Tectonic evolution of the Andes of Neuquén: constraints derived from the magmatic arc and foreland deformation

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Abstract: The Andes of the Neuquén region (36°–38°S latitude) of the Central Andes have distinctive characteristics that result from the alternation of periods of generalized extension followed by periods of compression. As a result of these processes the Loncopué trough is a unique long depression at the foothills parallel to the Principal Cordillera that consists of a complex half-graben system produced during Oligocene times and extensionally reactivated in the Pliocene–Pleistocene. Its northern sector represents the present contractional orogenic front.

The nature and volume of arc-related igneous rocks, the location of the volcanic fronts, expansions and retreats of the magmatism, and the associated igneous activity in the foreland, together with the analyses of the superimposed structural styles, permit the constraint of the alternating tectonic regimes. On these bases, different stages from Jurassic to Present are correlated with changes in the geometry of the Benioff zone through time. Periods of subduction-zone steepening are associated with large volumes of poorly evolved magmas and generalized extension, while shallowing of the subduction zone is linked to foreland migration of more evolved magmas associated with contraction and uplift in the Principal Cordillera.

The injection of hot asthenospheric material from the subcontinental mantle into the asthenospheric wedge during steepening of the subduction zone produced melting and poorly evolved magmas in an extensional setting. These periods are linked to oceanic plate reorganizations in the late Oligocene and in the early Pliocene.

The tectonic evolution of the sub-Andean Neuquén Basin is a consequence of the interaction of different processes along the continental margin. The geological history of the Andes in the Neuquén region is somewhat different to the rest of the Central Andes. Most of the fault segments between the Guayaquil (4°S latitude) and the Penas (46°30′S latitude) gulfs have active orogenic fronts that have been under contraction since the late Cenozoic (Allmendinger *et al.* 1997; Ramos 1999; Jaillard *et al.* 2000; Ramos & Alemán 2000). As a consequence of subduction erosion and changes in the geometry of the Wadati–Benioff zone the magmatic arcs of the Central Andes have shifted towards the foreland during the Late Cretaceous–late Cenozoic Andean cycle (Kay *et al.* 1987; Mpodozis & Ramos 1989; Ramos *et al.* 1991; Kay 2002). Secondly, with the exception of the Pampean flat-slab segment, the orogenic fronts segments are located between the thrust front and the undeformed foreland (Jordan *et al.* 1983; Ramos *et al.* 2002). The foothills of these regions concentrate most of the intraplate shallow seismicity, and earthquake epicentres are related to the wedge top of the fold-and-thrust belts that coincide with the active contraction of the foreland system (DeCelles & Gilest 1996). The orogenic front in the study region is now contracting the Plio-Pleistocene arc, westward from the Neogene fold and thrust belt that is currently inactive.

The Neuquén Andes record an oscillatory behaviour since the Jurassic, with the shifting and expansion of the location of arc magmatism of the order of a few tens of kilometres. This is in contrast with the evolution of the other segments of the Central Andes that record arc migrations to the foreland of 400–750 km from the trench (Fig. 1). Consequently, the Neuquén Andes have, at present, an extensional depression between 36°30′ and 39°00′S, known as the Loncopué Graben (Ramos 1977), which is absent from the segments. The Loncopue Graben is located parallel to the cordilleran axis, between the foothills and the foreland region, and the present

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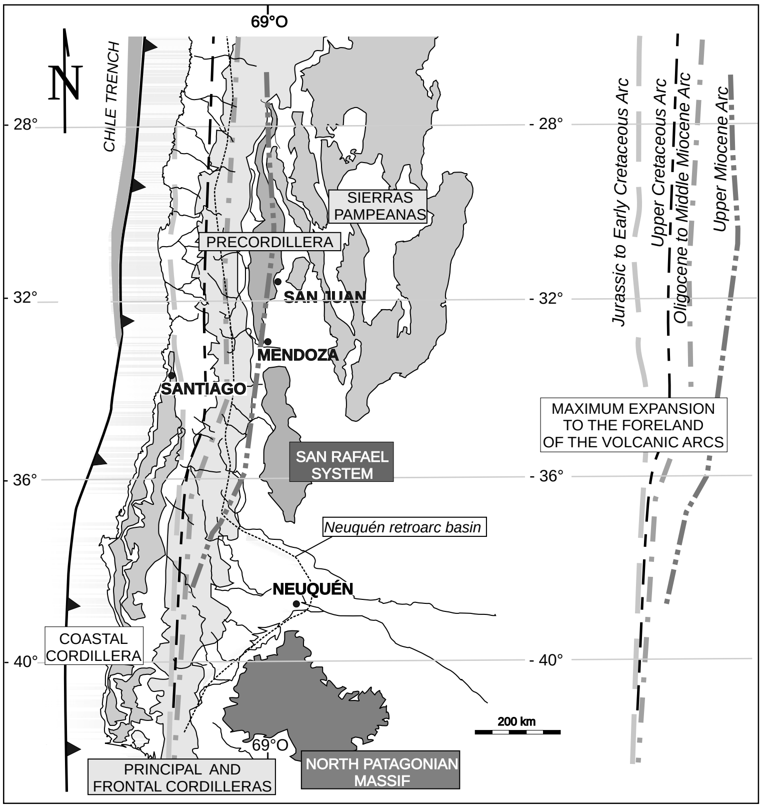

Fig. 1. Location of the Neuquén Andes within the Central Andes showing the maximum expansion of the volcanic front towards the foreland in the different magmatic arcs (based on Mpodozis & Ramos 1989).

morphology was developed during late Cenozoic times. The present orogenic front is located in the inner retro-arc sector, west of a fossil fold and thrust belt developed during Late Cretaceous and Miocene times.

The objective of this paper is to describe the geology along the axis of the cordillera and the main characteristics of the Loncopué Graben in order to reconstruct the evolution of the Neuquén Andes and the geological history of the adjacent Neuquén Embayment. There is a close relationship between the age of foreland migration of the magmatic arc and deformation, and the age of extensional collapse and large volumes of igneous activity during the period of arc retreat.

The study area comprises the main Andes and the foothills between 36° and 39°S. Most of the information is derived from extensive fieldwork and mapping along the foothills and in the inner region of the cordillera (Folguera & Ramos 2000; Folguera *et al.* 2003*a*, *b*, 2004) (Fig. 2). Data from the forearc and the western slope are based on the observations of Suárez & Emparán (1997), Melnick *et al.* (2002, 2005) and Radic *et al.* (2002).

Present tectonic setting

An outstanding feature of the Andes within the study area is the Loncopué Graben (also called the Loncopué trough), a morphological depression 300 km long and about 30–40 km wide (Fig. 3). The graben is located between the eastern foothills of the Andes and a fossil antithetic belt (*sensu* Roeder 1973) called the Agrio Fold and Thrust Belt (Ramos 1977). The Agrio Fold and Thrust Belt has a long and complex long history, and the main contractional deformation ended in the late Miocene (see Zapata & Folguera 2005). The Loncopué trough south of Loncopué is presently bounded to the east by Quaternary normal faults. Triangle facets and recent scarps indicate neotectonic activity along these faults (see García Morabito 2004). These neotectonic features may be

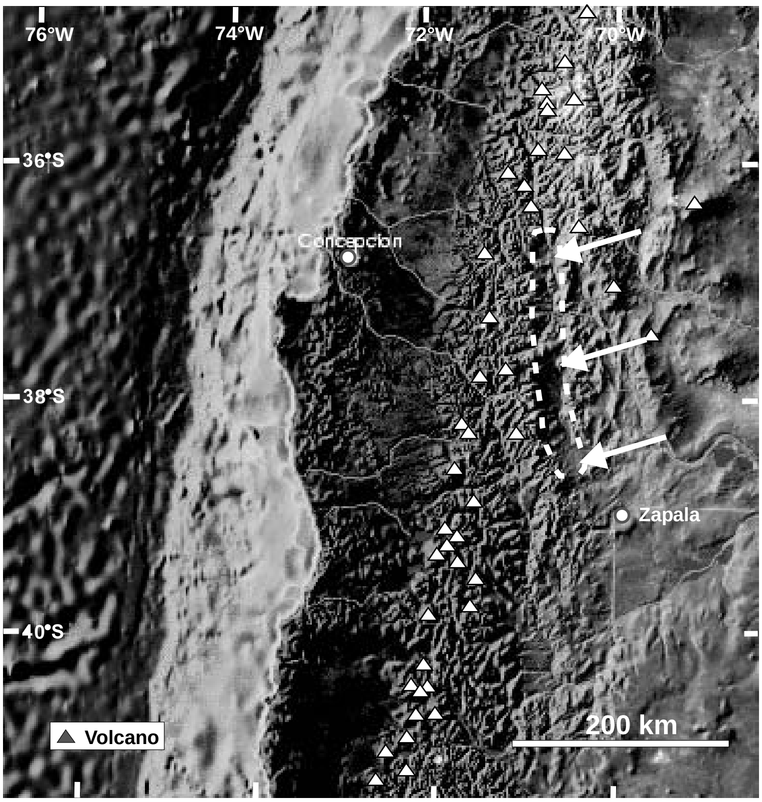

Fig. 2. Topographic map of the Neuquén Andes showing the location of the present volcanic arc and the extension of the Loncopué depression in the foothills (based on IUGS digital elevation model). Arrows indicate the eastern tectonic boundary of the Loncopué trough.

inherited from an older normal fault developed during the Oligocene that consists of a W-dipping extensional fault that is seen in seismic lines along the eastern margin in the northern sector of the depression (Jordan *et al.* 2001).

A large part of the depression is covered by Quaternary alkaline basalts, as first described by Muñoz & Stern (1985). Several lava flows, tens of metres thick, have flowed to the east. Many monogenic pyroclastic cones of basaltic composition are spread over the area. Scarce geochronological data, mainly from the southern end of the depression at about 39°S, indicate ages between 2.30 ± 0.3 and 0.47 ± 0.2 Ma (K–Ar whole rock: Linares & González 1990). Similar ages of 0.130 ± 0.02 and 0.167 ± 0.005 Ma by Ar–Ar have been reported by Rabassa *et al.* (1987) in basaltic lavas further south along the same structure. Other Quaternary ages between 1.6 ± 0.2 and 0.9 ± 0.3 Ma (by K–Ar whole rock) have been obtained by Muñoz & Stern (1985, 1988) around Paso Pino Hachado. Interbedded basaltic flows or overlying glacial deposits have also been reported along the Loncopué trough (Folguera *et al.* 2003*b*).

The poorly evolved alkaline magmatism that characterizes the thick lava flows, the low $^{87}Sr/^{86}Sr$ initial ratios near 0.7040, similar to the main orogenic arc (Muñoz Bravo *et al.* 1989), as well as the abundance of monogenic small volcanoes, together with scattered evidence of normal faults as depicted by Folguera *et al.* (2004), indicate an extensional regime in the retro-arc during Pleistocene times.

The Principal Cordillera at these latitudes is bounded to the west by a Holocene volcanic front, and is located 250 km east of and parallel to the trench with a NNE trend. There are a few isolated volcanoes along the axis, such as Llaima, Callaqui, Copahue, Antuco and Chillán (Fig. 3). Geochemical composition and $^{87}Sr/^{86}Sr$ ratios ranging from 0.7038 to 0.7041, independent of SiO_2 content in the main orogenic arc, indicate crystal fractionation without

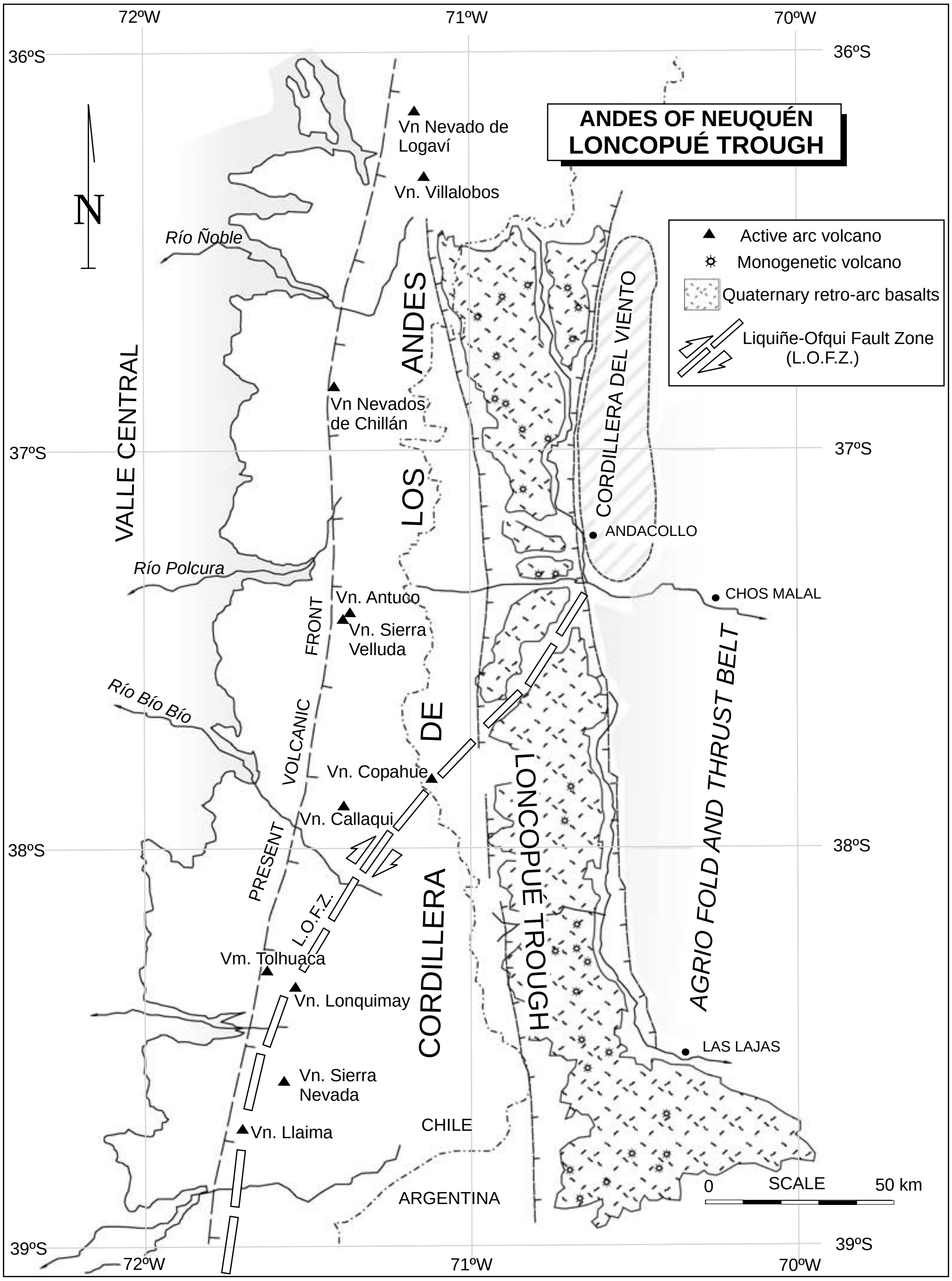

Fig. 3. Location of the Loncopué trough with the main tectonic elements. Note the position and trend of the present volcanic front in comparison with the Quaternary retro-arc basalts of the Loncopué trough. L.O.F.Z., Liquiñe–Ofqui Fault Zone.

significant contamination by the crust as the dominant process in an extensional regime similar to the retro-arc (Muñoz & Stern 1988).

Geophysical data, mainly gravity and preliminary seismological surveys, indicate an unusually thin crustal root beneath the Neuquén Andes. Recent data on receiver function beneath Neuquén at 39°S indicate an abnormally thin crust beneath the Loncopué trough (Kind *et al.* 2001). The interpretation of the crustal structure (Fig. 4) is based on the gravity surveys of Couch *et al.* (1981), Pacino (1993) and Martínez *et al.* (1997), as well as on the receiver function data. The gravity data feature a small crustal root, less than 42–43 km deep. This poses important constraints on the structural style of the Agrio Fold and Thrust Belt, as it implies that crustal shortening cannot exceed

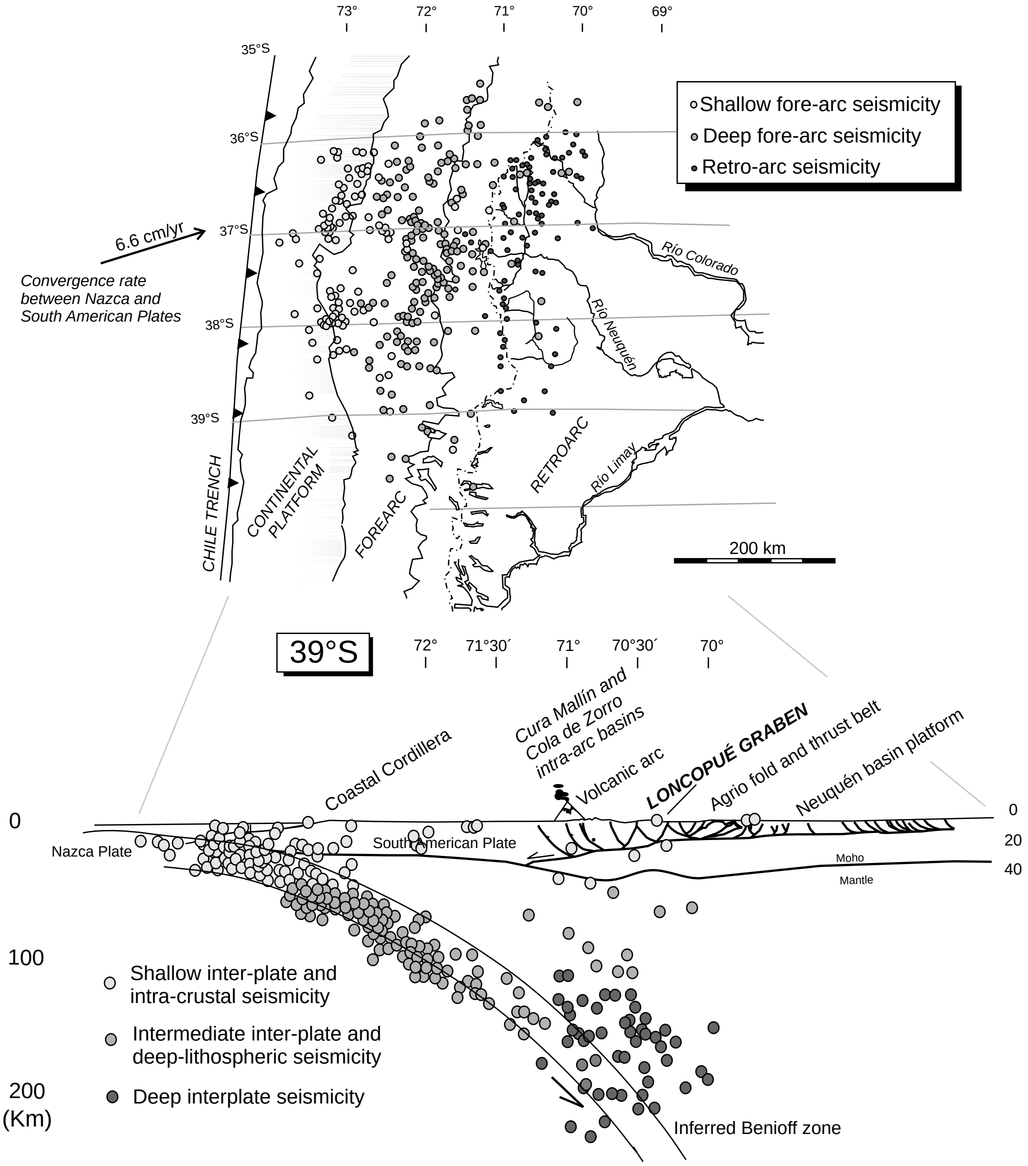

Fig. 4. Location of the earthquake epicentres and crustal section of the Neuquén Andes showing the present Benioff zone (based on Kind *et al.* 2001; Bohm *et al.* 2002; Ramos *et al.* 2004).

44 km at 37°S and 20 km at 39°S (Martínez *et al.* 1997) if it is assumed that arid conditions prevailed since the late Cretaceous and no significant erosion took place. This is in accordance with the Moho depth observed beneath the main Andes from broadband seismology by Kind *et al.* (2001).

Preliminary receiver function data, obtained by broadband teleseismic stations along a west–east profile between the trench and the Neuquén Embayment just a few kilometres north of 39°S, confirm a maximum thickness of between 40 and 45 km beneath the Neuquén Andes (Kind *et al.* 2001). Significantly, the minimum crustal thickness is reported west of 70.2°W longitude, below the Loncopué trough. Although these data are preliminary, a shallow Moho is reported at less than 30 km depth, considerably less than the 40 km recorded in the plains of the Neuquén Embayment. If these data are confirmed it would be a clear indication of significant crustal thinning developed in the retro-arc during an extensional regime that began in the Oligocene, was interrupted in the late Miocene and lasted until the Pleistocene.

Seismological data reported by INPRES indicate different behaviour within the foothills north and south of 37°30′S (Fig. 4). The northern area records an active orogenic front with more frequent intraplate earthquakes that coincides with the northern sector of the Loncopué trough where active compressional neotectonics has been recently described (Folguera *et al.* 2003*a*, 2004). The southern area is far less active in comparison and there is no evidence of compressional neotectonic features.

Previous magmatic arcs and intra-arc basins

In order to understand the present tectonic framework, it is important to analyse the magmatic history of the volcanic arc through time. This includes the location of the volcanic front, the characteristics of the volcanic products, the basin formation and the subsequent tectonic regime. In the following section several different magmatic episodes are described as well as the resulting tectonic regime. These episodes include: the Jurassic–Early Cretaceous; the Late Cretaceous–Palaeogene; the Oligocene–early Miocene; the middle–late Miocene; and the Pliocene–Pleistocene. The outstanding characteristic of these episodes is the oscillatory nature of the migration and expansion of magmatic activity, and a somewhat stationary volcanic front (Ramos 1988; Mpodozis & Ramos 1989). The subduction complex is preserved along the Pacific margin at these latitudes and it has no evidence of erosion. The lack of important subduction erosion as depicted further north by Stern (1991) and Kay (2002), rules out this mechanism as a cause for the migration and expansion of the magmatic activity toward the foreland.

Jurassic–Early Cretaceous arc and intra-arc basin

Volcanic and plutonic rocks of this age are widely preserved along the axis of the cordillera north of 36°S. However, to the south of this latitude, scarce outcrops are partially exposed beneath thick covers of Cenozoic volcanic rocks. For example, west of Cordillera del Viento, between Bella Vista and Nahueve (*c.* 37°S), there are volcanic domes and necks of andesitic–dacitic composition that have been dated at 167.7 ± 8.2 Ma (K–Ar whole rock) by Rovere (1998). These volcanic rocks have a typical calc-alkaline composition (56.04% SiO_2; 1.16% K_2O) and are correlated with the arc volcanism developed further north.

Jurassic volcanic rocks have also been described near Lonquimay, at 38°30′S, in the lower and upper members of the Nacientes del Biobio Formation by De la Cruz & Suárez (1997). The age of these volcanic sequences is constrained between the Lower and Upper Jurassic based on the interbedded sedimentary facies with abundant ammonites. The tholeiitic basalts of the lower member have been assigned to a magmatic arc developed in an extensional regime in a wide intra-arc basin that reached the Argentine side of the Andes (Ramos 1999). The upper member has been correlated with Kimmeridgian volcanic rocks well developed north of 36°S.

The batholith of the Principal Cordillera, from Temuco (*c.* 38°30′S) to the south, consists of granitoids ranging in age from 176 to 164 Ma (Rb–Sr isochrones: Munizaga *et al.* 1988; Niemeyer & Muñoz 1983). Similar granitoids of Cretaceous age, emplaced at these latitudes in the Principal Cordillera, yielded ages of 94 ± 2 Ma, showing the wide distribution of the Mesozoic granitic rocks along the axis of the cordillera.

Based on the general characteristics of the Jurassic and Early Cretaceous rocks where they are well exposed in the adjacent areas, an extensional regime was suggested for these igneous rocks between 35° and 39°S by Muñoz (1984). Similar conclusions were obtained by De la

Cruz & Suárez (1997) who proposed a volcanic arc front west of the Principal Cordillera. However, the scarcity of exposures precludes a precise palaeogeographic reconstruction. It is generally accepted that they were emplaced during an important period of negative trench roll-back velocity when extensional conditions were widespread in the arc and retro-arc regions (Ramos 1999).

Late Cretaceous–Palaeogene arc

There was a striking change in the distribution of volcanic and plutonic rocks in the Late Cretaceous when an important expansion of magmatism to the foreland occurred. Within the Principal Cordillera there are many granitoids of Late Cretaceous age that sit within a main batholith which forms the roots of the magmatic arc. K–Ar ages between 36° and 38°S range from 90.36 ± 3.63, 85.4 ± 5.2 and 83.9 ± 3.8 to 76.5 ± 1.8 and 64.0 ± 1.9 Ma (Munizaga *et al.* 1985). There was a migration of the magmatism to the foreland soon after the emplacement of the batholith that coincides with a magmatic lull of Eocene volcanic rocks along the Chilean side of the Andes at 36°–39°S (López Escobar & Vergara 1997). The important Late Cretaceous change along the Pacific margin of South America coincides with a well-documented adjustment of the tectonic regime associated with the final breakaway of the South American Plate from the African Plate and the beginning of the drift stage (Somoza 1995). This transition caused a change from a negative to a positive roll-back velocity, marking the beginning of the contraction along the continental margin (Daly 1989).

Volcanic rocks of Late Cretaceous–Eocene age are widely developed between 36°30′ and 38°30′S (Fig. 5). These rocks have been described by Llambías & Rapela (1987, 1989) as part of a calc-alkaline suite of volcanic domes, dykes and lavas that range in composition from basaltic to andesitic. New geochronological data and geochemical analysis of this belt have recently been presented by Franchini *et al.* (2003).

The oldest rocks belong to the Campana Mahuida igneous complex, with an age of 74.2 ± 1.4 Ma, interpreted as a porphyry copper system by Sillitoe (1977). However, recent K–Ar dating indicates a younger age of 60.7 ± 1.9 Ma (Franchini *et al.* 2003). These intrusive rocks have La–Yb ratios of between 10 and 30, typical of a thick crust as seen further north in the Quaternary magmatic arc (Kay *et al.* 1991; Franchini *et al.* 2003).

The granitoids of the Cerro Nevazón area are stocks, sills and dykes of intermediate composition. They range from gabbro to granodiorite, diorite being the dominant facies. They are metaluminous rocks, with a normal potassium content (0.6–2.3%). The La–Yb ratio ranges from 5 to 15, and probably indicates a thinner crust in the northern sector. The age of these rocks is constrained between 56.0 ± 1.7 and 59.6 ± 10.6 Ma (K–Ar in hornblende) (Franchini *et al.* 2003).

Further south, in the Quebrada Mala and Cerro Pelán east of Cordillera del Viento, andesitic sills yielded a K–Ar age of 71.5 ± 5 Ma (Llambías & Rapela 1989). Another magmatic system, known as Los Maitenes–El Salvaje was emplaced in the southern end of the Cordillera del Viento. There, a tonalitic stock has an age of 64.7 ± 3.2 Ma (Domínguez *et al.* 1984). Similar Paleocene ages were obtained in a stock near Varvarco, NW of Cordillera del Viento (Fig. 5). The Varvarco tonalite yielded an age of 64.7 ± 3.0 Ma (K–Ar whole rock) (JICA 2000).

The regions of Caicayén and Collipilli in the central part of this belt preserve a series of intrusive domes and volcanic rocks. They have been assigned to the Collipilli Formation, which is predominantly composed of concordant intrusive bodies like sills and laccoliths. They range in composition from hornblende andesites to diorites and quartz-diorites. There are also small dacitic intrusives. They are calc-alkaline, with normal potassium, and have been interpreted as typical magmatic arc rocks by Llambías & Rapela (1989). A microdiorite from Las Mellizas yielded an age of 49.9 ± 3.2 Ma, while a laccolith at Cerro del Diablo had an age of 48.4 ± 2.4 Ma; a similar age has been obtained in Cerro Caicayén with 44.7 ± 2.2 Ma (K–Ar whole rock) (Llambías & Rapela 1989). For a sill at Cerro Mayal, Cobbold & Rossello (2003) have recently obtained a late Eocene age (39.7 ± 0.2 Ma) by Ar/Ar on whole rock.

New Ar/Ar ages from a coarse-grained granodioritic plutonic unit, north of the town of Varvarco in the Cordillera del Viento, were interpreted as cooling ages by Kay (2001). The age of 69.09 ± 0.13 Ma (Ar/Ar in biotite) indicates at least 3 km of uplift during the late Cretaceous, with an extra 3 km uplift prior to the deposition of the Serie Andesítica lavas (Kay 2001). These volcanic rocks, known as the Cayanta Formation, consist of hornblende andesite lava flows, volcanic breccias and volcanic agglomerates widely exposed west of Andacollo town (Llambías & Rapela 1989). New Ar/Ar ages in hornblende dates these rocks at 56.9 ± 1.1, 56.5 ± 0.6 and 50.3 ± 0.6 Ma (Jordan *et al.* 2001) within the

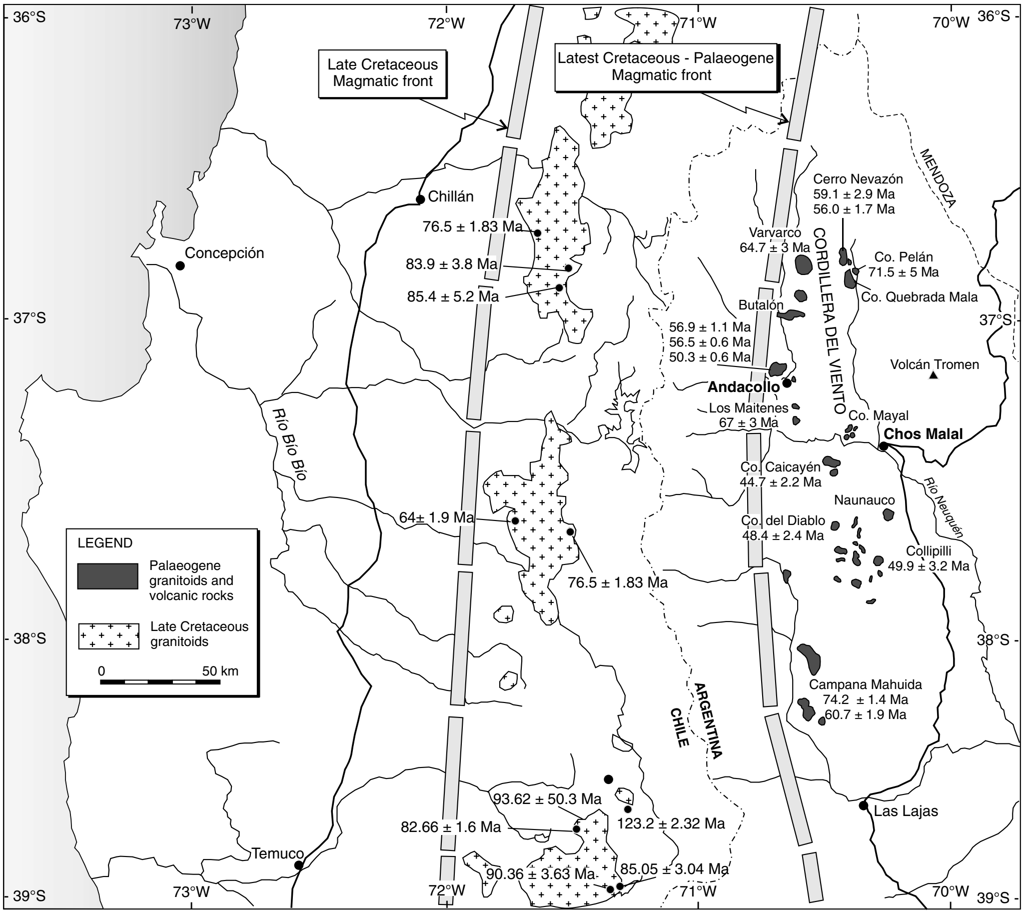

Fig. 5. Migration of the location of plutonic and volcanic arc rocks, with the magmatic front during Late Cretaceous–Palaeogene times indicated (based on Munizaga *et al.* 1985; Llambías & Rapela 1989; Jordan *et al.* 2001; Franchini *et al.* 2003). Note that in latest Cretaceous time the magmatic front was east of the Loncopué trough.

same rank of the diorites located east of Cordillera del Viento.

As a whole, these rocks indicate that a belt of normal arc characteristics developed to the of east of the Jurassic–Early Cretaceous arc emplaced in a normal–thick crust. The change in composition and nature of the plutono-volcanic arc indicates a thickening episode produced during the Late Cretaceous, with an estimated uplift in the order of 6 km in the northern segment as a result of eastward migration of the magmatic arc toward the foreland.

Previous authors have proposed an important transpression during the late Eocene in the northern part of the Neuquén Basin (e.g. Cobbold *et al.* 1999). This interpretion is based on the orientation of subvertical bitumen veins emplaced mainly in the Jurassic and Cretaceous rocks (Cobbold *et al.* 1999). The lack of important Palaeogene synorogenic sequences south of 37°30′ S may indicate either that the deformation was concentrated in the inner sector of the Andes or that it was milder than in the northern sector. New findings of growth strata along the flank of the Cortaderas Fault have been interpreted as evidence of Oligocene transpression (Cobbold & Rossello 2002, 2003), but may correspond to a Miocene reactivation depending on the age assigned to this sequence.

Oligocene–early Miocene arc and intra-arc basin

During this period the volcanic activity between 37° and 41°S underwent further important change in location and character. The Arauco and Valdivia coal basins show evidence that an extensional regime controlled the sedimentation of continental deposits in half-graben systems with a NNE trend along the Coastal Cordillera and the Central Valley during the Oligocene–early Miocene (Cisternas & Frutos 1994). These basins received abundant volcaniclastic and pyroclastic deposits from the Principal Cordillera.

Andesites and dacites from the western flank of the Andes between 37.5° and 39°S are geochemically and isotopically similar to Quaternary andesites and dacites of the Nevados de Chillán Volcanic Group (36.8°S), which are some of the most primitive andesites and dacites of the Southern Volcanic Zone of the Andes (López Escobar & Vergara 1997). These volcanic sequences were deposited in half-graben systems (Radic *et al.* 2002), with thicknesses up to 1500 m observed on subsurface data. These rocks with flat rare earth element (REE) patterns and La–Yb ratios close to 1 are interpreted to have been erupted during an extensional regime (Vergara *et al.* 1997*a, b*).

The lower part of the sequence was included in the Cura Mallín Formation by Suárez & Emparán (1997). It consists of lacustrine and fluvial deposits, interfingered with volcanic and volcaniclastic rocks. The Cura Mallín Basin was described by Radic *et al.* (2002) as an extensional basin with two depocentres of different polarities (Fig. 6). The northern sub-basin has dominant west-dipping normal faults with a NNE trend, and a 2800 m-thick succession along the eastern border of the Loncopué trough at 37°S. A seismic line presented by Jordan *et al.* (2001) shows a normal west-dipping fault bounding the eastern margin of the basin west of Andacollo. The volcanic, alluvial and lacustrine deposits of the Cura Mallín Formation were deposited between 24.6 and 22.8 Ma (Ar/Ar: Jordan *et al.* 2001), and are overlain by the Trapa–Trapa Formation, a thick andesitic pile deposited between 18.2 and 14.7 Ma. The southern sub-basin with a maximum thickness of 2400 m has opposite polarity with a NE trend where the volcanic, alluvial and lacustrine deposits of Cura Mallín Formation were formed between 19.9 and 10.7 Ma. This southern succession is covered by the Mitrauquén Formation, another thick pile of andesites and dacites deposited between 9 and 8.5 Ma. Between both depocentres there is an ENE-trending transfer zone (Radic *et al.* 2002).

The volcanic rocks exposed in the western part of the Neuquén Embayment, such as those in Cerro Cabras, Cerro Tormenta, Desfiladero Negro and Cerro Sur de Los Overos (at approximately 37°30′S), are alkaline basalts that have ages between 23 and 19 Ma, Oligocene–early Miocene (Ramos & Barbieri 1989). These rocks have very low initial $^{87}Sr/^{86}Sr$ ratios of the order of 0.7035, smaller than the present magmatic arc (Ramos & Barbieri 1989) and are interpreted as having been formed in an extensional setting, with no influence from the subducted slab (Kay 2001, 2002). These low initial ratios of $^{87}Sr/^{86}Sr$ associated with high neodymium isotopic ratio εNd (>+5), have been reported as far south as the 41°S latitude at both sides of the Principal Cordillera by Muñoz *et al.* (2000).

Several authors have emphasized the large volume of volcanic rocks erupted in a short time span during late Oligocene–early Miocene times (Jordan *et al.* 2001; Muñoz *et al.* 2000; Folguera *et al.* 2003*b*). This fact, together with the unusually primitive nature of the magmas at these latitudes (López Escobar & Vergara 1997), indicate an important extension of forearc, arc and intra-arc regions at that time. This extensional regime is linked with an important shift to the trench of the magmatic activity after the late Eocene.

Middle–late Miocene arc

The eruption of the Trapa–Trapa and Mitrauquén Formations along the axis of the Neuquén Andes between 18 and 8 Ma coincides with the emplacement of middle–late Miocene stocks of granodioritic composition with ages between 16 and 10 Ma (Moreno & Parada 1976; Munizaga *et al.* 1985). The emplacement of these stocks is coeval with a new pulse of expansion of the volcanic activity in the foreland. This broadening of the magmatic activity was recorded mainly to the north of the Cortaderas lineament in the Sierra de Huantraico (37°S), where hornblende andesites and dacites were erupted, like the Pichi Tril Andesite at about 18 ± 2 Ma (K–Ar whole rock: Ramos & Barbieri 1989). Near Cerro Bayo, on the eastern edge of the Huantraico syncline and at Filo Morado on its NW edge, Cobbold & Rossello (2003) have sampled lava flows, obtaining early Miocene ages of 22.1 ± 0.5 and 22.2 ± 0.2 Ma, respectively, by Ar/Ar on whole rock. There are several other centres with comparable characteristics in the Sierra de Huantraico and further north. These andesitic rocks extend north of Río Colorado up to the Sierra de Chachahuén where they have been studied by Kay (2002). The hornblende-bearing andesite of this locality are about 480 km away from the trench.

This important period of broadening of the magmatism was associated with several

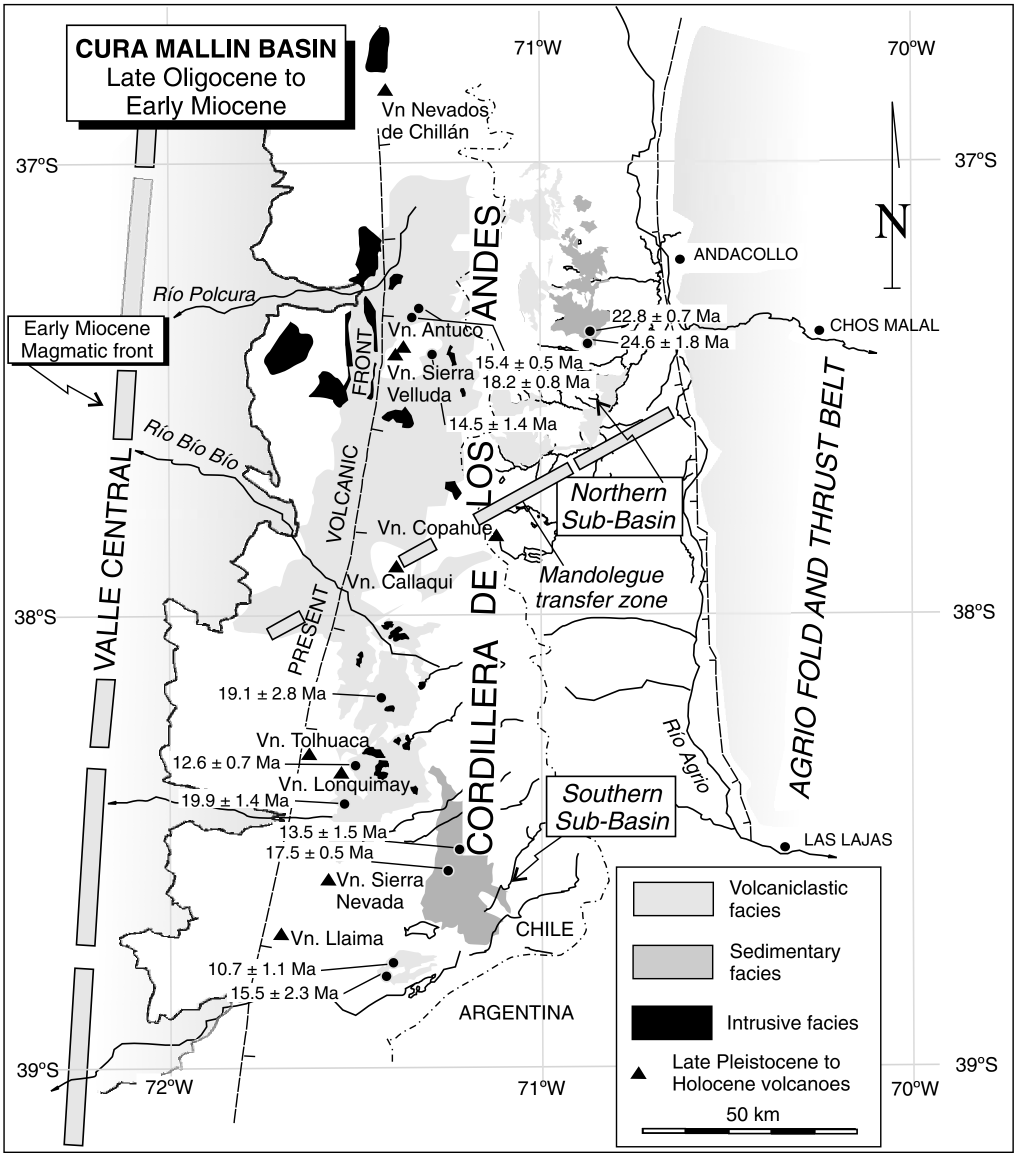

Fig. 6. Palaeogeographic map of the Cura Mallin Basin with indication of the early Miocene magmatic front, the extension of the outcrops and available ages of the interbedded volcanic rocks.

subvolcanic centres. The associated volumes of volcanic material were far less than those produce during the Oligocene–early Miocene period described above. The geochemistry of these rocks indicates a normal magmatic arc with hornblende-bearing calc-alkaline rocks.

Several authors recognized an important period of deformation between 16.3 ± 0.1 (Ar/Ar) and 6.7 ± 0.5 Ma (K–Ar) by Kozlowski *et al.* (1996) in the Coyuco syncline, north of Huantraico, where deposits of latest Miocene age and Pliocene are not folded. These values are similar to the constraints proposed by Ramos & Barbieri (1989) for the folding of the lavas and pyroclastic rocks of the southern end of Huantraico bracketed between 18 and 9 Ma. The deformation in the inner sector of the Cura Mallín Basin was constrained between 8 and 5 Ma on the basis of the unconformity that separates folded products of the Cura Mallín Basin and Pliocene volcanic rocks (Folguera *et al.* 2003*b*).

Pliocene–Pleistocene arc and intra-arc basin

A new period of intense volcanic activity and migration to the trench of the volcanic front started in the early Pliocene. The widespread magmatism of this period led Muñoz & Stern (1985, 1988) to recognize two belts of volcanic rocks. The volcanic front along the axis of the Principal Cordillera and an extensive belt with intra-arc volcanics, both of which are characterized by poorly evolved lavas with low initial $^{87}Sr/^{86}Sr$ ratios (of the order of 0.7038–0.7040), erupted in an extensional regime.

The Pliocene rocks were assigned to the Cola de Zorro Formation by Vergara & Muñoz (1982), and consist of volcanic breccias and lavas of basaltic–dacitic composition. This volcanic sequence records large volumes of erupted material and numerous evidence for synextensional deposition (Folguera *et al.* 2003*b*). Rapid thickness variations from 1900 m to a few tens of metres, changes in the polarity of the half-graben system, as well as syndepositional discontinuities indicate generalized extension in this period. These volcanic rocks were erupted between 5 and 3 Ma. These rocks covered most of the Loncopué trough and extend along the axis of the Principal Cordillera, west of the drainage divide. Similar basalts in Paso Pichachén have been dated at 3.6 ± 0.2 and 3.6 ± 0.5 Ma (Muñoz Bravo *et al.* 1989) and in Paso Pino Hachado at 4.8 ± 0.2 Ma (Linares & González 1990).

Coeval with this Pliocene eruption, there are isolated cones and lava flows of alkaline basalts developed in the foreland region along the northern end of the Sierra de Los Chihuidos that have been described by Ramos (1981). These volcanic rocks erupted in the western sector of the Neuquén Embayment, such as in the Cerro Parva Negra volcano, and were dated at 4.5 ± 0.5 Ma (Ramos & Barbieri 1989). Further east, in Aguada Rincón and in Cerro La Manea, alkaline basalts described by Holmberg (1964) in the foothills of the Auca Mahuida volcano yielded ages of 4.8 ± 2 and 3.4 ± 0.5 Ma at the base of the volcanic sequence (Valencio *et al.* 1979). These alkaline rocks in the retro-arc have been attributed to a mild within-plate extension without relationship to the subducted slab (Kay 2001).

A new period of volcanic activity took place between 2 and 0.5 Ma. The erupted volcanic rocks were concentrated in a narrower belt than those of the previous pulse (Folguera *et al.* 2003*b*; Melnick *et al.* 2003, 2005). Rocks of this new event have been recognized in Laguna del Barco area, west of Copahue volcano, with ages ranging from 2.68 to 2.60 Ma (Melnick *et al.* 2005). They are widespread in Río Pino Solo and Piedra Blanca, east of Paso Pino Hachado, with several ages ranging from 1.40 ± 0.2 to 1.6 ± 0.2 Ma (K–Ar whole rock: Muñoz & Stern 1988). There is a spatial coincidence between the early Pliocene and late Pliocene–Pleistocene volcanic fronts, as denoted by Muñoz Bravo *et al.* (1989) and Lara *et al.* (2001), but the volume of eruption and the area are more restricted in the younger event.

During the Pliocene–Pleistocene important volcanic activity was registered in the retro-arc. The Auca Mahuida Volcano, located 500 km from the trench, erupted through a series of abundant but small monogenic centres extruding large amounts of basaltic lavas ranging in age from 1.7 ± 0.2 to 0.9 ± 0.07 Ma (Ar/Ar, plateau and isochron ages: Rossello *et al.* 2002).

The last activity is interpreted to be related to the trench migration of the late Pleistocene–Holocene volcanic front described by Muñoz & Stern (1988), in which a 30–50 km displacement is reported. At this time, a reactivation of the Loncopué trough controlled the eruption of many monogenic basaltic cones and small lava flows as seen west of Loncopué town and along the foothills of the Neuquén Andes.

Magmatic and tectonic styles

The alternation of periods of voluminous arc magmatism and intra-arc basin development with intervals of reduced arc magmatism and deformation has captured the attention of several previous authors (e.g. Folguera *et al.* 2002). However, the mechanism and causes of such links are still poorly understood. Several hypotheses have been advanced, mainly to explain the voluminous magmatism associated with intra-arc development. Muñoz & Stern (1988) proposed thermal or mechanical perturbations of the subcontinental mantle associated with subduction. These perturbations were interpreted as being the result of diapiric mantle upwelling or some other process of lithospheric thinning and erosion associated with continental extension. Other authors have proposed that extension could be a consequence of important strike–slip displacement of the Liquiñe–Ofqui Fault Zone (McDonough *et al.* 1997; Suárez & Emparán 1997).

Muñoz Bravo *et al.* (1997) considered that melting during Oligocene–early Miocene was caused by asthenospheric upwelling driving the crustal extension, rather than slab dehydration in the asthenospheric wedge. The presence of alkali basalts along the Central Valley, comparable with those erupted in intra-arc and retro-arc basins associated with the active arc products, suggests derivation from an oceanic-type mantle unmodified by components derived from a subducted slab. The asthenospheric upwelling during the late Oligocene–early Miocene times was explained by Muñoz *et al.* (2000) and Stern *et al.* (2000) as a consequence of an asthenospheric window developed during a period of plate reorganization.

Based on the widespread seismic evidence for extension Jordan *et al.* (2001) proposed that, instead of localized transtension, the bulk strain was horizontal extension. The abnormal melting in the Central Valley 170 km from the trench may reflect an increased flux of water as a consequence of more rapid subduction and this high pore pressure may have favoured a decrease in forearc topography. The same authors also recognized that increased heat flux would produce uplift and, in turn, would provoke moderate extension. This abnormal heat flux could be related to a transient hot spot as proposed further east at 27 Ma by Kay *et al.* (1993).

The link between rapid subduction and extension during the Oligocene–early Miocene, followed by later shortening, was challenged by Stern *et al.* (2000) and Godoy (2002). This last author presented evidence that along the Chilean margin there were segments that did not record any extension at that time, as well as others with extension and no subsequent shortening.

There are several facts that should be considered when trying to understand the alternation of different magmatic and tectonic styles along the Andes at these latitudes. First, that this alternation is almost unique along the Central Andes, and therefore the explanation should have some exceptional causes. Secondly, that although extension was generalized at these latitudes in the forearc (Cisternas & Frutos 1994), arc and intra-arc (Jordan *et al.* 2001; Radic *et al.* 2002; Folguera *et al.* 2003*a, b*), and a mild extension in the retro-arc (Kay 2001), subsequent shortening was not that important (Ramos *et al.* 2004).

The common magmatic and structural features of the alternating Mesozoic and Cenozoic settings can be summarized in the following two-stage process.

Intense intra-arc magmatism and extension

Large volumes of igneous activity and poorly evolved magmas, located at a short distance (typically less than 170 km) from the trench, are recurrent in the Jurassic–Early Cretaceous, Oligocene–early Miocene and Pliocene times. The presence in extreme cases, as in the Oligocene, of alkali basalts, typical of retro-arc settings together with arc products, were interpreted as the result of an input of hot and undepleted asthenosphere, different from a typical asthenospheric wedge. Geochemical characteristics show flat RREE patterns with low La–Yb ratios, which is common for low-pressure crystallization, typical of a thinned crust (Muñoz & Stern 1988).

These magmatic episodes were produced during periods in which the magmatic activity retreated toward the trench. The periods are associated with large areas of eruption that are significantly different to the normal, narrower volcanic arcs. At this time the volcanic front was associated with wide intra-arc basins and, in certain cases, with retro-arc alkali magmatism. The increase in alkali contents, mainly potassium (Kay *et al.* 2005), is interpreted as evidence of decreased melting toward the foreland.

Where subsurface data are available, or when the palaeogeography can be reconstructed, well-defined half-graben systems are recognized as controlling the eruption of large volumes of lava associated with alluvial and lacustrine deposits. Evidence of syntectonic deposition has been observed in lavas and interfingered sediments as growth discontinuities and rapid changes in thickness. The structural trend of the half-grabens resulted from pre-existing basement fabrics or the changing orientation of the stress field as a consequence of convergence vector adjustments (Fig. 7).

Extension at those times was generalized, affecting a great part of the continental margin from the forearc to the foreland. The greatest stretching was concentrated along the axis of the cordillera with mild extension detected in the foreland.

Magmatic arc shifting and deformation

The periods of major volcanic activity described above alternated with periods in which narrow belts of plutono-volcanic complexes were formed. The main difference is the presence of coarse-grained tonalites and granodiorites that implies important uplift and consequent denudation after crystallization. The volcanic rocks of these periods are more evolved products that include dacites and andesites as the dominant rock types and indicate important differentiation from parental magmas, either by fractional crystallization or by assimilation of the crust. Geochemical characteristics show the typical trends of calc-alkaline rocks, with steep RREE patterns and higher La–Yb ratios, formed at a higher pressure, probably in a thickened crust.

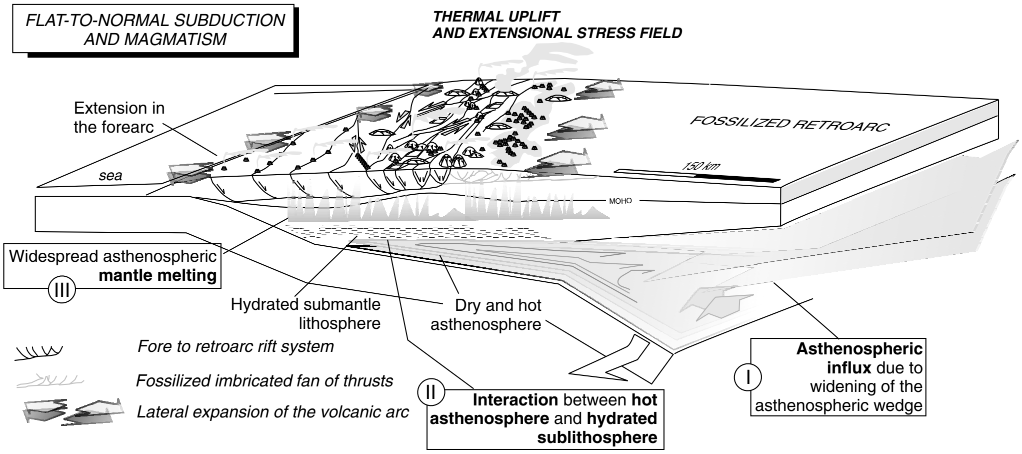

Fig. 7. Conceptual cross-section illustrating the processes related to the steepening of the subduction zone and related magmatism.

The magmatic belts indicate a conspicuous foreland migration with respect to the previous arcs, as observed during the Late Cretaceous–Palaeogene, and from middle Miocene to late Miocene times (Fig. 8). The volcanic products were emplaced in previously deformed rocks. For example, the Late Cretaceous–Palaeogene intrusives have deformed Cretaceous deposits as country rocks. Overall the magmatic deposits are associated with synorogenic deposits such as the clastic sequences of red beds and conglomerates of the Neuquén Group (Late Cretaceous), and the clastics and carbonates of the Malargüe Group (Maestrichtian–Paleocene).

The magmatic front migrated towards the foreland more than 350 km away from the trench, and there was no magmatic activity along the previous magmatic axis, or it is punctuated by the emplacements of plutonic stocks of coeval granitoids.

The lack of significant subduction erosion at these latitudes, as postulated by Ramos (1988), Stern (1991) and Kay *et al.* (2005), precludes crustal erosion in the forearc as a mechanism of arc migration toward the foreland. The decrease in magmatic volume, together with the expansion of the magmatic activity to the foreland, can be better explained by changes in the Benioff geometry.

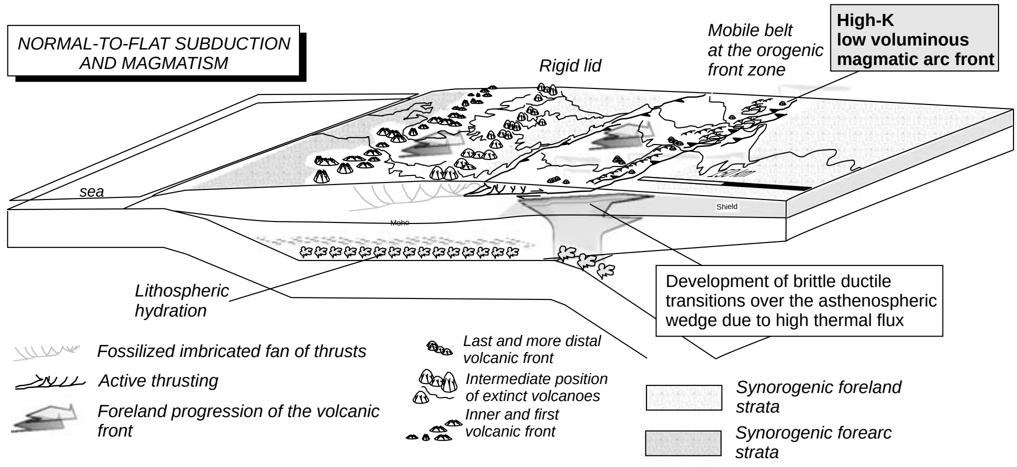

Fig. 8. Conceptual cross-section illustrating the processes related to the flattening of the subduction zone and related magmatism.

Integrated model

In order to explain the alternation of periods with intense intra-arc and arc magmatism and volcanic front retreats, with periods of arc magmatism and foreland expansion and deformation, an integrated model based on the processes presented by James & Sacks (1999) will be analysed. These authors emphasized the profound tectonic and magmatic effects that result from the interaction of hot asthenosphere and hydrated mantle during the transition from flat to normal subduction. Steepening of the angle of subduction brings an influx of hot asthenospheric mantle from depth to fill the opening mantle wedge. When this happens in a thin crust, such as the present setting of the Neuquén Basin, the process will induce large amounts of melting in the asthenospheric wedge and crustal extension with the eruption of large volumes of poorly evolved magmas. In contrast, during a shallowing of the subduction zone, the mantle wedge closes progressively during flattening and asthenospheric material is expelled eastward. Volcanism is shut off along the main volcanic arc (Kay *et al.* 1991).

Such a process may account for the observed distribution of magmatic rocks and extension in the Neuquén Andes since the Jurassic (Fig. 9). Variations in the angle of subduction in the different Benioff zones can explain both the observations from the main arc and also the interactions observed between uplift and collapse of the Principal Cordillera and the tectonic effects in the Neuquén Embayment.

The variations in the angle of subduction are generally attributed to changes in slab buoyancy, probably by subduction of thickened oceanic crust and retardation of the basalt–eclogite transition in the young and relatively hot oceanic plate (Pilger 1984; James & Sacks 1999; Gutscher 2002).

The different cycles of intense magmatism and extension, alternating with foreland shifting of the magmatism and compression, have general similarities in the Neuquén Andes in the last 200 Ma. However, a detailed analysis shows some striking differences generated by the changing kinematics of the interaction between the different Pacific plates and the continental plate. As a result of these changes each cycle has some important peculiarities superimposed on the general trend of steepening and shallowing of the subduction zone.

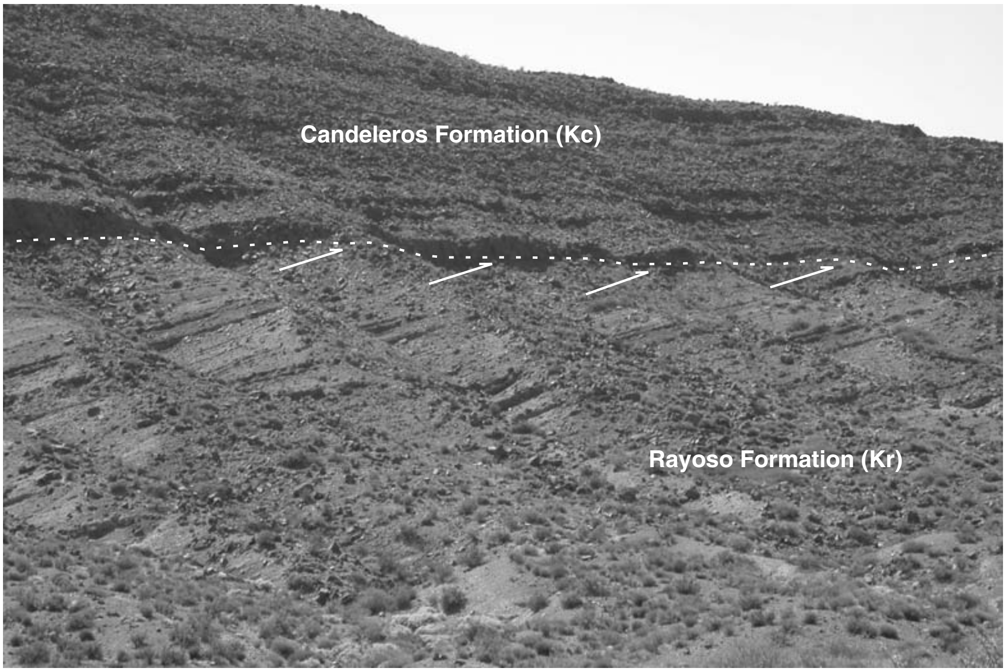

Fig. 9. View to the east of the Late Cretaceous angular unconformity between the upper member of the Rayoso Formation (Kr) and the red beds of the Candeleros Formation (Kc). The Candeleros Formation is the lower unit of the Neuquén Group east of Cerro Rayoso on the western margin of Río Neuquén.

Tectonic interaction of the Andes and the Neuquén Basin

The alternation of periods of intense deformation with others of extension has received considerable attention since plate tectonic concepts were first applied to the formation of orogenic belts (Charrier 1973). However, these changes can be addressed only through the recent understanding of the sublithospheric processes, based on geophysical, petrological and tectonic studies. On these bases, the interaction between the processes observed in the main cordillera and the effects in the Neuquén Basin will be examined.

Jurassic–Early Cretaceous stage

Although rocks of this stage are poorly exposed in the Neuquén Andes at these latitudes, there is enough information at both ends of the segment. The magmatic activity occurred in an extensional regime (Muñoz 1984; De la Cruz & Suárez 1997). Owing to the onset of subduction in the earliest Jurassic (Kay 1993; Franzese & Spalletti 2001), the extensional tectonic regime was characterized by pulses of negative rollback velocity in the trench. As a consequence of this, the Neuquén Basin was affected by generalized rifting enhanced along pre-existing crustal weakness zones, such as the Huincul Fault Zone. Several pulses of horizontal extension, partitioned by the orientation of the weakness zones, resulted in pure extension and localized transtension–transpression. Detailed examples of this interaction have been presented from along the Huincul Fault Zone by Vergani *et al.* (1995), Pángaro *et al.* (2002) and Mosquera (2002). This widespread rifting was also depicted in several parts of the basin by Zapata *et al.* (2002).

Late Cretaceous–Palaeogene stage

The emplacement of the Late Cretaceous batholith was followed by the migration of the magmatic arc to the foreland. This migration is associated with the deformation of the main Andes as it is observed in the 6 km uplift of Cordillera del Viento, which exposed coarse-grained granitoids prior to the Paleocene volcanics. Deformation is also evidenced by growth strata in the red beds of the Diamante Formation. These facts clearly indicate a period of progressive deformation that started in the Late Cretaceous and continued until the late Eocene. The beginning of compressive deformation was produced by tectonic inversion of pre-existing normal faults during a period of shallowing of the Benioff zone. The Agrio Fold and Thrust Belt was formed at this time, with a combination of inversion tectonics in the inner sectors (Vergani *et al.* 1995; Ramos 1998) and localized thin-skinned tectonics in the outer areas (see Zapata & Folguera 2005). As a result of this, the first foreland basin was formed at these latitudes and filled with the synorogenic deposits of the Neuquén Group. The angular unconformity with the pre-orogenic deposits is seen between the top of Rayoso Formation and the base of Neuquén Group along the Chihuidos Ridge east of Río Neuquén (Fig. 9). Compelling evidence for a Late Cretaceous deformation was also presented by Cobbold & Rossello (2003).

This deformation was associated with a high rate of orthogonal convergence in the Late Cretaceous (Larson 1991) that became quite oblique during the Paleocene (Pardo Casas & Molnar 1987). Cobbold *et al.* (1999) interpreted the structures formed during the Eocene deformation as mainly transpressive. New fission-track data (Gräfe *et al.* 2002) indicate that north of 39°S, the axial part of the main cordillera was uplifted during the Eocene. In contrast, immediately to the south, the northern extreme of the intra-arc Liquiñe Ofqui Fault Zone (Fig. 3) has imprinted younger deformations on the highest parts of the cordillera.

Palaeogene synorogenic deposits are more developed in southern Mendoza than in Neuquén where they are restricted north of the Cortaderas lineament (Ramos 1981). However, the Malargüe Group has a depositional system controlled by the flexural subsidence as a result of tectonic loading of the Principal Cordillera (Tunik 2000).

Oligocene–early Miocene stage

The retreat of the magmatic activity toward the trench, associated with the steepening of the subduction zone, produced the Cura Mallín Basin and the generalized extension of the Pacific continental margin as described by Cisternas & Frutos (1994). This extensional process has been described from the latitudes of the present study down to the 41°S latitude (Muñoz *et al.* 2000).

The injection of hot asthenosphere from the foreland sublithospheric mantle to the newly formed asthenospheric wedge produced a large amount of melting and the formation of arc products and alkali basalts near the Central Valley closer to the trench than in previous periods. Large volumes of poorly evolved magmas produced the Oligocene–early Miocene volcanics in the Neuquén Andes.

At that time, the Loncopué trough was the down-thrown block of a normal fault with almost 3 km of displacement located west of Andacollo (Jordan *et al.* 2001). Except for the generation of a series of extensional basins, such as the Cura Mallín, Collón Cura and Ñirehuao, along the foothills of the Neuquén Andes, as described by González Díaz & Nullo (1980) and Dalla Salda & Franzese (1987), most of the Neuquén Basin only records a mild subsidence with deposition of fall tuffs of Palaeogene age.

Middle–late Miocene stage

This was the second period of deformation of the Neuquén Basin. The present structures of the Agrio Fold and Thrust Belt were formed at this time, as well as the final uplift of the Chihuidos ridge, and the Añelo synorogenic depocentre was formed east of the Chihuidos. The deformation was dated at less than 16 Ma by Kozlowski *et al.* (1996) north of Huantraico. Localized synorogenic deposits, such as the Tralalhue Conglomerates (Ramos 1998) west of Río Neuquén and other depocentres, show the limited subsidence of the western part of the embayment during this period of compressional deformation.

This period coincides with an important flattening of the subduction that recorded arc-related volcanic rocks of late Miocene age in the Sierra de Chachahuén (Kay 2002), almost 500 km away from the trench. The Neuquén Andes at this time recorded an important deformation of the Cura Mallín Basin (Folguera *et al.* 2003*b*, 2004) controlled by tectonic inversion of previous normal faults. Although total contraction is not as important as in the northern segments of the Central Andes (Ramos *et al.* 2004), the maximum shortening of the Neuquén Andes was attained at this stage.

Pliocene–Pleistocene stage

This period is characterized by steepening of the flat subduction proposed by Kay (2002) in the late Miocene in the Chachahuén region. As the flat subduction was at a maximum north of Cortaderas lineament, this area recorded the maximum extension and magmatic activity as denoted by Muñoz Bravo *et al.* (1989). The northern areas have not only the arc and intra-arc basin developed, but also important retro-arc volcanoes such as the Tromen and Auca Mahuida.

The retreat of the magmatic front controlled the development of the half-graben system filled by the volcanic rocks of the Cola de Zorro Formation. The early Pliocene corresponds with the maximum horizontal extension and a large volume of volcanic rocks were extruded (Folguera *et al.* 2004). From the early to late Pliocene–Pleistocene the area of maximum subsidence was shifted to the east, to the present Loncopué trough. This time marks the maximum development of the Loncopué trough, and neotectonic features indicate localized transtension such as the collapse of Caldera del Agrio and other rhomboidal pull-apart basins observed in the foothills (Folguera & Ramos 2000; Melnick *et al.* 2005). Contractional deformation related to the Liquiñe–Ofqui Fault Zone during the Pleistocene deformed the northern segment of the Loncopué trough. The Plio-Pleistocene volcanic arc is currently being cannibalized by the thrust front north of 37°30′ S, as indicated by recent neotectonics (Folguera *et al.* 2004).

Along the axis and on the western slopes of the cordillera there is evidence of extension (e.g. in Laguna La Laja), where seismic sections show negative flower structures, along transtensional segments (Melnick *et al.* 2003). The southern sector of the Loncopué trough, south and east of the Loncopué town, shows evidence of extensional neotectonics along the eastern margin of the trough, although there are no available subsurface data.

Conclusion

The analysis of the expansions and retreats of the magmatic arc through time shows a strong control over the tectonic regime of the Neuquén Embayment. As a result of this, two periods of progressive deformation to the foreland can be identified. The first period of contraction post-dated the generalized extension that lasted from the Early Jurassic to the Early Cretaceous. A progressive deformation started with the emplacement of the Late Cretaceous granitoids in the arc and the foreland migration of the magmatism that lasted until the late Eocene. Late Cretaceous deformation began with orthogonal contraction and ended in the Palaeogene with generalized transpression (Cobbold & Rossello 2002). The second contractional deformation began in the middle Miocene and lasted until the late Miocene. Both periods of contraction were linked to shallowing of the subduction zone as postulated by Kay (2002) for the late Miocene (Fig. 10).

The two compressional periods were followed by steepening of the subduction zone, in the Oligocene and the Pliocene. This resulted in hot asthenosphere from the subcontinental mantle being injected into the asthenospheric wedge,

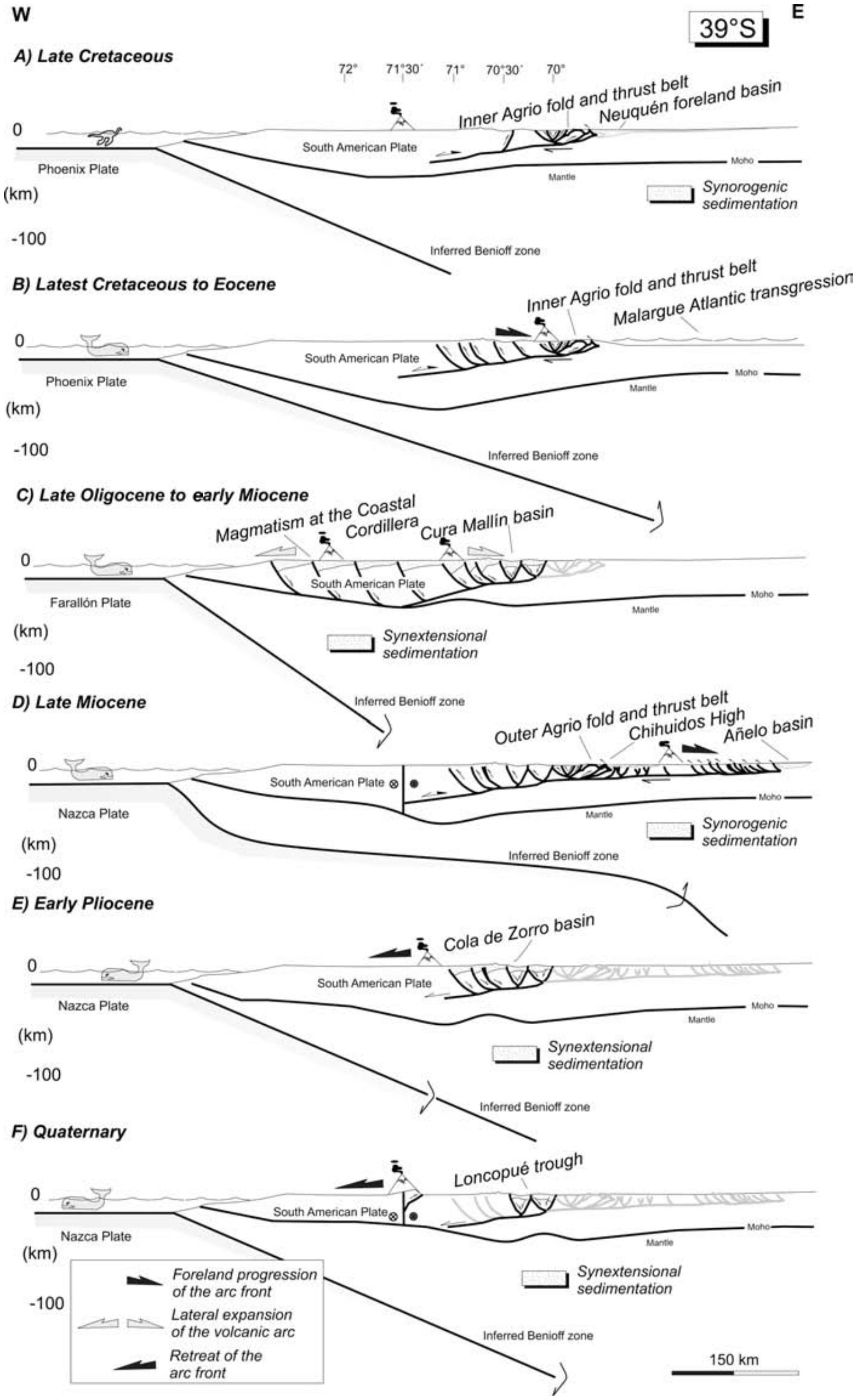

Fig. 10. Summary of changing geometries of the palaeo-Benioff zones through time, based on the magmatic evidence and structural styles. See discussion in the text.

inducing large amounts of melting and the formation of voluminous magmatism. Generalized extension prevailed at Oligocene times associated with oceanic plate reorganization and the break-up of the Farallones Plate. Extension in the Pliocene, although possibly related to a minor reorganization of the oceanic plates at about 5 Ma, progressively changed to transtension in late Pliocene and Pleistocene times, as proposed by Folguera *et al.* (2003*b*). These episodes of extension produced the Loncopué trough that attained its present morphology during the late Pliocene and Pleistocene. Active shortening is concentrated in the foothills north of 37°30′S.

The alternation of short intervals of compression with minor shortening and periods of generalized extension produced the unique morphology of the Neuquén Andes.

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