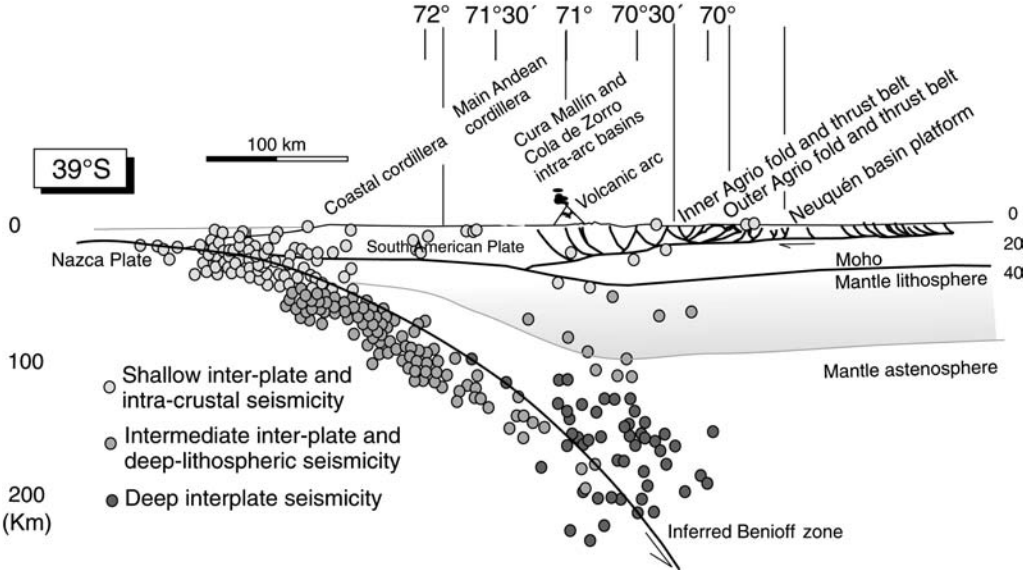

Fig. 2. Lithospheric cross-section representing the Agrio FTB and inner areas of deformation linked to intra-plate seismicity. The forearc seismicity was taken from Bohm *et al.* (2002) and the retro-arc seismicity from Folguera *et al.* 2003.

of the Choiyoi Group (Fig. 3). These units are related to an episode of crustal extension that affected most of the Andean region and Patagonian platform during the Permian (Kay *et al.* 1989). These rocks crop out at the NE and SW basin border, where the Late Jurassic–Early Cretaceous tectonic subsidence that formed the Neuquén Basin did not take place; and along the inner sector of the Agrio FTB (Cordillera del Viento, Fig. 1), (Zollner & Amos 1973) as part of uplifted basement blocks during the Andean deformation (Kozlowski *et al.* 1996; Ramos 1998; Zapata *et al.* 1999, 2002).

The oldest Mesozoic units exposed on the western side of the fold and thrust belt correspond to the Kimmeridgian continental sandstone of the Tordillo Formation (Gulisano & Gutierrez Pleimling 1994). The older Jurassic sequence and basement units crop out at the core of the Cordillera del Viento range (Fig. 1), and has been documented by borehole data from the Cerro Mocho x-1, drilled by YPF (the former National Oil Company). Coeval Jurassic volcanic units west of the Cordillera del Viento are dated at 167.7 ± 8 Ma (Rovere 1993, 1998).

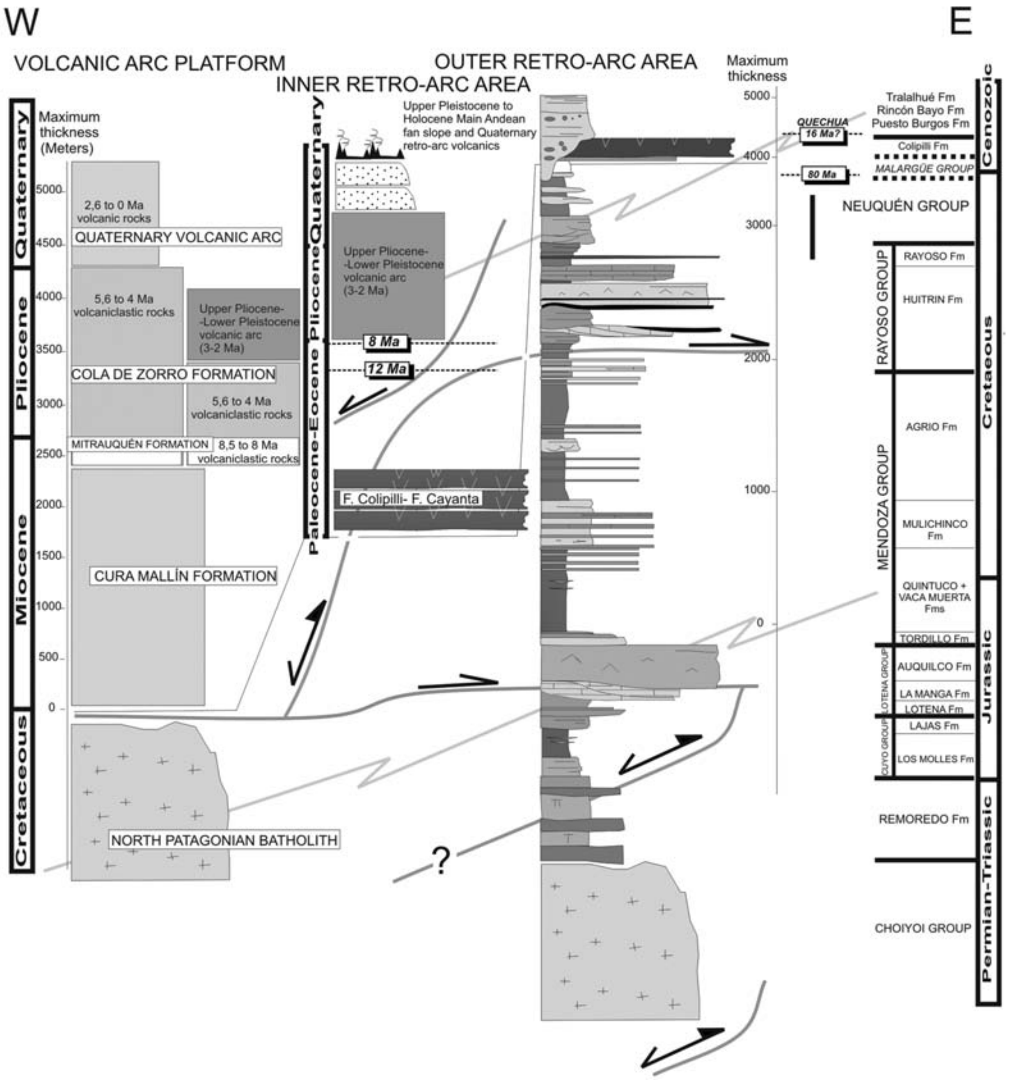

Fig. 3. Stratigraphic chart corresponding to the western slope of the Andes between 36° and 39°S.

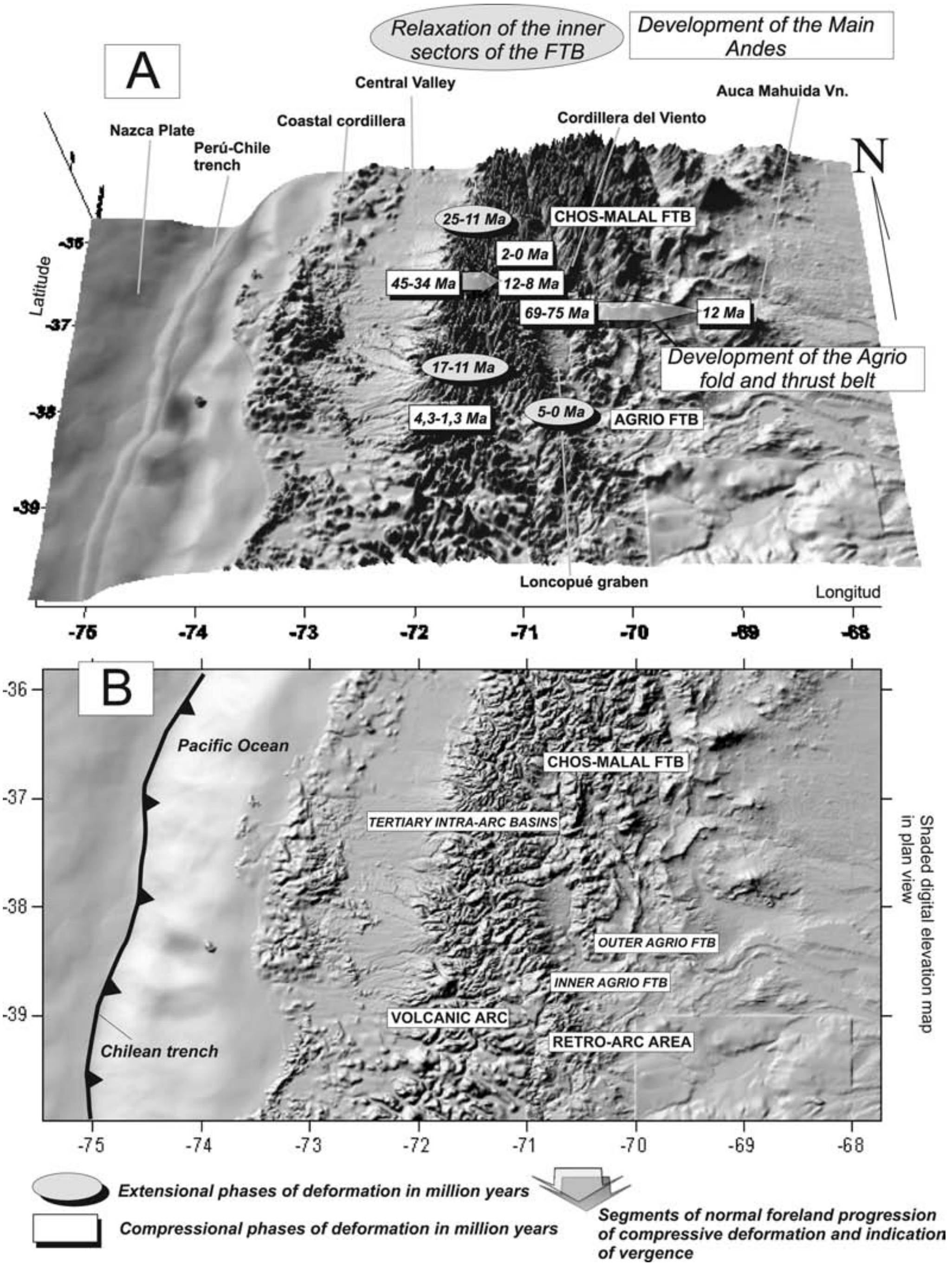

Fig. 4. (**A**) Agrio and Chos Malal FTB to the right and the main cordillera to the left and main episodes of deformation registered by fission-track data, fossil associations in synorogenic strata and regional unconformities (ages were taken from Suárez & Emparán 1997; Ramos 1998; Zapata *et al.* 1999, 2002; Jordan *et al.* 2001; Gräfe *et al.* 2002). (**B**) Shaded topographic model. Plan view of the area represented in (A), where main tectonic elements are displayed with their corresponding morphological expression.

The Jurassic sandstones are overlain by Tithonian–Neocomian marine shales, platform carbonates, salt and gypsum units (Huitrín Formation) of the Mendoza Group (Fig. 3). These successions represent the period of basin expansion throughout the whole retro-arc region. At this stage, the Neuquén Basin was a back-arc basin strongly affected by tectonic and eustatic sea-level changes due to a narrow connection with the ocean toward the NW (Ramos 1977). These Mesozoic units are capped by evaporites and continental sandstones – Huitrín Formation (Aguirre-Urreta & Rawson 1997). The Jurassic Auquilco and Lower Cretaceous Huitrín evaporites constitute the regional decóllements (treated here as compressional detachment zones) (Fig. 3) of both the inner and outer Agrio FTB (Ploszkiewicz 1987).

The westernmost outcrops, related to the Mesozoic extensional sequences of the Neuquén Basin, can be traced to the Quaternary arc on the Chilean slope of the Andean cordillera, where Lower Jurassic turbidites are thrust over Upper Miocene volcaniclastic sequences in the Lonquimay region (De la Cruz & Suárez 1997).

The Mesozoic rocks were intruded along the eastern slope of the Andes by andesitic–dacitic subvolcanic bodies of the Collipilli Formation, which are unconformably overlaid by dacitic–andesitic lavas of the Cayanta Formation. These units are also known as *Serie Andesítica* (44–49 Ma: Llambías & Rapela 1987, 1989). However, ages as old as Paleocene have been determined (Rovere 1998; Jordan *et al.* 2001). In the Argentinean side, these volcanic facies regionally overlie the Mesozoic deposits with an angular unconformity (Fig. 3). These volcanics and related rocks are also found in a N–S trend along the western Neuquén Basin, although the western edge is not precisely defined due to the presence of profuse upper Palaeogene deposits.

Structure

The structure of the Agrio FTB is characterized by a combination of thin-skinned and thick-skinned structures (Fig. 5). This FTB is bounded to the east by the Los Chihuidos high and to the west by the Loncopué trough (Fig. 1). The Agrio FTB is divided into two regions: the Inner Sector, where the exposed folds are related to the inversion of a Mesozoic extensional structure called the 'Tres Chorros extensional system', and the Outer Sector (Ramos 1977; Ramos & Barbieri 1989; Vergani *et al.* 1995), which is composed of tight axially extended anticlines that bound basement blocks (Fig. 5) (Zapata *et al.* 2002). The deformation in this part of the fold and thrust belt has experienced several episodes (Zapata *et al.* 2002), that have been recorded by synorogenic deposits. The last compressional pulse of deformation is as old as Middle Miocene, when the whole FTB was thrust towards the foreland area, probably using the pre-existing Jurassic detachment (Zapata *et al.* 2002) inherited from the extensional period of the Neuquén Basin (Figs 1 & 2). The related synorogenic deposits of the Agrio FTB are buried in the Bajo de Añelo area to the east of the study area (Fig. 1) (Ramos 1999*a*).

Structure of the Inner Sector

The Inner Sector of the Agrio FTB includes the southern extent of the 'Cordillera del Viento' basement uplift (Figs 1 & 4). It corresponds with the 'Tres Chorros extensional system' (Vergani *et al.* 1995) that is composed of a series of NW-trending broad anticlines associated with an inverted half-graben, inherited from the Jurassic Neuquén Basin opening (Ramos 1998) (Fig. 5). One such structure is the Cerro Mocho anticline (Fig. 5); a doubly-vergent basement uplift that resembles a 'pop-up' structure. Two-dimensional (2D) seismic data show that the eastern limb of the structure is affected by a deep fault that cuts across the sedimentary sequence through the Auquilco Jurassic evaporites; transferring more than 6 km of shortening to the thin-skinned structures of the Outer Sector (Zapata *et al.* 2002) (Fig. 5). Borehole data of the CMO x-1 well documented more than 1500 m of Jurassic synrift sequences (Fig. 5). This anomalous thickness is interpreted to be associated with an extensional half-graben that was inverted during the Andean orogeny.

Structure of the Outer Sector

The structure of the Outer Sector is composed of thin-skinned tight folds associated with deep faults (Fig. 5). Borehole and 2D seismic data show that the deep faults are detached from the Jurassic Auquilco evaporites and propagate up through the sequence until they reach the Cretaceous Huitrín evaporites (Fig. 5), conforming fault-bend fold structures. The upper units of these structures, corresponding to the Agrio Formation (Figs 3 & 5), have been locally deformed by flexural folding, adding a detachment folding component (Zapata *et al.* 2002). Borehole data show that the external structure of the Agrio FTB is characterized by a refolded triangle zone bounded on the eastern side by a backthrust that cores fault-related fold (Zapata *et al.* 2002) (Fig. 5).

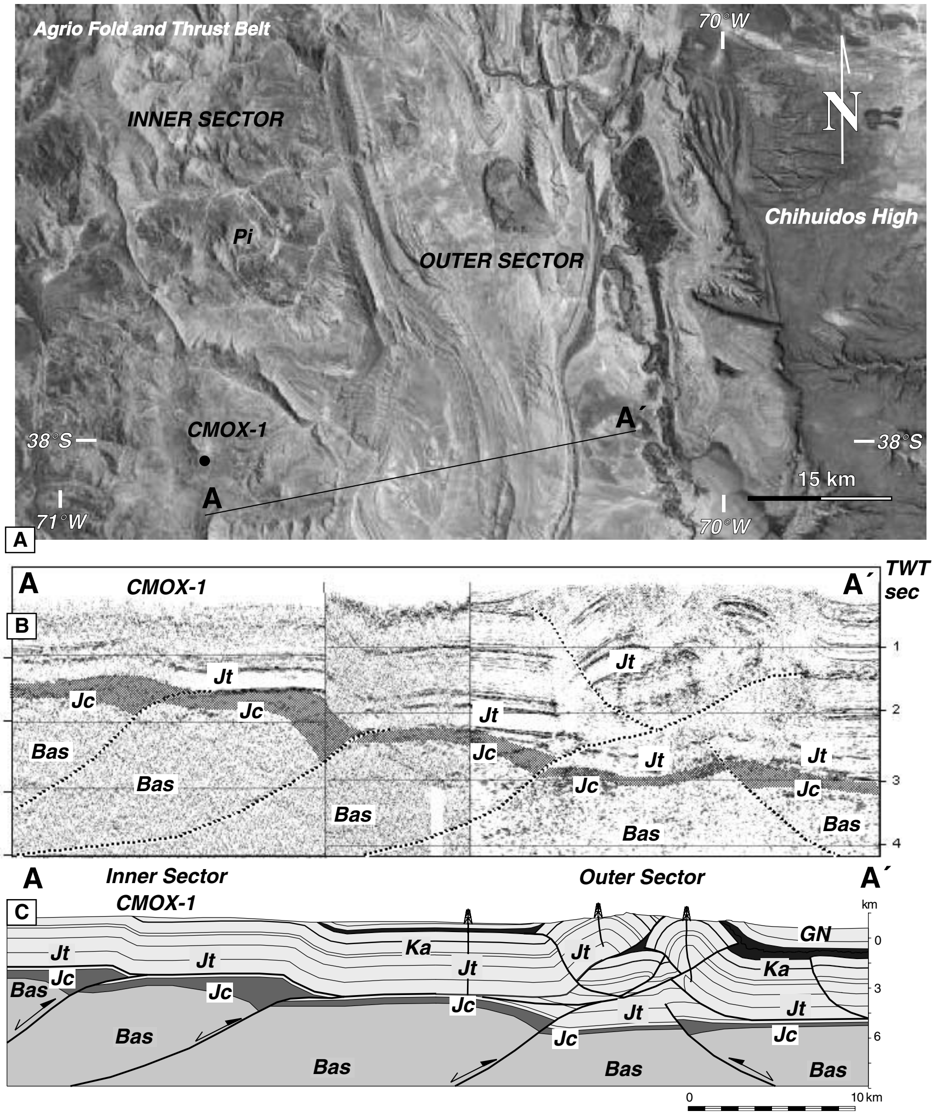

Fig. 5. Agrio FTB and the relationship between the inner and outer sectors. (**A**) Thematic mapper image and main localities cited in the text. (**B**) Integrated seismic line. (**C**) Structural section from the inner to the outer sector of the fold and thrust belt. Bas, basement of the Jurassic–Cretaceous succession Choiyoi – Group; Jc, Cuyo Group; Jt, Tordillo Formation, Ka, Agrio Formation, GN: Neuquén Group. CMOX-1: Cerro Mocho anticline. Pi: Pichaihué syncline. The black colour of the structural cross-section indicates the Huitrín evaporite (used as the upper detachment of the Agrio FTB structures).

Uplift and temporal constraints

The beginning of the Andean deformation of the Inner Sector of the Agrio FTB took place during the Late Cretaceous (Ramos 1977). An Ar/Ar biotite cooling age of 69.09 ± 0.13 Ma from igneous rocks of the Cordillera del Viento (northern continuation of the Inner Sector of the Agrio FTB, Fig. 4) (Kay 2001) supports the Late Cretaceous timing for uplift. The study also revealed that at that time there was already 3000 m of exhumation. Fission-track cooling ages from an igneous stock located at the core of the Cordillera del Viento and from sedimentary units from the eastern side recorded two main cooling events (Burns 2002): the first episode took place between 80 and 70 Ma (Late Cretaceous), and the second one between 7 and 5 Ma (Late Miocene). The Late Cretaceous cooling event coincides with a 71.5 ± 5 Ma K/Ar emplacement age for andesitic dykes of the Pelán Formation that intrude previously deformed Cretaceous sediments south of the Domuyo Volcano (Llambias *et al.* 1978), 50 km to the north of the Cordillera del Viento (Fig. 4).

An uppermost constraint for the Late Cretaceous deformation event of the Andean deformation is present on the western flank of the Cordillera del Viento. There an angular unconformity separates the *Serie Andesítica* igneous rocks from the Permian basement of the Choiyoi Group (Zollner & Amos 1973). Ar/Ar radiometric ages of the Serie Andesítica rocks yielded an age of 56 Ma (Jordan *et al.* 2001).

The uplift of the Cordillera del Viento is interpreted to be related to a deep fault (bounded by a backthrust on its western side) that has transferred the shortening to the Outer Sector of the Agrio FTB (Kozlowski *et al.* 1996). This fault may be connected to a previous Jurassic extensional detachment (reactivated as a décollement, i.e. compressional detachment, during the Andean deformation) that formed the Neuquén Basin (Zapata *et al.* 2002), (Fig. 5). If this interpretation is correct, part of the Upper Cretaceous Andean deformation had to affect the Agrio FTB.

Field cross-cutting relationships on the Inner Sector of the Agrio FTB show that there are extrusive volcanic rocks of the Lower Eocene Cayanta Formation (44–49 Ma: Llambías & Rapela 1989) covering the previously deformed Cretaceous units of the Neuquén Basin (Fig. 3) (Repol *et al.* 2002). The Cayanta Formation is mostly preserved in a regional synclinorium (the Pichaihue syncline; Fig. 5) as lavas that overlie the Huitrín and Agrio formations. This fact, together with other field relationships, documents that during early Eocene times not only the Pichaihue syncline was already formed (it has clearly controlled the locus of the lava flows), but also there was more than 1000 m of uplift (the Rayoso and Neuquén groups were already eroded). Consequently, during the early Eocene, most of the major structures of the Agrio FTB were already formed.

Finally, evidence of Late Cretaceous uplift is also found on the thrust-front structures of the Outer Sector of the Agrio FTB, where the Puesto Burgos ignimbrites of early Eocene age (based on flora ages of the *Nectandra patagónica* sp.) unconformably overlie the lower units of the Neuquén Group (Zapata *et al.* 2002).

Synorogenic deposits of the Conglomerados de Tralahué (Ramos 1998) and He Rincón Bayo Formation (Zapata *et al.* 2002) are associated with structures of both the Inner and Outer sectors of the Agrio FTB. These deposits are found on the limbs of the large anticlines showing growth strata relationships and, hence, demonstrate a Miocene episode of deformation (Ramos 1998; Repol *et al.* 2002; Zapata *et al.* 2002). Field relationships, together with seismic data, suggest that during this period some of the pre-existing structures were reactivated with no more than 500 m of uplift. The Agrio FTB structures were carried over the regional décollement (Fig. 5), as deformation was transferred toward the Chihuidos High and the Neuquén Basin platform structures (Figs 1 & 2).

Unfortunately, the age of these units has been established using mammal fossil fauna recognized up to genus (not to species) such as *Notoungulate* (Repol *et al.* 2002; Zapata *et al.* 2002), and therefore the age range is somewhat broad. Regional correlations suggest that the upper limit for this deformation should not exceed 12 Ma (see discussion below).

Main Andean cordillera

Stratigraphy of the main corillera

Mesozoic rocks. Jurassic rocks along the axial zone of the cordillera have formed part of an intra-arc basin, isolated in terms of superficial exposure from the western Neuquén Basin which constituted a retro-arc embayment at these latitudes. These rocks are upper Pliensbachian–middle Callovian and probably up to Kimmeridgian (Suárez & Emparán 1997), and comprise submarine clastic carbonate and andesitic–dacitic rocks. At the top of the sequence conditions became subaerial for the whole intra-arc axis and retro-arc area.

Early Cenozoic volcanic rocks. The intrusive subvolcanic and volcanic facies associated with the Cura Mallín Formation of late Oligocene–Early Miocene age define an ancient volcanic belt in Chile (25–15 Ma) (Suárez & Emparán 1995, 1997; Burns & Jordan 1999; Jordan *et al.* 2001; Radic *et al.* 2002). The corresponding arc front was located in the Coastal Cordillera (Muñoz *et al.* 2000; Stern *et al.* 2000).

Equivalent rocks are located in the Huantraico area, more than 300 km from the trench, where slab-related volcanics were dated as 20–18 Ma (Fig. 1B, C) (Kay 2002).

During Oligocene–Miocene times a regional episode of sedimentation caused by regional extensional deformation affected the Southern Central Andes (Fig. 6) (Cazau *et al.* 1987; Hervé *et al.* 1995; Charrier *et al.* 1996; Spalletti & Dalla Salda 1996; McDonough *et al.* 1997; Godoy *et al.* 1999; Muñoz & Araneda 2000; Rivera & Cembrano 2000). Two units have been distinguished in the main cordillera: the Cura Mallín Formation (Niemeyer & Muñoz 1983) that represents most of the intra-arc stratigraphic column; and the Mitrauquén Formation capping the sequence (Fig. 3) (Suárez & Emparán 1997). The Cura Mallín Formation is a volcanic–sedimentary unit, deposited in lacustrine and fluvial environments, dated between 20 and 11 Ma (Suárez & Emparán 1995; Jordan *et al.* 2001; Radic *et al.* 2002). The Mitrauquén Formation lies over the former and is composed of ignimbrites and upwards-coarsening fluvial conglomerates, with ages between 10 and 8 Ma (Suárez & Emparán 1997).

The Cura Mallín Basin (Fig. 6) formed diachronously during the late Oligocene–Early Miocene north of 37°30′S (Jordan *et al.* 2001), and during the Middle Miocene in the Lonquimay area south of 38°S (Fig. 4) (Suárez & Emparán 1995). The composition of the sediments accumulated in the basin is also variable between depocentres and is dependent on its regional position within the basin (Suárez & Emparán 1995; Jordan *et al.* 2001; Radic *et al.* 2002). The depocentre located north of 37°30′S has a predominance of sedimentary non-marine facies to the east, while to the west these are replaced by thick volcanic successions (Rovere *et al.* 2000). However, in the southern depocentre, the sedimentary facies are located next to the western limit of the basin (Suárez & Emparán 1995). Based on this change in polarity a major transfer zone is located between these two areas, under the Quaternary Mandolegüe chain around 37°45′–38°S (Figs 6 & 7) (Melnick *et al.* 2002; Radic *et al.* 2002).

The Cura Mallín Formation is either conformably overlain by the 10–8 Ma Mitrauquén Formation, or separated by an unconformity (Suárez & Emparán 1997). These deposits correspond with alluvial fans accumulated in intermontane basins, being proximal equivalents in the main cordillera of a foreland basin, equivalent to the Tralahué and Rincón Bayo Formations in the Inner Sector of the Agrio FTB.

The Cura Mallín Basin is bounded by the Patagonian Batholith to the west and the western Mesozoic outcrops of the Neuquén Basin and the Cordillera del Viento (Inner Sector of the Agrio FTB) to the east (Figs 1B, C&6). Its western basement is formed by Jurassic–Cretaceous granitoids corresponding to the Northern Patagonian Batholith. The eastern basement is Carboniferous–Permian volcanic and sedimentary rocks, Lower Jurassic sequences, and volcaniclastic and intrusives of 57–50 Ma (Fig. 3) (Ramos & Nullo 1993; Rovere 1993).

Late Cenozoic volcanic rocks. Three different volcanic pulses with distinct arc fronts can be distinguished during the Late Cenozoic. (1) The oldest one corresponds to the Cola de Zorro Formation (Vergara & Muñoz 1982), which is formed by volcanic breccias and lavas of basaltic–dacitic composition, minor sedimentary facies and related intrusive bodies (Fig. 3) (Vergara & Muñoz 1982; Niemeyer & Muñoz 1983). Its age is constrained between 5 and 3.5 Ma, and its maximum thickness is around 1900 m, although in most cases it varies between 100 and 1000 m. The regional distribution of this unit constitutes a band of north–south development between 70°45′W and 71°15′W, and with a latitudinal range of 36°–39°S (Fig. 6) (Niemeyer & Muñoz 1983; Suárez & Emparán 1997; Linares *et al.* 1999; Rovere *et al.* 2000). (2) A relatively stable arc position corresponds to Upper Pliocene–Lower Pleistocene (2–0.5 Ma) volcanics that constitute a narrow belt with its front at 72°W (Lara *et al.* 2001). According to these authors the Upper Pliocene volcanic width of the belt and its front are more or less coincident with the Lower Pliocene one. The width drastically diminished during the Late Pleistocene–Holocene, and attained a third stable arc position coincident with (3) the present volcanic front.

The Cola de Zorro Formation covers and, consequently post-dates, the Late Miocene deformation (Fig. 8). This unconformity is of regional importance, existing at both sides of the Andes at these latitudes.

Description of the structure

Palaeogene structure–Cura Mallín Basin. The extensional nature of this basin has been interpreted from 2D seismic lines along the eastern edge of the basin (Burns & Jordan 1999; Jordan *et al.* 2001). Two sectors (northern and southern) of the Palaeogene basin have been separated, based on sediment thickness, structure and age

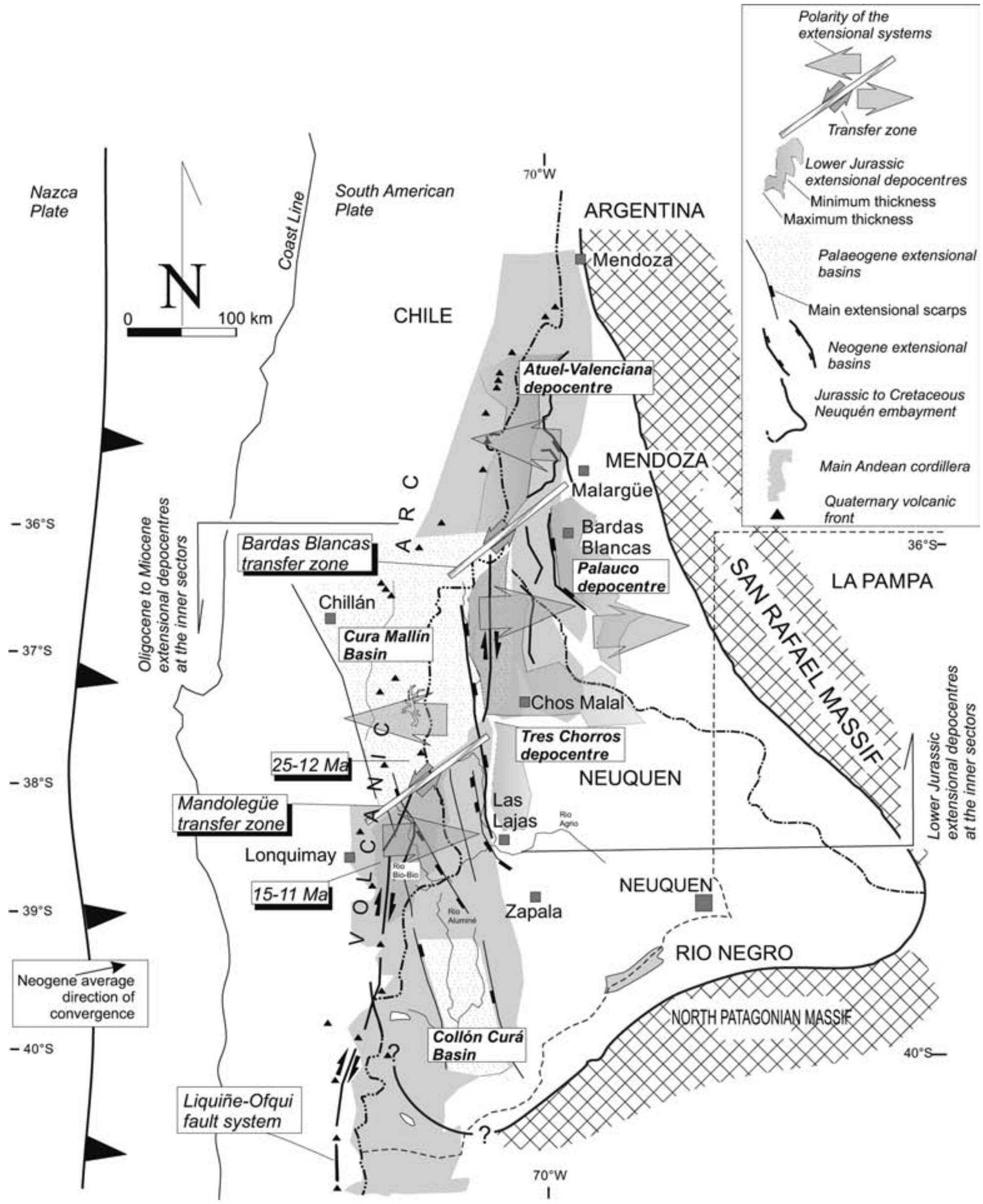

Fig. 6. Relationship between regional Mesozoic structure and the development of intra-arc and inner retro-arc extensional structures along the inner sectors of the Neuquén FTB. Modified from Manceda & Figueroa 1995; Vergara *et al.*, 1997*a*–*c*; Ramos 1998; Lavenu & Cembrano, 1999; Radic *et al.* 2002. Note the similarities between the Jurassic and Palaeogene rifting geometries.

(Radic *et al.* 2002): (1) a northern sector (24.6–22.8 Ma) is mainly located along the eastern slope of the Andean cordillera, where a thick sequence, around 2800 m, is exposed by a W-dipping inverted extensional fault (Jordan *et al.* 2001); and (2) a southern sector (17.5–13 Ma) 2600 m thick (Suárez & Emparán 1995) (Fig. 7). Consequently, the Cura Mallín Basin

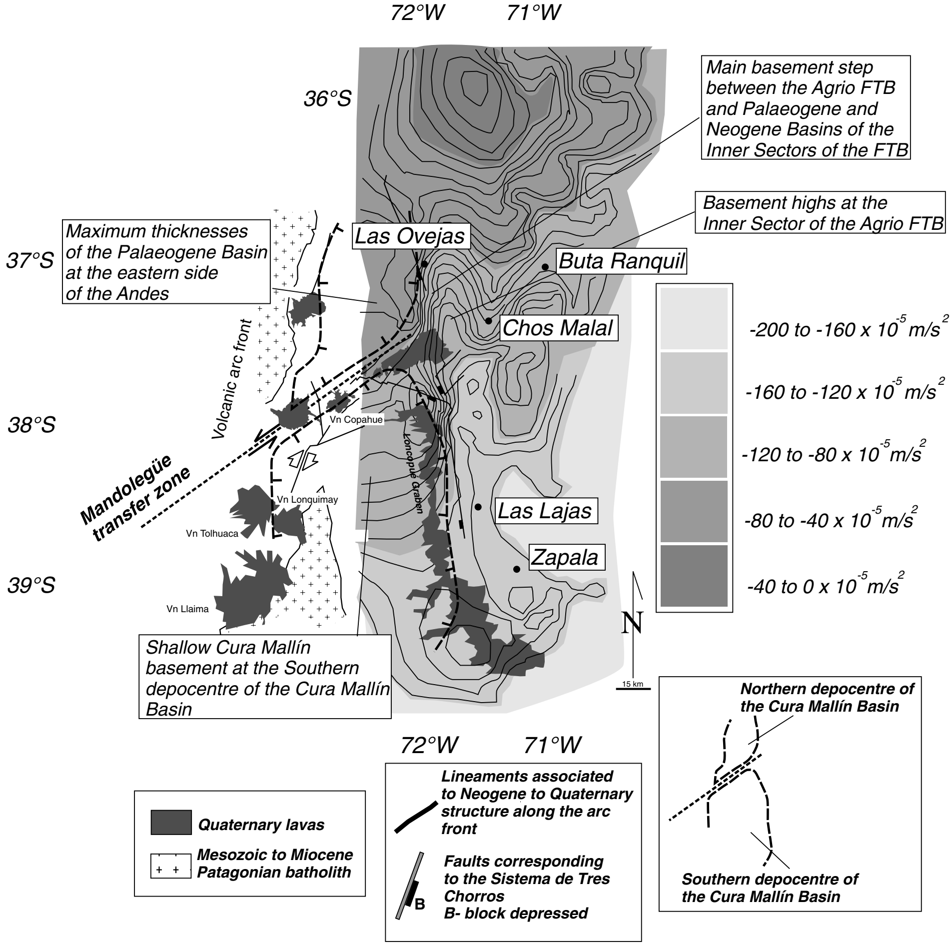

Fig. 7. Bouger anomalies beneath the inner sectors of the Agrio FTB, and segmentation of the Palaeogene Cura Mallín Basin by the Mandolegüe transfer zone, similar to the geometries proposed for the Lower Jurassic rift by Manceda & Figueroa (1995) immediately to the north (see Fig. 6). Note the parallelism between the Lower Jurassic extensional structures corresponding to the Tres Chorros extensional system (Vergani *et al.* 1995; Ramos 1998) and the Neogene structure developed along the volcanic arc.

did not behave in a homogeneous way and, moreover, the corresponding polarity also alternated with time (Radic *et al.* 2002).

The fold and thrust belt that closed the basin during the Late Miocene was controlled by polarity changes and transfer zones in the upper Oligocene rift architecture (Jordan *et al.* 2001; Melnick *et al.* 2002; Radic *et al.* 2002) (Figs 6–8). The Río Picunleo constituted an east–west transfer zone during the formation of the fold and thrust belt at these latitudes (Fig. 8). To the north, an east-verging structure is exposed, meanwhile to the south between this river and the Las Damas valley the thrusts are dipping to the east (Fig. 9). Therefore, based on the extensional structure that has controlled the basin, the Río Picunleo would have been a transfer zone corresponding to extensional panels, subsequently inverted during the Late Miocene.

Neogene–Quaternary structure. The Cola de Zorro Formation displays important changes in thickness, from more than 1000 m locally up to 1900 in the Laguna de la Laja area (Niemeyer & Muñoz 1983), to less than 200 m in the Sierra de Trocomán and other regions on the eastern side of the Andes at these latitudes.

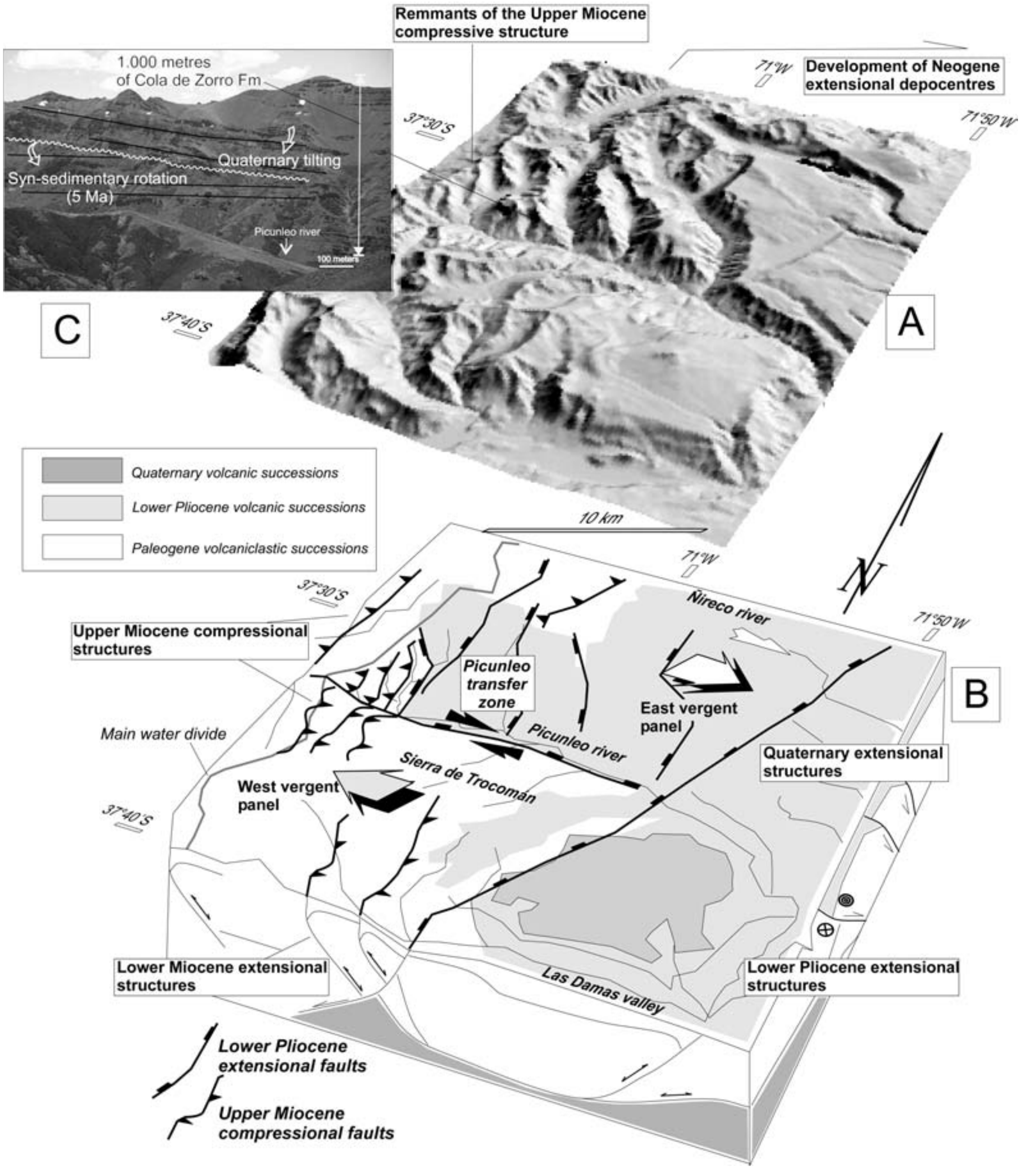

Fig. 8. (**A**) 3D shaded relief image corresponding to (B). (**B**) Block diagram showing alternating panels in the Upper Miocene compressive structure as a function of the Palaeogene rifting architecture. Note the superposition of the Lower Pliocene depocentres using transfer faults of Miocene age. (**C**) Internal unconformities in the Lower Pliocene sequences associated with synextensional accumulation.

The Sierra de Trocomán acted as a structural high during the Early Pliocene (Figs 8 & 9). The east–west Río Picunleo and the east–west Las Damas valley flank this structural high and limit the two Lower Pliocene depocentres. Therefore, the Caldera del Agrio zone has been the locus of the Lower Pliocene accumulations south of the Las Damas valley, where the Cola de Zorro unit dips to the north against a normal scarp along which the upper Palaeogene sequence is exposed.

The unconformity between the Miocene and Lower Pliocene sequences is dismembered through the eastern slope of the Neuquén Andes, by the Neogene extensional structure. Particularly, the main N–S branch of the

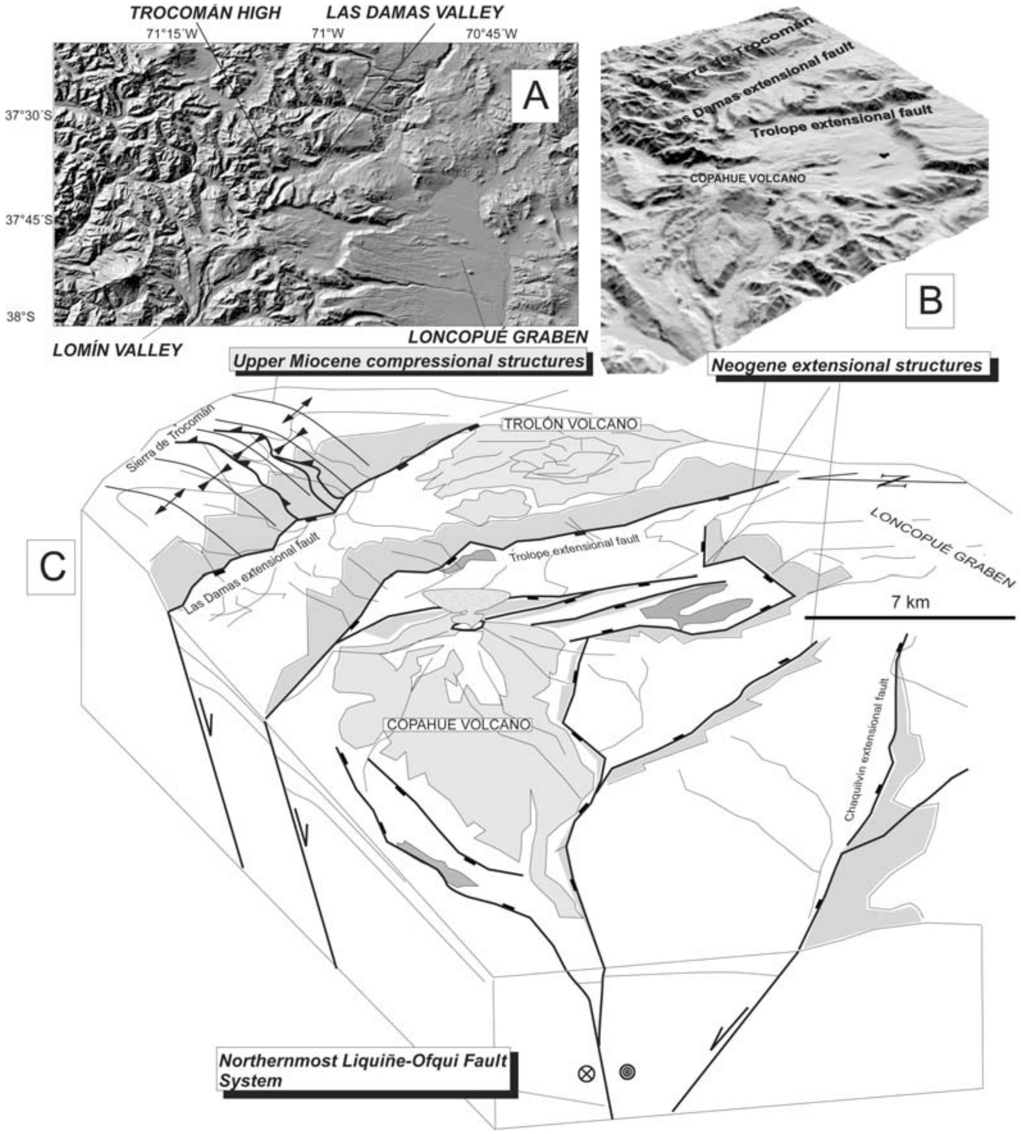

Fig. 9. (**A**) Shaded relief image, where the main structural features of the inner sectors eastern side of the main cordillera and Loncopué trough are represented. (**B**) 3D shaded relief image corresponding to (C). (**C**) Inner sectors of the Neuquén fold and thrust belt between 38°15′ and 37°30′S. Note that extensional structures are affecting the compressive structure at the northern part of the slide. These are interpreted as an Early Pliocene relaxation of the compressive wedge in response to subtle changes in subductive border conditions.

Río Picunleo runs through an extensional fault that bounds the Picunleo–Reñileuvú depocentre on its western side (Fig. 8).

Therefore, two main sets of faults control the Lower Pliocene depocentres, one of N–S strike, which bounds the Upper Miocene fold and thrust belt on its eastern slope provoking the collapse of the Palaeogene sequences, and the other of E–W strike defining a series of highs and lows aligned with the meridian (Figs 8 & 9).

In addition, to the recognition of extensional faulting controlling the Lower Pliocene accumulations, evidence of synsedimentary deformation associated with the structures was also found in the area. Unconformities separate rotated packages of Lower Pliocene basal sequences from almost flat members corresponding to the same unit (Fig. 8). This situation is visible in the northern divide of the Picunleo valley, where a block has been rotated with N–S strike prior to the accumulation of the uppermost stage of the Cola de Zorro Formation (Fig. 8). To the south, along the northern side of the Caldera del Agrio, other synextensional faults have been identified in the Trolope valley (Fig. 9). Therefore, extensional activity is documented from the initial stages of the Early Pliocene, when the fold and thrust belt seems to have delayed its progression to the foreland and its inner sector collapsed forming a narrow intra-arc basin (Figs 6 & 8).

A long intra-arc feature, the dextral strike–slip Liquiñe–Ofqui Fault Zone (LOFZ), active since at least the Late Cretaceous (Fig. 1) (Lavenu & Cembrano 1999; Cembrano *et al.* 2000), ends in a more complex structural array at 38°S (Melnick *et al.* 2003) (Figs 1 & 9). In this area, a series of NNW- to NW-striking faults, of which the Bío–Bío left-lateral fault and the Chillán lineament are the main features (Fig. 2) (Ramos 1977; Dalla Salda & Franzese 1987; Muñoz & Stern 1988; Melnick *et al.* 2002), are related to regional upper Palaeogene fractures, developed in the Southern Central Andes segment of the Andean chain between 36° and 40°S (Vergara *et al.* 1997*a–c*; Rivera & Cembrano 2000; Jordan *et al.* 2001; Radic *et al.* 2002). The area under extension coincides with the western Tres Chorros structural system inferred beneath the Cenozoic cover based on the main Mesozoic faults to the west (Fig. 7). Many Pliocene–Quaternary extensional faults recognized in the basement of the main polygenetic volcanoes, as the edges of the Caldera del Agrio (Fig. 9), coincide with the projections of these faults (Vergani *et al.* 1995; Ramos 1998) to the arc platform (Fig. 7).

The Liquiñe–Ofqui Fault Zone is a relatively continuous feature from 40° to 46°S, which runs through the Main Cordillera and the Quaternary volcanic arc (Lavenu & Cembrano 1999). The fault zone changes to a series of en echelon NNE to NE-trending faults between 38° and 39°S (Fig. 1). These faults have recently been recognized as normal faults related to the late Oligocene–Early Miocene extension, controlling the thickness of units of corresponding age (Radic *et al.* 2002). Therefore, neotectonics associated with the volcanic front shows control by Palaeogene structures, as well as Mesozoic ones.

The volcanic lineament Callaqui–Copahue–Cordillera de Mandolegüe (CCM) is the longest volcanic fissure in the Cordillera Patagónica, reaching 80 km, and is transversally oriented to the volcanic-arc front (Fig. 7). This feature is formed by a series of coalescent polygenetic and monogenetic centres, which from west to east are: the Callaqui and Copahue volcanoes of 1–0 Ma; the Coladas de Fondo de Valle monogenetic field of 1.6–0.8 Ma; the Bayo and Trolope dome complexes of 0.6 Ma; and the Trolón eroded strato-volcano of 0.6 Ma (Pesce 1989; Linares *et al.* 1999), together with an extensive monogenetic basaltic field that is part of the northern extent of the extensional Loncopué trough (Ramos & Folguera 1999*a*, *b*). This belt lies in the middle of the rhomboedric Damas–Chaquilvín structure and crosses the Caldera del Agrio through its mid part (Fig. 9) (Melnick *et al.* 2002).

Finally, the Damas–Chaquilvín structure coincides with a major left-lateral transfer zone in the Cura Mallín Basin (Melnick *et al.* 2002), forming part of the Quaternary volcanic basement, separating two diachronous sub-basins (Radic *et al.* 2002). This observation supports the structural control exerted by the Palaeogene structure in the neotectonics and arc-front geometry (Fig. 7).

Uplift and temporal constraints

Apatite fission-track ages from the main cordillera, immediately south of the studied sector (40°S), range between 4.3 and 1.3 Ma indicating a very young period of exhumation in the inner sectors of the fold and thrust belt (Fig. 4) (Gräfe *et al.* 2002). This uplift is out of sequence with respect to the rest of the Cretaceous–Miocene Agrio FTB. However, around 38°30′S, corresponding to the inner sector of the presently analysed section, the apatite fission-track ages fall within the Eocene, without any younger imprints (Fig. 4) (Gräfe *et al.* 2002).

Tectonic evolution of the Andean FTB

Fission-track data together with Ar/Ar ages are conclusive in relation to the beginning of deformation of the Andes of the Neuquén Basin. Local angular unconformities, particularly at the northern and southern edges of the basin, reveal that retro-arc deformation was an active process during the Jurassic and Early Cretaceous (Vergani *et al.* 1995). Such observations are consistent with the existence of a subduction zone and related magmatic arc (Kay *et al.* 1989). However, the formation of the Andean FTB seems to have been delayed until the Late Cretaceous (Fig. 4) (Ramos 1977; Zapata *et al.* 1999;

Kay 2001). The Andean FTB was then characterized by the inversion of the pre-existing Jurassic extensional structures (Vergani *et al.* 1995; Ramos 1998), now preserved in the Agrio FTB, associated with limited thin-skinned deformation focused at the basement block boundaries (Figs 5 & 9). The synorogenic-related sediments either are associated with the base of the Neuquén Group (Ramos 1977) or at least to the Cretaceous Malargüe Group deposits (Fig. 3) (Barrio 1990; Zapata *et al.* 2002).

Deformation of the intra-arc region occurred at least until the Early Eocene, based on apatite fission-track data, indicating that the main Cordillera suffered an episode of uplift (Fig. 4) (Gräfe *et al.* 2002) related to the inversion of Lower Jurassic structures of a pre-existing intra-arc basin (De la Cruz & Suárez 1997). During this time, Lower Eocene intrusives were emplaced in the upper crust in previously deformed Upper Cretaceous structures.

Early Oligocene–Early Miocene was a time of orogenic relaxation, which affected the core of the Andes with the opening of the Cura Mallín Basin. The extensional deformation was restricted to the west of the Cordillera del Viento (i.e. west of the Inner Sector of the Agrio FTB) (Figs 6 & 7) occupying part of the volcanic arc. The sedimentation in the intra-arc area was non-marine, although the Pacific Ocean occupied an important sector of the forearc area (McDonough *et al.* 1997; Vergara *et al.* 1997*a–c*).

The Late Miocene was, again, a period of contractional deformation. The Oligocene–Miocene intra-arc basin was closed due to minor reactivation of Mesozoic structures and localized inversion of intra-continental extensional faults of the Cura Mallín Basin (Fig. 8). The closure of the Cura Mallín Basin structures, as they were transported toward the foreland region, produced the reactivation of the Late Cretaceous Agrio FTB structures. The deformation front migrated eastwards toward the Chihuidos High and Platform areas of the Neuquén Basin, causing tectonic inversion of the pre-existing Jurassic half-grabens (Fig. 10).

During the Early Pliocene, once again, tectonic relaxation affected a restricted latitudinal band between 36° and 39°S at the inner sectors of the Andean FTB, forming a narrow rift locally coincident with the previous Tertiary intra-arc basin (Figs 6 & 7). The corresponding normal faults displaced and buried the compressive structure formed during the Late Miocene, particularly at the eastern slope of the main Andes today (Fig. 10). Late Pliocene–early Quaternary times south of 37°30′S are marked by inner collapse of the fold and thrust structure related to the northern prolongation of the dextral strike–slip Liquiñe–Ofqui Fault Zone (Ramos & Folguera 1999*a*, *b*; Melnick *et al.* 2003).

Fission track-data (Gräfe *et al.* 2002) reveal that, in contrast to the south of 39°S, at 38°30′S the main cordillera remained static during the Neogene, while to the south around 40°S out-of-sequence thrusting was related to a new period of fold and thrust development that is still active, as revealed by seismicity (Fig. 2) (Barrientos & Acevedo 1992; Bohm *et al.* 2002).

Discussion

The tectonic evolution of the Andes within the Neuquén Basin has experienced recurrent episodes of compression and extension that affected different components of the orogen. Each event has overprinted the previous one and, therefore, it is not likely that the available data allow a complete reconstruction of the history of the orogen. In addition, this study shows that all of the different structural and tectonic styles of deformation have been strongly controlled by the pre-existing extensional Jurassic features, mostly half-graben rift geometries driven by deep crustal discontinuities, associated with the opening of the Neuquén Basin.

The first-order crustal features that define the deformation styles are the crustal discontinuities that may be a consequence of Late Proterozoic–Early Palaeozoic terrane accretion (Ramos 1989). Seismic, borehole, gravity and geochemistry data suggest that the depocentres of the Jurassic rift of the Neuquén Basin are concentrated on the upper plate of these crustal discontinuities (Zapata 1997). Following the simple-shear asymmetric extensional model (Wernicke & Burchfield 1982), the polarity of the crustal discontinuity should be directed towards the area of maximum subsidence, parallel to the basin half-graben polarity. Some of these first-order crustal discontinuities are located at the NE flank of the Neuquén Basin beneath the Auca Mahuida Volcano, with NE-directed polarity (Fig. 10) (Zapata 1997), and at the basin depocentre beneath the Chihuidos High (Ramas 2002; Zapata *et al.* 2002), with E-directed polarity, etc. (Fig. 10).

One of the most important crustal discontinuities is the one that lies immediately to the west of the Cordillera del Viento (Fig. 10) at the Inner Sector of the Agrio FTB. Borehole and seismic data show that the Jurassic synrift depocentres become progressively deeper toward the west as they lie closer to the crustal discontinuity,

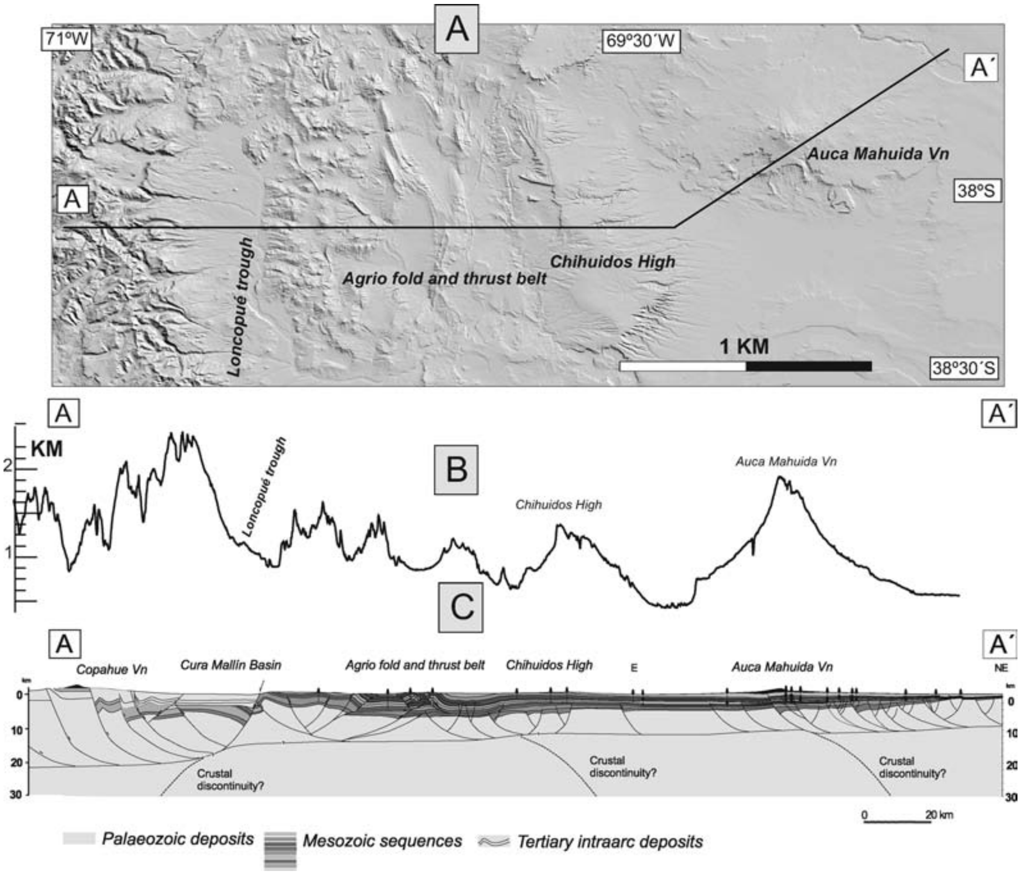

Fig. 10. (**A**) Shaded relief image where, cross-section position corresponding to (C) is displayed. (**B**) Exaggerated topography along (C), to visualize Loncopué-active extensional retro-arc zone at the transition between main cordillera and Agrio FTB. (**C**) Cross-section near 38°S from the Quaternary volcanic axis to the retro-arc area.

showing that the amount of subsidence was higher in that direction.

Consequently, the crustal discontinuity associated with the asymmetric Jurassic rift should be westward-directed (Zapata *et al.* 1999) (Fig. 10). According to this model, the asymmetry of the Cura Mallín Oligocene basin depocentres (Jordan *et al.* 2001) may be related to such crustal discontinuity (Fig. 10).

Gravity data show that there is another major westward-directed crustal discontinuity beneath the actual volcanic arc region between 37°30′ and 38°S (Fig. 7). This discontinuity may have controlled the change in polarity of the Cura Mallín and younger extensional basins recognized by previous workers in the area (Melnick *et al.* 2002; Radic *et al.* 2002).

Finally, the second-order crustal discontinuities are those related to the geometry of the Jurassic half-graben. These pre-existing structures have controlled the vergence and geometry of the Andean structures of the Agrio FTB, as well as the local depocentres and transfer zones of the Cura Mallín and younger basins, as it was described before (Figs 6 & 7).

Conclusions

The Andean building processes determined from the presented data contain the following elements.

- First-order crustal discontinuities have controlled the deformational styles. A Late Cretaceous compressional event has been preserved at the present volcanic arc and Agrio FTB areas. This event produced a significant amount of uplift, particularly concentrated on the Cordillera del Viento (Inner Sector of the Agrio FTB), as a reactivation of the pre-existing rift geometry controlled by a westward-directed crustal discontinuity (Fig. 10). This event was also extended towards the foreland area on the Outer Sector of the Agrio. Unfortunately, there are not enough data preserved to reconstruct the uplift history for the present volcanic arc. These compressional events may have lasted until the earliest Eocene.

- During the latest Oligocene–earliest Miocene, as a consequence of a change in the geodynamic conditions (Jordan *et al.* 2001), a regional extensional event formed the Cura Mallín intra-arc basin. This extensional event was confined to a region to the west of the Cordillera del Viento where the pre-existing westward-directed crustal discontinuity was reactivated. No extensional movements have been recorded further to the east, toward the foreland basin (Fig. 4).
- For the Late Miocene, compressional movements closed the Cura Mallín Basin and reactivated the Agrio FTB structures. The shortening was transferred toward the foreland using the inherited Jurassic detachment (reactivated as a décollement) (Fig. 10).
- Early Pliocene–Quaternary has been a period of relaxation of the inner sectors of the Agrio Fold and Thrust Belt, probably reactivating a Jurassic deep detachment, as suggested at a local scale by (a) parallelism between Lower Jurassic structures of the Tres Chorros extensional system and Neogene structures; and at a broad scale by (b) similarities between Tertiary rift geometry and Jurassic rift geometry exposed north of 36°S (Fig. 6). In other cases, Pliocene–Quaternary extensional faults have cut the Upper Miocene compressional structure without tracing any particular pattern (Fig. 8).

The structural evolution of the Neuquén Basin Andean orogeny is characterized by compressional events affecting the region from the present volcanic arc through to the foreland. However, the extensional events have been restricted to the major crustal boundaries of the present volcanic arc and high cordillera (plateau?) regions, with minor propagation toward the foreland area.

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References

Aguirre-Urreta, M. & Rawson, P. 1997. The ammonite sequence in the Agrio Formation (Lower Cretaceous), Neuquén Basin, Argentina. *Geological Magazine*, **134**, 449–458.

Allmendinger, R. & Gubbels, T. 1996. Pure and simple shear plateau uplift, Altiplano-Puna, Argentina and Bolivia. *Tectonophysics*, **259**, 1–13.

Barrientos, S. & Acevedo, P. 1992. Seismological aspects of the 1988–1989 Lonquimay volcanic eruption (Chile). *Journal of Volcanology and Geothermal Research*, **53**, 73–87.

Barrio, C. 1990. Late Cretaceous–Early Tertiary sedimentation in a semi-arid foreland basin (Neuquén Basin, Western Argentina). *Sedimentary Geology*, **66**, 255–275.

Beaumont, C., Fullsack, P. & Mamilton, J. 1992. Erosional control of active compressional orogens. *In*: McClay, K.R. (ed.) *Thrusts Tectonics*. Chapman & Hall, New York, 1–18.

Bohm, M., Lüth, S. *et al.* 2002. The Southern Andes between 36° and 40°S latitude: seismicity and average seismic velocities. *Tectonophysics*, **356**, 275–289.

Burns, W.M. 2002. *Tectonics of the Southern Andes from stratigraphic thermochronology and geochemical perspectives.* PhD Thesis, Cornell University, Ithaca, NY.

Burns, W. & Jordan, T. 1999. Extension in the Southern Andes as evidenced by an Oligo-Miocene age intra-arc basin. *In*: *4th International Symposium on Andean Geodynamics, Göttingen, Extended Abstracts*. IRD, Paris, 115–118.

Cazau, L., Mancini, C., Cangini, J. & Spalletti, L. 1987. *In*: Chebli, G. & Spalletti, L. (eds), *Cuencas Sedimentarias de Argentina. Cuenca de Ñirihuao.* Serie de Correlación Geológica, Instituto Superior de Correlación Geológica, Universidad Nacional de Tucumán, **6**, 299–318.

Cembrano, J., Schermer, E., Lavenu, A. & Sanhueza, A. 2000. Contrasting nature of deformation along an intra-arc shear zone, the LOFZ fault zone, southern Chilean Andes. *Tectonophysics*, **319**, 129–149.

Charrier, R., Wyss, A. *et al.* 1996. New evidence for late Mesozoic–Early Cenozoic evolution of the Chilean Andes in the upper Tinguiririca Valley (35°S), central Chile. *Journal of South American Earth Sciences*, **9**, 393–422.

Dalla Salda, L. & Franzese, J. 1987. Las megaestructuras del macizo y cordillera norpatagónica argentina y la génesis de las cuencas volcano-sedimentarias terciarias. *Revista Geológica de Chile*, **31**, 3–13.

De la Cruz, R. & Suárez, M. 1997. El Jurásico de la Cuenca Neuquina en Lonquimay, Chile: Formación Nacientes del Bío Bío (38°–39°S). *Revista Geológica de Chile*, **24**, 3–24.

Godoy, E., Yañez, G. & Vera, E. 1999. Inversion of an Oligocene volcano tectonic basin and uplifting of its superimposed Miocene magmatic arc in the Chilean Central Andes: First seismic and gravity evidences. *Tectonophysics*, **306**, 217–236.

Gräfe, K., Glodny, J., Seifert, W., Rosenau, M. & Echtler, H. 2002. Apatite fission track thermochronology of granitoids at the South Chilean active continental margin (37°S. 42°S): implications for denudation, tectonics and mass transfer since the Cretaceous. *In*: *5th International Symposium on Andean Geodynamics, Toulouse*. IRD, Paris, 275–278.

Gulisano, C.A. & Gutierrez Pleimling, A.R. 1994. *Field Guide to the Jurassic of the Neuquén Basin, Province of Neuquén.* Dirección Nacional del Servicio Geológico, **158**.

Hervé, F., Pankhurst, R.J., Drake, R. & Beck, M.E. 1995. Pillow basalts in a mid-Tertiary extensional basin adjacent to the Liquiñe Ofqui fault zone: The Isla Magdalena area, Aysén, Chile. *Journal of South American Earth Sciences*, **8**, 33–46.

Introcaso, A., Cristina Pacino, M. & Guspi, F. 2000. *The Andes of Argentina and Chile: Crustal Configuration, Isostasy, Shortening and Tectonic Features from Gravity Data.* Temas de Geociencia, UNR Editora.

James, D. & Sacks, S. 1999. Cenozoic formation of the Central Andes: A geophysical perspective. *In*: Skinner, B.J. (ed.) *Geology and Ore Deposits of the Central Andes. Society of Economic Geologists, Special Publications* **7**, 1–25.

Jolivet, L. & Faccenna, C. 2000. Mediterranean extension and the Africa–Eurasia collision. *Tectonics*, **19**, 1095–1106.

Jordan, T., Burns, W., Veiga, R., Pángaro, F., Copeland, P., Kelley, S. & Mpodozis, C. 2001. Extension and basin formation in the Southern Andes caused by increased convergence rate: A Mid-Cenozoic trigger for the Andes. *Tectonics*, **20**, 308–324.

Kay, S 2001. *Tertiary to recent magmatism and tectonics of the Neuquén basin between 36°05′ and 38°S latitude.* Repsol-YPF report, Buenos Aires.

Kay, S. 2002. Tertiary to Recent transient shallow subduction zones in the Central and Southern Andes. *XV° Congreso Geológico Argentino* (Calafate), *Actas*, **3**, 282–283.

Kay, S., Ramos, V.A., Mpodozis, C. & Sruoga, P. 1989. Late Paleozoic to Jurassic silicic magmatism at the Gondwanaland margin: analogy to the Middle Proterozoic in North America? *Geology*, **17**, 324–328.

Kley, J., Monaldi, C. & Salfity, J. 1999. Along-strike segmentation of the Andean foreland: causesand consequences. *Tectonophysics*, **301**, 75–94.

Kozlowski, E., Cruz, C. & Sylwan, C. 1996. Geología estructural de la zona de Chos Malal, cuenca Neuquina, Argentina. *XIII° Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos, Actas*, **I**, 15–26.

Lamb, S. & Hoke, L. 1997. Origin of the high plateau in the Central Andes, Bolivia, South America. *Tectonics*, **16**, 623–649.

Lara, L., Rodríguez, C., Moreno, H. & Pérez de Arce, H. 2001. Geocronología K–Ar y geoquímica del volcanismo plioceno superior-pleistoceno de los Andes del sur (39°–42°S). *Revista Geológica de Chile*, **28** 67–90.

Lavenu, A. & Cembrano, J. 1999. Compressional and transpressional stress pattern for Pliocene and Quaternary brittle deformation in fore arc and intra arc zones (Andes of Central and Southern Chile). *Journal of Structural Geology*, **21**, 1669–1691.

Linares, E., Ostera, H.A. & Mas, L. 1999. Cronología Potasio-Argón del complejo efusivo Copahue–Caviahue, Provincia del Neuquén. *Revista de la Asociación Geológica Argentina, Buenos Aires*, **54**, 240–247.

Lyon-Caen, H., Molnar, P. & Suárez, G. 1985. Gravity anomalies and flexure of the Brazilian Shield beneath the Bolivian Andes. *Earth and Science Planetary Science Letters*, **75**, 81–92.

Llambías, E. & Rapela, C. 1987. Las vulcanitas de Collipilli y su relación con las Provincias volcánicas del Terciario inferior de Neuquen–Mendoza y Patagonia. *In*: *Simposio de Vulcanismo Andino. X° Congreso Geológico Argentino, Actas*, **IV**, 249–251.

Llambías E. & Rapela, C. 1989. Las vulcanita de Collipilli, Neuquen (37°S) y su relación con otras unidades paleógenas de la cordillera. *Asociación Geológica Argentina, Buenos Aires*, **44**, 224–236.

Llambías, E., Danderfer, J., Palacios, M. & Brogioni, N. 1978. Las rocas ígneas cenozoicas del volcán Domuyo y áreas adyacentes. *VII° Congreso Geológico Argentino, Actas*, **II**, 569–584.

Manceda, R. & Figueroa, D. 1995. Inversion of the Mesozoic Neuquén Rift in the Malargüe Fold and Thrust Belt, Mendoza, Argentina. *In*: Tankard, A.J., Suárez, R.S. & Welsink, H.J. (eds) *Petroleum Basins of South America.* AAPG Memoirs, **62**, 369–382.

McDonough, M., Duhart, P. & Crignola, P. 1997. Naturaleza del alzamiento del basamento costero y la apertura de la cuenca de Osorno-Llanquihue, X Región: Nuevos antecedentes sísmicos y observaciones de terreno. *VIII° Congreso Geológico chileno, 1, Sesión Temática*, **1**, 164–168.

Melnick, D., Folguera, A., Rosenau, M., Echtler, H. & Potent, S. 2002. Tectonics from the Northern segment of the Liquiñe–Ofqui fault system (37°–39°S), Patagonian Andes. *In*: *5th International Symposium on Andean Geodynamics, Toulouse*. IRD, Paris, 609–612.

Melnick, D., Folguera, A., Echtler, H., Charlet, F., Büttner, O. & De Batist, M. 2003. The Lago del Laja Fault System: Active intra-arc orogenic collapse in the Southern Central Andes (37°15′S). *X° Congreso Geológico Chileno*, (*Concepción*), *Actas*, Universidad de Concepción, Concepción.

Morley, C. 2001. Combined escape tectonics and subduction rollback-back arc extension: a model for the evolution of Tertiary rift basins in Thailand, Malaysia and Laos. *Journal of the Geological Society, London*, **158**, 461–474.

MPODOZIS, C. & RAMOS, V.A. 1989. The Andes of Chile and Argentina. *In*: ERICKSEN, G.E., CAÑAS PINOCHET, M.T. & REINEMUD, J.A. (eds), *Geology of the Andes and its Relation to Hydrocarbon and Mineral Resources.* Circumpacific Council for Energy and Mineral Resources, Earth Science Series, **11**, 59–90.

MUÑOZ, J. & ARANEDA, M. 2000. Extensión cortical en el Oligoceno-Mioceno entre los 39° y los 42°S región de los lagos Chile: Antecedentes geológicos y geofísicos. *IX° Congreso Geológico Chileno (Puerto Varas), 2, Simposio Internacional* **2**, 609–612.

MUÑOZ, J. & STERN, C. 1988. The Quaternary volcanic belt of the southern continental margin of South America: Transverse structural and petrochemical variations across the segment between 38° and 39°S. *Journal of South American Earth Sciences*, **1**, 147–161.

MUÑOZ, J., TRONCOSO, R., DUHART, P., CRIGNOLA, P., FARMER, L. & STERN, C. 2000. The relation of the mid-Tertiary coastal magmatic belt in south-central Chile to the late Oligocene increase in plate convergence rate. *Revista Geológica de Chile*, **27**, 177–203.

NIEMEYER, H. & MUÑOZ, J., 1983. *Geología de la hoja 57 Laguna de La Laja, Región de Bío Bío.* Map 1:250 000. *Servicio Nacional de Geología y Minería Santiago.*

PE-PIPER, G., PIPER, D., KOTOPOULI, C. & PANAGOS, A. 1995. Neogene volcanoes of Chios, Greece: the relative importance of subduction and back-arc extensión. *In*: SMELLIE, J.L. (ed.) *Volcanism Associated with Extension at Consuming Plate Margins. Geological Society, London*, Special Publications, **81**, 213–231.

PESCE, A. 1989. Evolución volcano-tectónica del complejo efusivo Copahue-Caviahue y su modelo geotérmico preliminar. *Revista de la Asociacón Geológica Argentina, Buenos Aires*, **44**, 307–327.

PETFORD, N. & ATHERTON, M. 1995. Cretaceous–Tertiary volcanism and syn-subduction crustal extension in northern central Peru. *In*: SMELLIE, J.L. (ed.) *Volcanism Associated with Extension at Consuming Plate Margins.* Geological Society, London, Special Publications, **81**, 233–248.

PLOSZKIEWICZ, J. 1987. Las zonas triangulares de la faja fallada y plegada de la Cuenca Neuquina Argentina. *X° Congreso Geológico Argentino, Actas*, **1**, 177–180.

RADIC, J., ROJAS, L., CARPINELLI, A. & ZURITA, E. 2002. Evolución tectónica de la Cuenca Terciaria de Cura Mallín, región cordillerana chileno-argentina (36°30′–39°S). *XV° Congreso Geológico Argentino (Calafate), Actas*, **3**, 233–237.

RAMOS, V.A. 1977. Estructura. *In*: ROLLERI, E.O. (ed.) *Geología y recursos naturales de la Provincia del Neuquén. VII° Congreso Geológico Argentino, Actas, Buenos Aires*, 9–24.

RAMOS, V.A. 1989. The birth of southern South America. *American Scientist*, **77**, 444–450.

RAMOS, V.A. 1998. Estructura del sector occidental de la faja plegada y corrida del Agrio, Cuenca Neuquina Argentina. *X° Congreso Latinoamericano de Geología, Buenos Aires*, **2**, 105–110.

RAMOS, V. A. 1999*a.* Los depósitos sinorogénicos terciarios de la región andina. *Geología Argentina, Instituto de Geología y Recursos Minerales, Buenos Aires, Anales*, **29**, 651–682.

RAMOS, V.A. 1999*b.* Rasgos estructurales del Territorio Argentino, Evolución Tectónica de la Argentina. *Geología Argentina, Instituto de Geología y Recursos Naturales, Buenos Aires, Anales*, **29**, 715–784.

RAMOS, V.A. 2002. El basamento de la Cuenca Neuquina y regiones adyacentes: Datos gravimétricos preliminares. *5° Congreso de Exploration y Desarrollo de Hidrocarburos (Mar del Plata), Actas.* IAPG, Buenos Aires, electronic files.

RAMOS, V.A. & BARBIERI, M. 1989. El volcanismo cenozoico de Huantraico: Edad y relaciones isotópicas iniciales, provincia de Neuquén. *Revista Asociación Geológica Argentina, Buenos Aires*, **43**, 210–223.

RAMOS, V.A. & FOLGUERA, A., 1999*a.* Estructura extensional cenozoica en la Cordillera Neuquina. *IV° Congreso de Exploración y Desarrollo de Hidrocarburos (Mar del Plata), Actas*, **2**, 661–664.

RAMOS, V.A. & FOLGUERA, A. 1999*b.* The Andes of Neuquen (36°–38°S): Evidence of Cenozoic transtension along the arc. *In*: *4th International Symposium on Andean Geodynamics. Göttingen. Extended Abstracts.* IRD, Paris, 606–609.

RAMOS, V.A. & FOLGUERA, A. 2005. Tectonic evolution of the Andean Fold and Thrust Belt of the Southern Neuquén Basin, Argentina. *In*: VEIGA, G.D., SPALLETTI, L., HOWELL, J.A. & SCHWARZ, E. (eds), *The Neuquén Basin: A Case Study in Sequence: Stratigraphy and Basin Dynamics.* Geological Soicety, London, 15–35.

RAMOS, V.A. & NULLO, F. 1993. El volcanismo de arco cenozoico. Geología y Recursos Naturales de Mendoza, Buenos Aires, 1, 149–160.

RAMOS, V.A., CRISTALLINI, E. & PÉREZ, D. 2002. The Pampean flat-slab of the Central Andes. *Journal of South American Earth Sciences*, **15**, 59–78.

RAMOS, V., ZAPATA, T., CRISTALLINI, E. & INTROCASO, A. 2004. The Andean thrust system: Latitudinal variations in structural styles and orogenic shortening. *In*: MCCLAY, K. (ed.) *Thrust Tectonics and Hydrocarbon Systems.* AAPG, Memoirs, **82**, 30–50.

REPOL, D., LEANZA, H., SRUOGA, P. & HUGO, C. 2002. Evolución tectónica del Cenozoico de la comarca de Chorriaca, Provincia del Neuquén, Argentina. *XV° Congreso Geológico Argentino*, **3**, 200–205. Buenos Aires, electronic files.

RIVERA, O.M. & CEMBRANO, J. 2000. Modelo de formación de cuencas volcano-tectónicas en zonas de transferencia oblicuas a la cadena andina: El caso de las cuencas oligo-miocenas de Chile Central y su relación con estructuras NWW–NW (33°–34°30′). *IX° Congreso Geológico Chileno, 2, International Symposium*, **2**, 631–636.

ROVERE, E. 1993. K/Ar ages of Magmatic rocks and Geochemical variations of volcanics from South

Andes (37° to 37°15′S–71°W). *Abstracts of the Japan Volcanological Society*, **2**, 107.

Rovere, E. 1998. Volcanismo Jurásico, Paleógeno y Neógeno en el Noroeste del Neuquén, Argentina. *X° Congreso Latinoamericano de Geología y VI° Congreso Nacional de Geología Económica, Actas*, **1**, 144–149.

Rovere, E., Leanza, H., Hugo, C., Casselli, A., Tourn, S. & Folguera, A. 2000. *Hoja geológica Andacollo, Provincia de Neuquen, 1:250 000.* Servicio Nacional de Geología y Minería Argentino, Buenos Aires.

Spalletti, L.A. & Dalla Salda, L. 1996. A pull apart volcanic related Tertiary basin, an example from the Patagonian Andes. *Journal of South American Earth Sciences*, **9**, 197–206.

Stern, C., Muñoz, J., Troncoso, R., Duhart, P., Crignola, P. & Farmer, G. 2000. Tectonic setting of the Mid-Tertiary Coastal Magmatic belt in South Central Chile: an extensional event related to Late Oligocene changes in plate convergence rate and subduction geometry. *IX° Congreso Geológico Chileno*, (*Puerto Varas*), *Actas, 2, International Symposium* **3**, 693–696.

Suárez, M. & Emparán, C. 1995. The stratigraphy, geochronology and paleophysiography of a Miocene fresh-water interarc basin, southern Chile. *Journal of South American Earth Science*s, **8**, 17–31.

Suárez, M. & Emparán, C. 1997. *Hoja Curacautín. Regiones de la Araucanía y del Bío Bío. Carta Geológica de Chile*, *1:250 000.* Servicio Nacional de Geología y Minería de Chile, Santiago, **71**, 105.

Thomson, S. 2002. Late Cenozoic geomorphic and tectonic evolution of the Patagonian Andes between latitudes 42°S and 46°S: An appraisal based on fission-track results from the transpressional intra-arc Liquiñe–Ofqui fault zone. *Geological Society of America, Bulletin*, **114**, 1159–1173.

Vergani, G., Tankard, A., Belotti, H. & Welsink, H. 1995. Tectonic evolution and paleogeography of the Neuquén Basin Argentina. *In*: Tankard, A.J., Suárez, R. & Welsink, H.J. (eds), *Petroleum Basins of South America.* AAPG Memoirs, **62**, 383–402.

Vergara, M. & Muñoz, J. 1982. La Formación Cola de Zorro en la Alta cordillera Andina Chilena (36°–39°S), sus características petrográficas y petrológicas: Una revisión. *Revista geológica de Chile*, **17**, 31–46.

Vergara, M., López Escobar, L. & Hickey-Vargas, R. 1997*a*. Geoquímica de las rocas volcánicas miocenas de la cuenca intermontana de Parral-Ñuble. *VIII° Congreso Geológico Chileno (Antofagasta), Actas*, **2**, 1570–1573,

Vergara, M., Moraga, J. & Zentilli, M. 1997*b*. Evolución termotectónica de la cuenca terciaria entre Parral y Chillán: Análisis por trazas de fisión en apatitas. *VIII° Congreso Geológico Chileno (Antofagasta), Actas*, **2**, 1574–1578.

Vergara, M., Puga, E., Morata, D., Beccar, I., Díaz de Federico, A. & Fonseca, E. 1997*c*. Mineral chemistry of the Oligocene–Miocene volcanism from Linares to Parral, Andean Precordillera. *VIII° Congreso Geológico Chileno (Antofagasta), Actas,* **2**, 1579–1583.

Wernicke, B. & Burchfield, B. 1982. Models of extensional tectonics. *Journal of Structural Geology*, **4**, 105–115.

Zapata, T. 1997. *La estructura cortical del volcán Auca Mahuida.* YPFSA internal Report, Bueros Aires.

Zapata, T., Brissón, I. & Dzelalija, F. 1999. The role of basement in the Andean fold and thrust belt of the Neuquén Basin. *In*: *Thrust Tectonics*. University of London, London, Abstracts, 122–124.

Zapata, T., Córsico, S., Dzelajica, F. & Zamora, G. 2002. La faja plegada y corrida del Agrio: Análisis estructural y su relación con los estratos terciarios de la Cuenca Neuquina Argentina. *V° Congreso de Exploración y Desarrollo de Hidrocarburos (Mar del Plata), Actas*. IAPG, Buenos Aires. electronic files.

Zollner, W. & Amos, A. 1973. *Descripción Geológica de la Hoja 32b, Chos Malal, 1:200 000.* Carta Geológico Económica de la Repúbica Argentina, Buenos Aires, **143**, 91.