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Cretaceous deformation of the southern Central Andes: synorogenic growth strata in the Neuquén Group (35° 30′–37° S)

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ABSTRACT

The Neuquén Group is an Upper Cretaceous continental sedimentary unit exhumed during the latest Miocene contractional phase occurred in the southern Central Andes, allowing a direct field observation and study of the depositional geometries. The identification of growth strata on these units surrounding the structures of the frontal parts of the Andes, sedimentological analyses and U–Pb dating of detrital components, allowed the definition of a synorogenic unit that coexisted with the uplift of the early Andean orogen since *ca*. 100 Ma, maximum age obtained in this work, compatible with previous assignments and constrained in the top by the deposition of the Malargüe Group, in the Maastrichtian (*ca*. 72 Ma). The definition of a wedge top area in this foreland basin system, where growth strata were described, permitted to identify a Late Cretaceous orogenic front and foredeep area, whose location and amplitude contrast with previous hypotheses. This wedge top area was mostly fed from the paleo-Andes with small populations coming from sources in the cratonic area that are interpreted as a recycling in Jurassic and Lower Cretaceous sections, which contrasts with other analyses performed at the foredeep zone that have mixed sources. In particular, Permian sources are interpreted as coming directly from the cores of the basement structures, where Neopaleozoic sections are exposed, next to the synorogenic sedimentation, implying a strong incision in Late Cretaceous times with an exhumation structural level similar to the present. The maximum recognised advance for this Late Cretaceous deformation in the study area is approximately 500 km east of the Pacific trench, which constitutes an anomaly compared with neighbour segments where Late Cretaceous deformations were found considerably retracted. The geodynamic context of the sedimentation of this unit is interpreted as produced under the westward fast moving of South America, colliding with two consecutive mid-ocean ridges during a period of important plate reorganisation. The subduction of young, anhydrous, buoyant lithosphere would have produced changes in the subduction geometry, reflected first by an arc waning/gap and subsequently by an arc migration that coexisted with synorogenic sedimentation. These magmatic and deformational processes would be the product of a shallow subduction regime, following previous proposals, which occurred in Late Cretaceous times, synchronous to the sedimentation of the Neuquén Group.

INTRODUCTION

The subduction of the Nazca and Antartic oceanic plates beneath the South American Plate is responsible for the origin and development of the Andes, the longest mountain range in the world, with about *ca*. 7000 km of some of the highest mountain peaks, along with active volcanoes and extense plateaus. This subduction-type orogen has been divided into three different sections by Gansser (1973) and Ramos & Aleman (2000): the Northern Andes, the Southern Andes and the Central Andes, being the last section where the study area is comprised. The evolution of the Central Andes can be understood through the analysis of its adjacent depocenters, whose deposits register the different processes that affected them. Thus, their uplift is diachronic, with compression beginning in Cretaceous times, defining a series of foreland basins, such as the Purilactis Group basin (Mpodozis *et al*., 2005), the Neuquén Group basin (Cazau & Uliana, 1973) and the Chubut Group basin (Barcat *et al*., 1989). The Neuquén Group basin, focus of our study, is currently exhumed by

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a series of fold and thrust belts, among which the Malargüe fold and thrust belt can be found, located more specifically in the southern Central Andes (Fig. 1).

For the last 20 years, since the first modern works defined the Malargüe fold and thrust belt, (Kozlowski *et al.*, 1993 and Manceda & Figueroa, 1995) – nowadays considered classic works, – Andean growth had been attributed fully to the Miocene deformational stage onwards. Afterwards, many authors working in this belt have followed this proposal (Giambiagi *et al.*, 2008; Silvestro & Atencio, 2009; Turienzo *et al.*, 2012; among others). However, other studies developed in areas much better known of the Andean orogen, particularly in the northern Central Andes, have described the presence of older phases responsible for the initial uplift of this subduction-related orogen, based on synorogenic strata and thermochronological data (see Pananont *et al.*, 2004; Mpodozis *et al.*, 2005; Oncken *et al.*, 2006). Similarly, some works have proposed the existence of older compressional phases in some specific places of the southern Central Andes, south of the Malargüe fold and thrust belt, at the Agrio and Chos Malal fold and thrust belts (Fig. 1), locating them mainly in the Late Cretaceous and Eocene times (Groeber, 1946; Ramos, 1981; Cobbold & Rosello, 2003; Tunik *et al.*, 2010; Di Giulio *et al.*, 2012). In this line, just a few works have cautiosly mentioned an early phase for the Malargue fold and thrust belt, as a Late Cretaceous contractional stage (Orts & Ramos, 2006; Galarza *et al.*, 2009; Orts *et al.*, 2012a; Spagnuolo *et al.*, 2012; Mescua *et al.*, 2013). These works mostly based their hypotheses on sedimentological, magmatic and seismic evidence. However, no direct description of structures that would have grown during these times is shown that is the main focus of this study.

So, to better constrain the surficial and temporal development of this deformational phase, the present work is aimed to accomplish direct field observations of synorogenic sections, accompanied by the determination of their age and provenance constraints based on U–Pb data.

These objectives were approached from two different angles. In the first place, the recognition of the structures that show Neuquén Group outcrops were visited and inspected where growth evidences were identified, accompanied by a sedimentological analysis, for an adequate understanding of the paleoenvironmental context of sedimentation. In the second place, in one of the localities presenting synorogenic strata and a complete section of the Neuquén Group, a series of samples were obtained for U–Pb dating and provenance analysis, for a full understanding of the Late Cretaceous depositional scenario.

This study describes synorogenic Cretaceous geometries associated with growth structures within the Malargüe fold and thrust belt, as well as new U–Pb data of detrital zircons of the Neuquén Group. The evidence provided would demonstrate that the initial uplift of this portion of the Andes occurred in Late Cretaceous times, and not totally in the Miocene as previous proposals have postulated and gives insight about the paleo-Andean anatomy and dimensions.

TECTONIC AND GEOLOGICAL SETTING

The area focus of this study is located in the southern Central Andes (Fig. 1), more specifically, in the Province of Mendoza in the Argentinian Andean slope, between 35°30′ and 37°S. At these latitudes, the Nazca Plate subducts with a 30°E angle beneath the South American Plate, at a velocity of 79 mm yr^{-1}. The development of

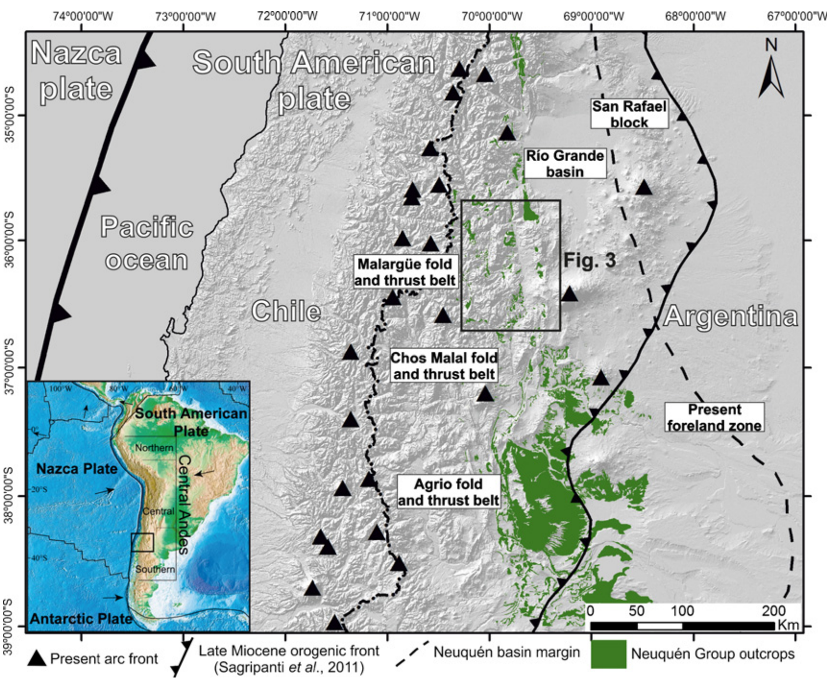

Fig. 1. Location of the study area in the Malargüe fold and thrust belt, in the retroarc of the southern Central Andes and outcrops of the Neuquén Group, whose subsidence mechanisms are the focus of this study. Inset at the lower left corner shows the tectonic setting of the Andes.

the Andean fold and thrust belts between 33–39° S have shortened the upper crust decreasingly from north to south along strike, from 55 km (39%) to 11 km (4.78%) (Giambiagi *et al.*, 2012; Rojas Vera *et al.*, 2014).

The active orogenic front (Fig. 1) is the result of the last Andean contractional phase, which started in Miocene times. This phase was responsible for the final reshaping of the fold and thrust belt at these latitudes, as well as the generation of new structures (Cobbold & Rosello, 2003; Zamora Valcarce *et al.*, 2007; Turienzo *et al.*, 2012; Sagripanti *et al.*, 2013), being the most important the uplift of the San Rafael Block in the present foreland area (Fig. 1) (Bastías *et al.*, 1993). This orogenic front is located 200–300 km eastward from the present volcanic arc – situated along the international boundary between Chile and Argentina – and at about 400–500 km from the Pacific Ocean trench (Fig. 1). Neogene foreland basin deposits are scattered all around the area, constituting, in the west, the infill of synclines at the footwall of the main anticlines and, in the east, a broad foreland basin (Río Grande basin; Fig. 1) (Silvestro *et al.*, 2005; Silvestro & Atencio, 2009; Sagripanti *et al.*, 2012; Álvarez Cerimedo *et al.*, 2013).

The southern Central Andes geology is complex, and is divided into two different tectonostratigraphic episodes, with quite distinctive characteristics. First, a Precambrian and Paleozoic history, characterised by the amalgamation of different terranes that constructed the western Gondwana margin, which nowadays constitute the basement of the Meso-Cenozoic basins. The southwestern Gondwana margin is formed by an older craton named Río de la Plata Craton, conformed by Paleoproterozoic aged rocks (Rapela *et al.*, 2007), and the younger Pampia, Cuyania and Chilenia terranes to the west, all of them with Grenvillian age basements (Escayola *et al.*, 2007; Naipauer *et al.*, 2010; Ramos *et al.*, 2010a). These terranes accreted to the Rio de la Plata and Amazonia cratons throughout a complex evolution that spans from the Late Proterozoic to Late Devonian times (see Ramos, 2010 for a synthesis). A series of magmatic arcs and metamorphic events accompanied each of these collisions, whose products were exposed in the Neuquén basin foreland, becoming part of the main sources for the sediments that filled the basins (Tunik *et al.*, 2010; Sagripanti *et al.*, 2011; Di Giulio *et al.*, 2012; Naipauer *et al.*, 2014).

A younger episode involves the development of a sedimentary basin during Mesozoic times known as the Neuquén Basin, presently developed along the Andean foothills between 32–40° S latitudes (Fig. 1), that was initially a thermal retroarc basin in the western margin of Gondwana (for a review see Uliana *et al.*, 1989).

The basement of the basin is known as the Choiyoi Group, a Middle Permian to Middle Triassic mainly volcanic unit, whose petrology and geochemistry record the passing from an arc setting to an extensional within-plate regime along the southwestern Gondwana margin (Llambías *et al.*, 2003; Martínez & Giambiagi, 2010). This stage continues into the Precuyano cycle (Legarreta & Gulisano, 1989), a Late Triassic to Lower Jurassic volcanic and sedimentary association deposited in a series of isolated depocenters, with predominant half-graben geometries (Silvestro & Zubiri, 2008; Cristallini *et al.*, 2009; Pángaro *et al.*, 2009). Since these rocks are exposed at the cores of the main contractional structures of the Malargüe, Agrio and Chos Malal fold and thrust belts, these constituted the main source for the Jurassic to Neogene sedimentary cycles (see Naipauer *et al.*, 2012, 2014, for recent syntheses).

The next stage that filled the Neuquén Basin started in the Early Jurassic, with the connection of these isolated depocenters, which registered the first marine transgression from the Pacific. The full cycle is represented in the basin by marine sandstones, shales and evaporites of the Cuyo and Lotena groups (Gulisano & Gutiérrez Pleimling, 1994). A second transgressive-regressive cycle takes place in the Late Jurassic, with thermal subsidence as the main responsible for the increase in the accommodation space. This space was filled up by the marine shales, limestones and sandstones of the Mendoza Group, and later with the evaporites and continental sediments of the Bajada del Agrio Group (Legarreta & Gulisano, 1989; Legarreta & Uliana, 1991, 1996).

A global-scale plate reorganisation took place in the Late Cretaceous, with the opening of the southern Atlantic Ocean, determining a steady westward displacement of the South American Plate against the subduction margin (Somoza & Zaffarana, 2008) that led to a change in the tectonic setting to a contractional regime, registered in different places. In this way, under some hypotheses, the Neuquén Basin evolved into a foreland stage, reflected by the start of a new sedimentation cycle (Bettini *et al.*, 1978; see Ramos *et al.*, 2011 for a discussion). Unlike previous cycles, this one was entirely continental, comprising 25 Ma and 1200 m of fluvial, aeolian and shallow lacustrine sequences (Garrido, 2010). These deposits are known as the Neuquén Group, developed between the Early Cenomanian and Middle Campanian, coinciding with the inset of the contractional deformation at other latitudes. Early evidence of a synorogenic deposition of the Neuquén Group comes from Bettini *et al.* (1978) work that shows through a detailed analyses a progressive thinning of these sequences from the Andean axis to the foreland area. Moreover, Legarreta *et al.* (1985), while measuring paleocurrents in a sedimentary profile of the Neuquén Group, found anomalous data that indicated a change in the paleotopography, locating the source of the sediments to the west. Indirect evidence for deposition in a synorogenic environment has been recently described by Sánchez *et al.* (2013) and Sánchez & Asurmendi (2014), who described seismites and Gilbert-type delta episodes interrupting low-energy systems. The presence of volcanic arc rocks interbedded with the upper terms of these deposits indicates that the volcanic arc migrated to the foreland and was partly coeval with the sedimentation of the Neuquén Group

(Franchini *et al.*, 2003; Llambías & Aragón, 2011; Spagnuolo *et al.*, 2012).

Finally, the Neuquén Basin recorded an Atlantic marine transgression that took place from the Latest Cretaceous to Paleocene times, represented by the Malargüe Group (see Aguirre Urreta *et al.*, 2011). This transgression was interpreted as due to the tectonic loading generated during these early phases of Andean uplift (Barrio, 1990) that coincided with an important highstand in the sea level (Uliana *et al.*, 1989).

During the rest of the Cenozoic, this basin predominantly continued as a foreland basin under a contractional regime, interrupted by a short extensional event in late Oligocene times (Jordan *et al.*, 2001; Silvestro & Atencio, 2009; Folguera & Ramos, 2011; Álvarez Cerimedo *et al.*, 2013). In the Neuquén retroarc, the tectonic regime seems to be controlled mainly by the angle of the subducted slab (Ramos & Folguera, 2009). In this sense, shallow to flat angles are associated with high interplate contact, which consequently drives orogeny and, ultimately, leads to the development of a broken foreland (Dickinson & Snyder, 1978; Lallemand *et al.*, 2005). On the other hand, extensional tectonic regimes have been linked to higher subduction angles, through the steepening of the slab (Lallemand *et al.*, 2005; Ramos & Folguera, 2011).

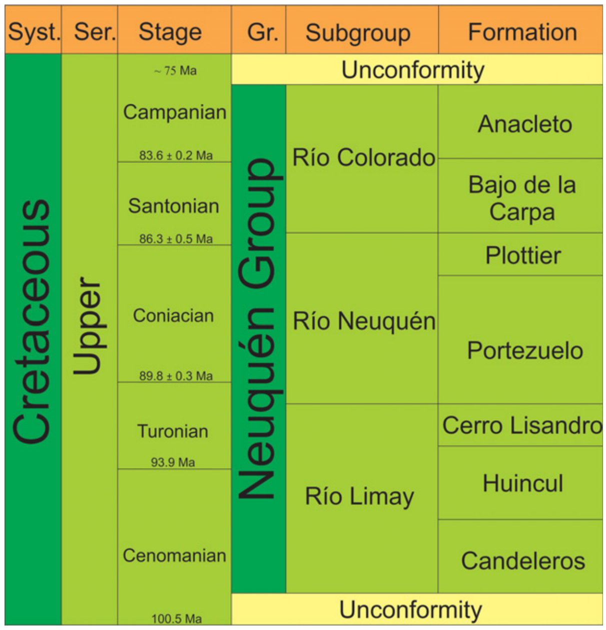

Fig. 2. Stratigraphy of the Neuquén Group, showing the subgroups and formations that compose it (modified from Ramos, 1981 and Garrido, 2010).

STRATIGRAPHY OF THE NEUQUÉN GROUP

Since this work is focused in the Late Cretaceous retroarc basin, represented by the Neuquén Group, an adequate stratigraphic frame is needed to understand its evolution. Unfortunately, the stratigraphy of this unit is not uniform throughout the entire basin, and the level of knowledge of this group differs depending on its location and density of studies developed on it. South of the study area, between 37° and 41° S several studies were carried out that have successfully characterised and divided the Neuquén Group in three subgroups and seven formations (see Garrido, 2010 for a summary and Fig. 2 for a stratigraphic chart). Contrastingly, the stratigraphy of this group is not that detailed to the north between 35° and 37° S, making weak correlations due to the lack of guide fossils, key beds or datings. Nevertheless, in most of the sedimentary profiles carried out in this northern part of the basin, three cycles can be differentiated using lithological criteria, which can be correlated with each subgroup defined to the south (Cazau & Uliana, 1973).

Thus, the base of the Neuquén Group is represented by the Río Limay Subgroup, which unconformably overlies the Bajada del Agrio Group (Leanza, 2009). This subgroup includes the Candeleros, Huincul and Cerro Lisandro formations, and spans from the Cenomanian to Early Turonian (Fig. 2). Lithologically, the Candeleros Formation consists in massive coarse- and medium-grained sandstones and conglomerates, with intercalations of thin siltstone beds, deposited in a fluvial environment under braided and meandering regimes, as well as in aeolian conditions (Leanza *et al.*, 2004; Sánchez *et al.*, 2008). The Huincul Formation is composed of medium to coarse-grained sandstones, interdigitated with conglomerates, sedimented by braided fluvial systems (Sánchez *et al.*, 2008), while the Cerro Lisandro Formation is constituted by claystones with intercalations of fine-grained sandstones and limestones, interpreted as deposits of a low-energy fluvial system and swamp environments (Sánchez *et al.*, 2008). Nevertheless, recent studies of this formation at 36.5° S described a cyclic alternation of lacustrine and Gilbert-type delta deposits, interpreted as the recording of ongoing uplift of the Andean orogen to the west (Sánchez & Asurmendi, 2014).

The Río Neuquén Subgroup constitutes the middle part of the Neuquén Group, which embraces the Portezuelo and Plottier formations, with an age considered to be Late Turonian-Coniacian (Fig. 2). The Portezuelo Formation is represented by sandy deposits, interdigitated with conglomerates and siltstones of a fluvial braided regime, and the Plottier Formation is composed of siltstone and sandstone lenses, deposited by low-energy fluvial systems with wide alluvial plains (Leanza *et al.*, 2004; Sánchez *et al.*, 2005, 2006, 2014).

Finally, the upper part of the Neuquén Group corresponds to the Río Colorado Subgroup, formed by the Bajo de la Carpa and Anacleto formations, ranging in age from the Santonian to the Early Campanian (Fig. 2). The Bajo de la Carpa Formation is constituted by coarse-grained sandstones of fluvial origin, interdigitated with thin beds of siltstones and claystones (Leanza *et al.*, 2004). The highest unit of the Neuquén Group is the Anacleto Formation, composed exclusively of siltstones and mudstones, interpreted as low-gradient fluvial deposits and proximal to mid-estuarine deposits, related to the onset of the first Atlantic transgression that affected the Neuquén Basin in the Late Campanian (Armas & Sánchez, 2011; Armas *et al.*, 2014). This transgression is recorded by the deposits of the Malargüe Group, whose contact with the Neuquén Group is defined by an unconformity (Fig. 2; Leanza, 2009).

ANALYSIS OF THE NEUQUÉN GROUP

The Neuquén Group developed quite uniformly throughout the entire Neuquén Basin, although the northern sector is partly covered by thick layers of Cenozoic volcanism, being their outcrops more limited than to the south (Fig. 1). In the study area, the Neuquén Group only outcrops near the biggest anticlines (Fig. 3), although its presence can be tracked in subsurface through seismic and borehole data (see Silvestro & Atencio, 2009; Galarza *et al.*, 2009; Orts *et al.*, 2012a for specific examples).

The biggest structures can be separated in two groups, depending on their location relative to the Río Grande (all the localities mentioned in the text have a number of outcrop assigned, refer to Fig. 3 for location): (i) west of the Río Grande, over the Andean zone, the structures where growth evidence was found, are in the surroundings of Sierra Azul (6) and Bardas Blancas (2) anticlines. Here, some works had mentioned growth evidence, based on seismic interpretations, in the Portezuelos Colorados (5) (Orts *et al.*, 2012a) and the Puntilla de Huincán areas (11) (Galarza *et al.*, 2009). (ii) East of the Río Grande, in the orogenic front zone, growth evidence has been found near the Malargüe (3), La Batra (4), Ranquil Co (8) and Sierra de Cara Cura (12) structures. Unfortunately, in the Sierra de Palaoco (7) and the Payenia (10) regions, broad volcanic Cenozoic rocks cover the potential exposures of the Neuquén Group.

Field evidence of synorogenic strata in the study area

The study area has abundant Neuquén Group outcrops (Fig. 4), although these are mostly of low quality, being difficult to identify geometries of deposition. However, near the biggest structures, coarser facies of the Neuquén Group are better preserved and synorogenic beds were identified.

Growth evidence has been found east of the Rio Grande, in the Neuquén Group near the La Batra anticline (4) (Fig. 4 for location and Fig. 5 for a view).

In this locality, medium to fine-grained sections show gradual change in the dip angles that range from 60° E in the bottom to 20° E towards the top in one of the sections (Fig. 5a), while in the other strata start overturned at the bottom dipping 75° W, passing to a vertical position and finishing with younger strata dipping 45° E (Fig. 5b). Both fans of strata are associated with the eastern-frontal flank of La Batra anticline (4) that constitutes the southern continuation of the same structural trend of the Malargüe anticline (3) to the north.

The Sierra Azul anticline (6) presents growth evidence in coarse sections of the Neuquén Group deposited over its frontal-eastern flank (Fig. 4 for location and Fig. 6 for a view). This section presents progressive unconformities that range, from 40° E in the bottom to 5° E in the top. Throughout the section, strata show wedge geometries

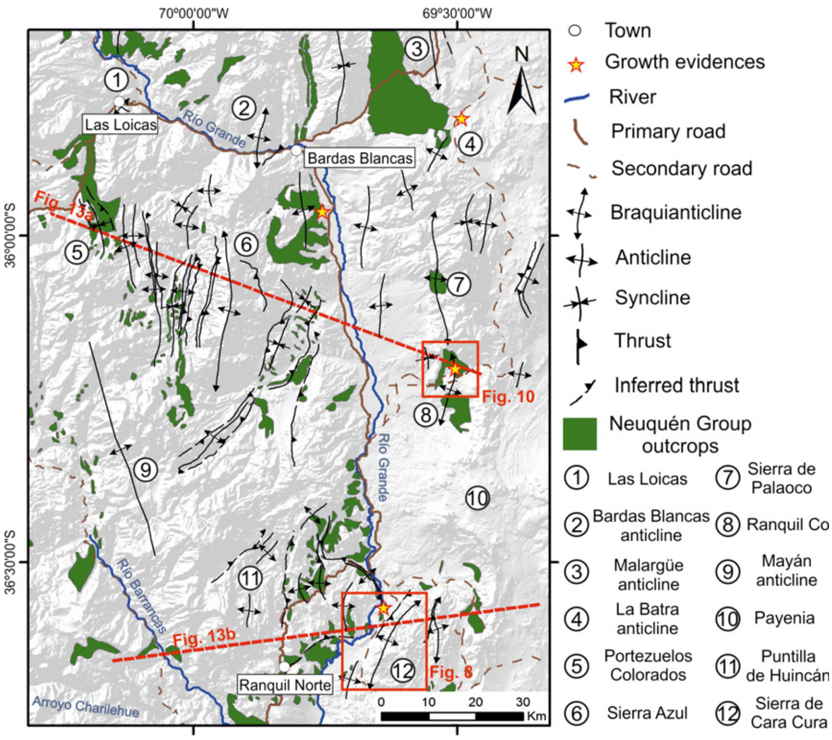

Fig. 3. Simplified map of the study area showing the location of the Late Cretaceous synsedimentary growth evidence and localities mentioned in the text.

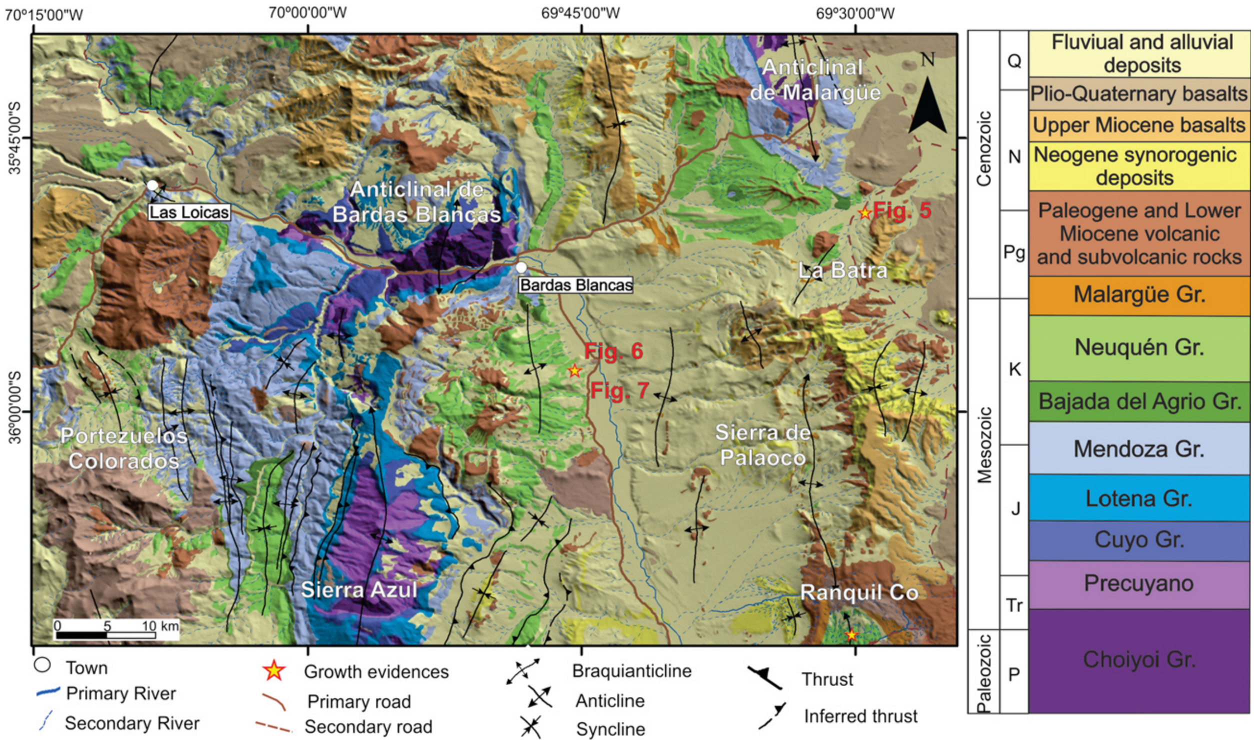

Fig. 4. Geological map of the northern part of the study area. Location of the identified Late Cretaceous growth evidences is indicated. Geology and structure are based on Legarreta *et al.* (1985), Narciso *et al.* (2004), Nullo *et al.* (2005), Silvestro *et al.* (2005), Giambiagi *et al.* (2009), Orts *et al.* (2012a), Álvarez Cerimedo *et al.* (2013) and data of this work.

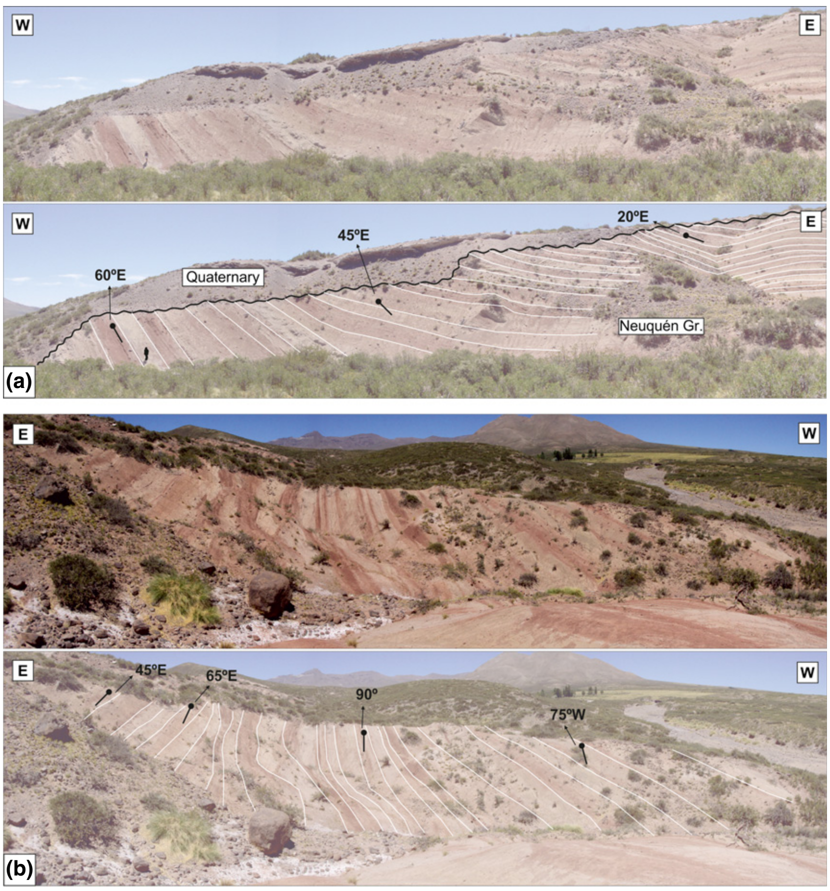

Fig. 5. Growth strata in the Neuquén Group associated with the frontal limb of La Batra anticline (4) in the orogenic front area, east of the Río Grande (see location in Fig. 4).

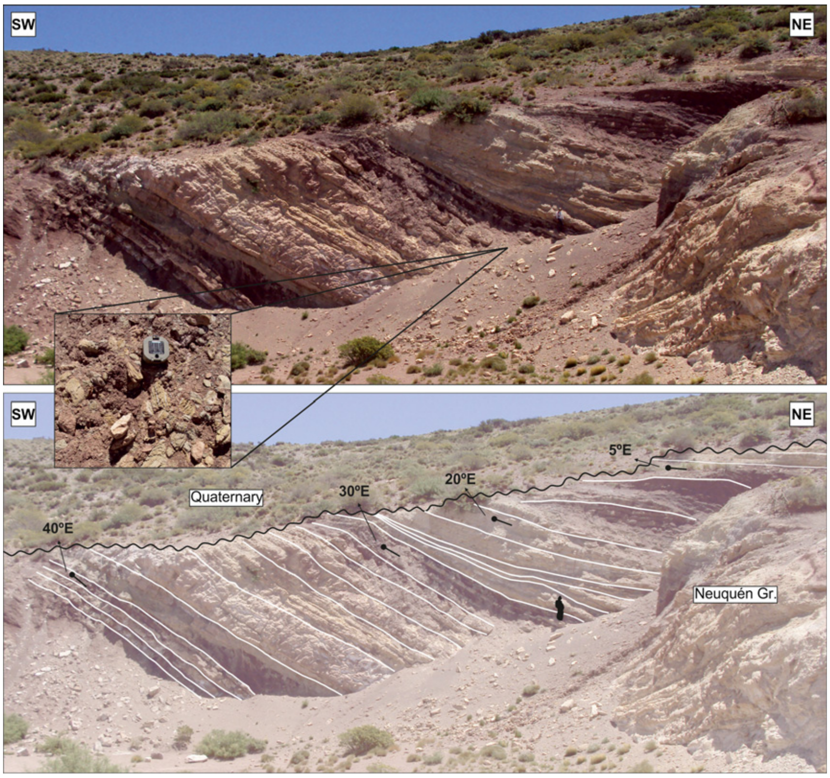

Fig. 6. Growth strata in the Neuquén Group associated with the frontal-eastern limb of the Sierra Azul anticline (6). To the left, an inset shows the composition of the deposits, corresponding to angular clasts of the same composition of the Neuquén Group, which could be implying a synsedimentary deformation.

and reworked material, as angular pebble sized clasts of the same composition of the Neuquén Group, which could indicate, among other interpretations (e.g. small-scale intrabasinal erosion, global eustatic fall), progressive cannibalisation during the uplift of the Sierra Azul (6) (Fig. 6).

Additional evidence of the Late Cretaceous uplift of this structure is the presence of deformational synsedimentary structures (Fig. 4 for location, Fig. 7 for a view), located 1 km to the east of the growth evidence descripted previously (Fig. 6). In these outcrop, fine-grained strata corresponding to the Neuquén Group are affected by normal and reverse faults of small magnitude, along with fluidisation structures. Similar events have been descripted in the Neuquén Group by Sánchez *et al.* (2013) to the south in the provinces of Neuquén and Río Negro, being interpreted as seismites.

Sedimentological analysis in two selected sections presenting synorogenic strata

The Sierra de Cara Cura (12) (Fig. 8) is one of the selected structures for a sedimentological analysis, to provide an appropriate framework for the synorogenic strata identified (Fig. 9). Located in the orogenic front, this thick-skinned structure presents excellent exposures of the Neuquén Basin units (Fig. 8). The Neuquén Group outcrops in a depocenter located northwest of the structure, in an area known as Puntilla de Huincán (11), west of the Río Grande. Nevertheless, on the eastern riverside of the Río Grande, a few short wavelength anticlines

Fig. 7. Synsedimentary deformation in the Neuquén Group potentially related to the growth of the Sierra Azul anticline (6). Note the coexistence of normal and reverse faults associated with fluidisation structures, interpreted as seismites related to the initial uplift of the Malargüe fold and thrust belt.

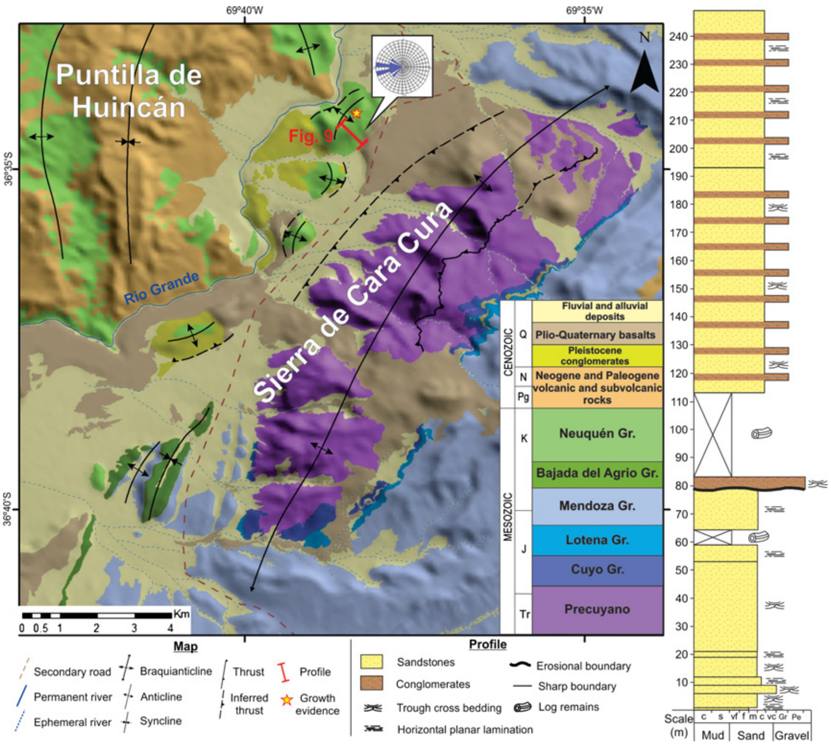

Fig. 8. Geological map of the Sierra de Cara Cura (12) in the retroarc area. Two folding domains are distinguished, a broad anticline in the east, and a series of small anticlines in the west, next to the Río Grande, in the Neuquén Group. A sedimentary profile was surveyed in one of these western structures that presented growth evidence in fluvial strata, where paleocurrents indicated a flow direction towards the west.

expose the Neuquén Group at their cores (Fig. 8). In one of these structures, a sedimentary section was described, where paleocurrents and strata attitudes were measured.

This study showed a coarsening upward *ca*. 250 m section of sandy to gravelly facies, which can be divided into two sections (Fig. 8). A lower section, *ca*. 80 m thick, is essentially composed of brown and red medium to coarse-grained sandstones presenting horizontal planar lamination and through cross-bedding, counting with the presence of unidentified log remains. The upper section is separated from the lower section by an erosional boundary and a pebble sized bank, upon which the lithology becomes coarser, presenting very coarse white and yellow sandstones interbedded with thinner massive banks of granule sized conglomerates. Unidentified log remains continue appearing along the profile, as well as the through cross-bedding and the horizontal planar lamination in the sandstones.

Since the purpose of the study is to give a general description of the Neuquén Group in this locality, a detailed analysis of the facies association and architectural elements was not performed. Nevertheless, from the profile we can deduce that the paleoenvironment was a sandy braided fluvial system, characterised by the migration of longitudinal and transverse bars, with a slight increase in the grain size towards the top (Fig. 8).

Under the microscope, the samples are classified as litharenites (Dott, 1964 diagram modified by Pettijohn *et al.*, 1987), constituted by angular and sub-angular clasts. A total of 30 paleocurrents were measured with compass along the profile, in each trough cross-bedding identified. The results are quite homogeneous, and indicate a direction of the flow towards the west, with variations towards the northwest and southwest (obtained values vary between 230° and 310°, and are represented in the rosette diagram of Fig. 8). The measurement of the strata attitudes shows that these have a general N- strike, with dips that go from 38° W in the bottom ranging to 21° W in strata located below an unconformity (Fig. 8 for the location of this unconformity in the profile and Fig. 9 for a general view). Over this unconformity, the dips have little variation and remain in the order of 25° W. In the field, this unconformity is highlighted by a lenticular coarse-grained bank, lying in an erosional and angular relation over the lower packages of the Neuquén Group sequence, which are in turn deformed, implying a synsedimentary deformation (Fig. 9).

The other selected structure, located 50 km north of the Sierra de Cara Cura (12), is the Ranquil Co anticline (8). This anticline consists in a combination of thin and thick-skinned structures that exposes shallower stratigraphic levels compared with the Sierra de Cara Cura (12), reaching only up to the Bajada del Agrio Group in its core (Fig. 10; refer to Álvarez Cerimedo *et al.*, 2013 for more details related to the geology and the structure). Unlike the Sierra de Cara Cura (12), here the Neuquén Group outcrops continuously, from base to top, constituting a good target for the construction of a sedimentological profile. Complementarily, a series of samples was taken to carry out U–Pb ages on detrital zircons for provenance analysis and determination of the maximum depositional age.

The sedimentological profile was made in the eastern flank of the structure, starting from the contact between the Bajada del Agrio and the Neuquén groups. Located 1 km to the north, in the same stratigraphic level corre-

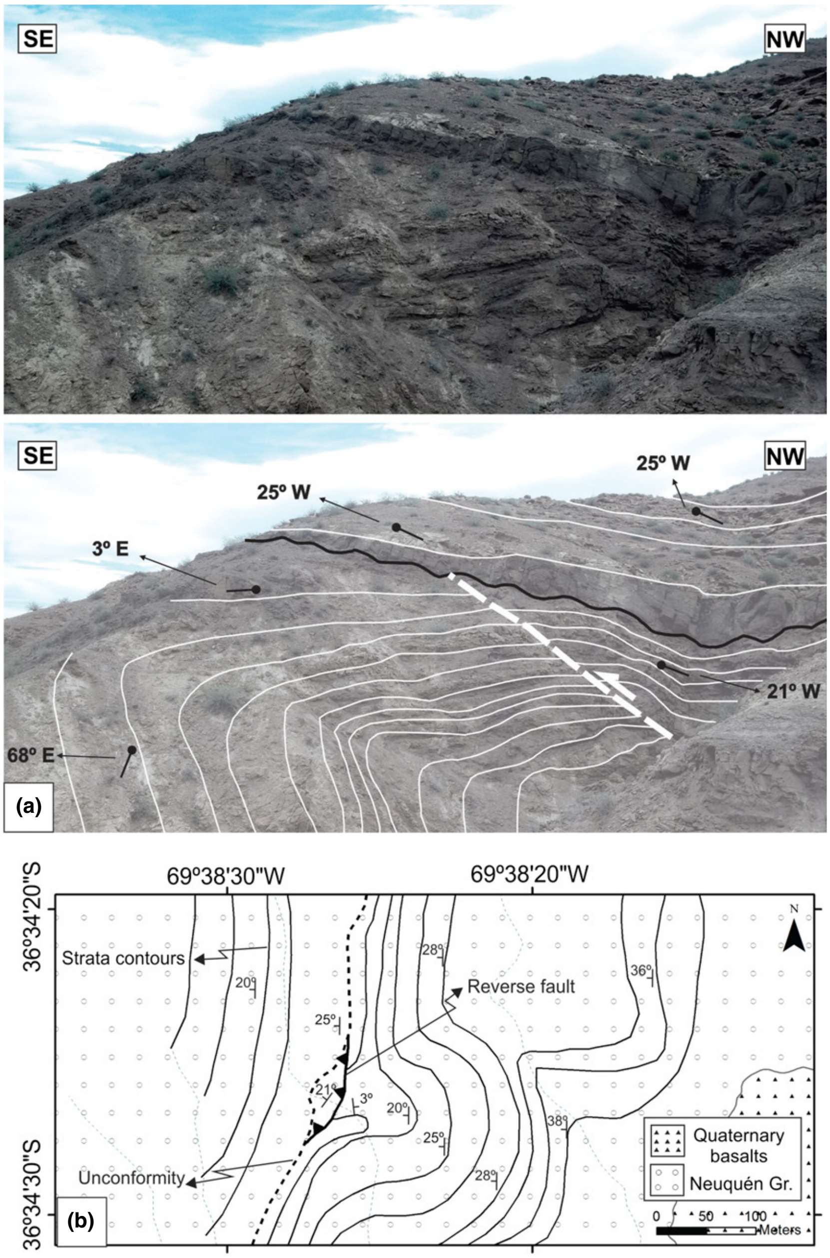

Fig. 9. (a) Unconformity separating the lower and upper sections of the sedimentary profile performed in the Neuquén Group located in one small structure west of Sierra de Cara Cura (12) (see location in Fig. 8). Note that the unconformity marks an erosional event during the syndepositional deformation of the Neuquén Group. (b) Map view of the growth evidence.

sponding to the base of the profile, growth evidence was found in the Neuquén Group (location in Fig. 10). This evidence is located in the core of the anticline, showing growth relations in both flanks (Fig. 11). On the western flank, a set of progressive unconformities were measured, starting with 43° W in the bottom to 21° W in the top (Fig. 11a). On the eastern flank, the strata start from a vertical attitude, in the contact with the Bajada del Agrio Group, progressively decreasing their angle to the east in a stratigraphic direction finishing in a horizontal position (Fig. 11b). Both sets of progressive unconformities were interpreted as Upper Cretaceous growth strata associated with the uplift of the Ranquil Co anticline (8).

Based on marked lithological and paleoenvironmental differences, the 866 m thick section of the Neuquén Group can be divided into three grain and strata-decreasing cycles (Fig. 10), using Cazau & Uliana (1973)'s criteria, which can be correlated with each of the subgroups.

The profile starts with the Río Limay Subgroup (231 m thick), composed on its base by a thick intercalation of massive, clast-supported conglomerates with levels of inverse gradation and coarse-grained sandstones. Towards the top, massive yellow and red sandstones with horizontal stratification complete the unit.

The Río Neuquén Subgroup (472 m thick) starts with an intercalation of massive conglomerates and gravelly sandstones in the base, continuing with an interdigitation of sandy coarse and medium-grained banks with trough cross-bedding, horizontal planar lamination and current ripple cross-lamination.

Finally, the Río Colorado Subgroup (163 m thick) corresponds to a fine-grained clastic succession, represented by fine-grained sandstones and massive to laminated clay-

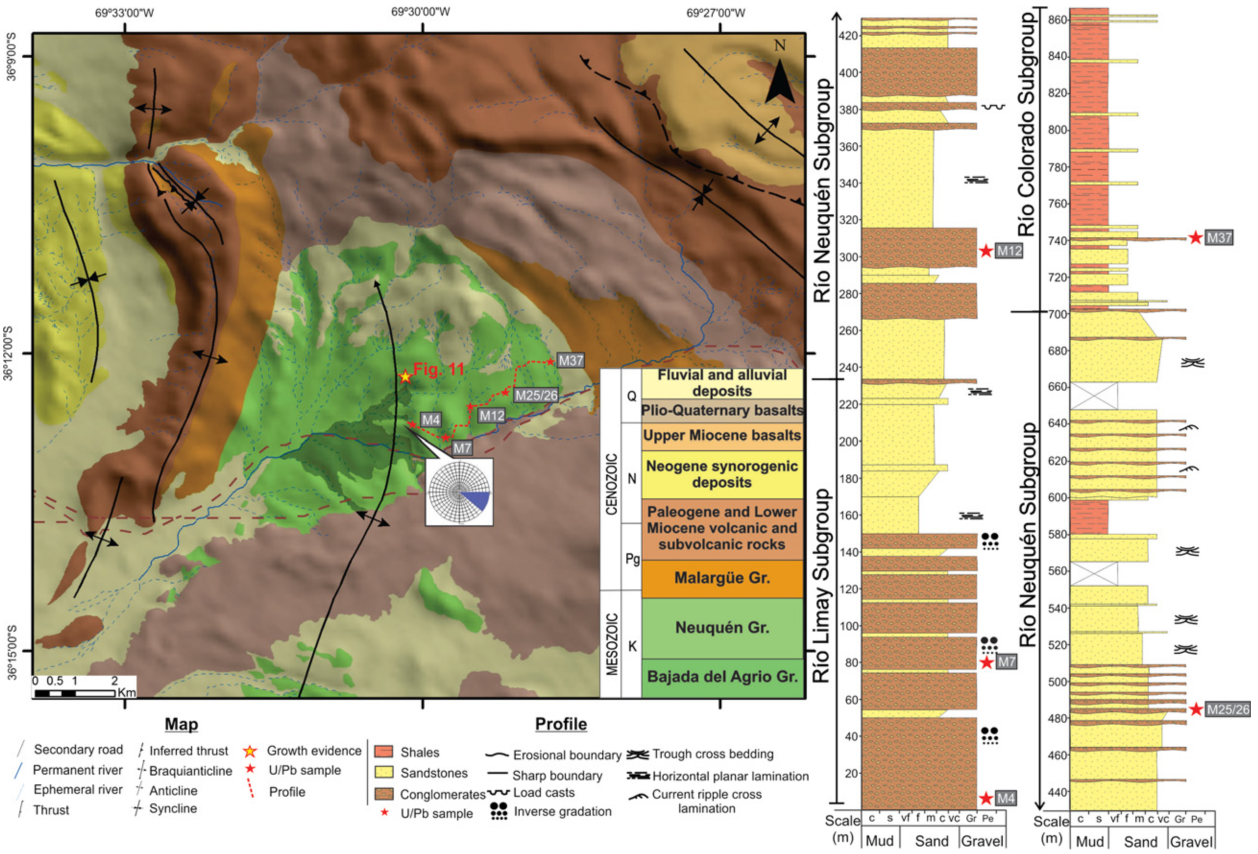

Fig. 10. Geological map of the Ranquil Co anticline (8) located in the orogenic front (see Fig. 3 for location). A sedimentary profile was performed for the entire Neuquén Group from its base in the contact with the Bajada del Agrio Group to the top in the contact with the Malargüe Group. These sequences show three grain and strata-decreasing cycles, passing from gravelly braided fluvial systems (Río Limay Subgroup), to sandy braided fluvial systems (Río Neuquén Subgroup) and finishing with fine deposits of a flood plain (Río Colorado Subgroup). Paleocurrents indicate an anomalous source area from the west, respect to other locations (Legarreta *et al.*, 1985). U–Pb sampling locations are indicated both in the profile and the map.

stones, interdigitated with scarce, 1 m thick, sandy and gravelly banks.

Since it was not part of the work's objectives, the amount of data collected is not enough for a detailed analysis of the facies and architectural elements. However, the profile shows that the paleoenvironmental evolution of the Neuquén Group in this location starts with a gravelly braided fluvial system (Río Limay Subgroup), which passes to a sandy braided fluvial system (Río Neuquén Subgroup) and finishes with fine deposits of a floodplain of an ephemeral braided fluvial system (Río Colorado Subgroup).

The microscope analysis shows that the Neuquén Group composition is quite homogeneous, consisting in feldspatic litharenites and litharenites (Dott, 1964 diagram modified by Pettijohn *et al.*, 1987) with rounded and subrounded clasts. The paleocurrents measured by Legarreta *et al.* (1985) in the base show a flow towards the east-southeast (90–130°), indicating a topographical high to the west-northwest (rosette diagram in the map of Fig. 10). These authors consider these data as anomalous, since all the other locations in the western slope of the Sierra de Palaoco (7), indicated dispersion of the sediments towards the west, with variations to the southwest and northwest. Based on this analysis, Legarreta *et al.* (1985) had considered the possibility that the Sierra de Palaoco (7) and Ranquil Co (8) structures constituted positive reliefs in Late Cretaceous times.

Detrital zircon U–Pb isotopic data

Five samples from the Neuquén Group located in the Ranquil Co anticline (8) (Fig. 10) were analysed by

Table 1. U/Pb dating results from analysed zircons in five samples of the Neuquén Group located in the Ranquil Co anticline (8). A: Jurassic and Cretaceous; B: Late Paleozoic and Triassic; C: Devonian; D: Early Paleozoic and Neoproterozoic; E: Mesoproterozoic; F: Paleoproterozoic and Archean

Sample	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)
M4	2	45	33	12	6	2
M7	4	42	24	18	11	1
M12	0	20	56	15	8	1
M25/26	0	15	59	17	7	2
M37	1	44	23	23	9	0

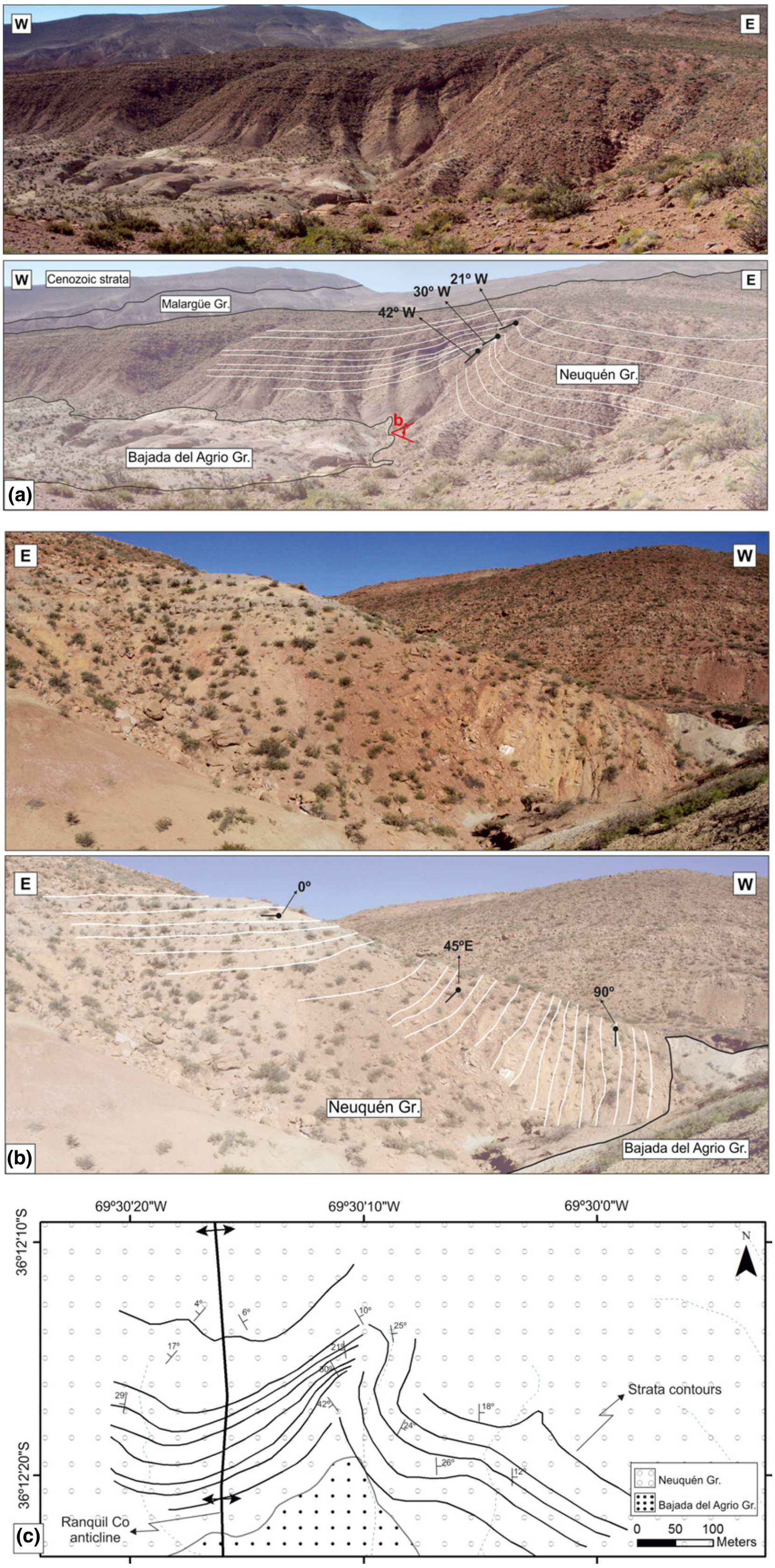

Fig. 11. Growth evidence in strata of the Neuquén Group, related to both flanks of the Ranquil Co structure (a and b), and a map view of the growth pattern (c).

U–Pb geochronology for provenance analysis. Results of the analysis can be observed in the Table 1, while frequency histograms, relative probability plots, and concordia plots of U–Pb ages from analysed zircons are showed in Fig. 12. Sample coordinates, analytical methods, and U–Pb (LAM-MC-ICP-MS) age measurements of zircons grains are available in the supplementary material.

DISCUSSION

Maximum depositional age

The youngest U–Pb ages found in the detrital zircons are commonly used to constrain the maximum depositional age of sequences, where the fossiliferous content is inconclusive (Fedo *et al.*, 2003; Dickinson & Gehrels, 2009). The youngest zircons of the study samples, in Upper Cretaceous rocks of the Ranquil Co anticline (8) located in the orogenic front area, have 100.2 ± 2.1 Ma and 109.7 ± 3.0 Ma (sample M4) and 102.6 ± 3.4 Ma (sample M7) in the base and 111.7 ± 0.7 (sample M37) in the top. This group of ages is not statistically robust, although it is coherent with the youngest age population (*ca*. 100 Ma) which is described in the Candeleros Formation (base of the Neuquén Group) south of the study area (Tunik *et al.*, 2010; Di Giulio *et al.*, 2012). Thus, according to the youngest zircons, the value of 100.2 ± 2.1 Ma is considered the maximum depositional age of the Neuquén Group in the study area, which is in accordance with the only radiometric age reported for the Neuquén Group, 88 ± 3.9 Ma, based on a fission-track analysis made on an ash-flow tuff at the base of the Huincul Formation (Corbella *et al.*, 2004).

Sedimentological interpretation and provenance analysis

From the above sections, strata with progressive unconformities interpreted as evidence of synsedimentary growth are systematically found associated with contractional structures. In the specific case of the western foothills of the Sierra de Cara Cura (12), paleocurrents show a flow direction coming from the east, being the Sierra de Cara Cura (12) the best candidate to constitute the source area. The analysed section is interpreted as the product of the erosion of this structure, behaving as a positive relief that was strongly eroded by fluvial systems in Late Cretaceous times. The presence of an angular and erosive unconformity could reflect an erosive event due to the slope increasing during the growth of the structure. As a result of this analysis, this depocenter can be interpreted as an intermontane basin that reflects the uplift of the Sierra de Cara Cura (12) in Late Cretaceous times, which was transported eastwardly into the orogenic wedge interposed between this structure and Puntilla de Huincán anticline (11) to the west.

Contrastingly, in growth strata of the Neuquén Group associated with the Ranquil Co anticline (8), the paleocurrents indicate a flow of the sediments towards the east-southeast, meaning that this structure, along with the Sierra de Palaoco (7) to the north and the Sierra Azul (6) to the west, were being uplifted at these times. The analysis under the microscope shows homogeneous composition along all the profile, medium to high textural and low mineralogical maturities. The high textural maturity most likely represents either a far source of the sediments or a second cycle of sedimentation. The fact that this profile is composed mainly of coarse-grained rocks points to the last hypothesis indicating that the source was rather close. This recycling of the sediments can be confirmed by the age pattern of the detrital zircons described before.

The detrital zircon age pattern of the five studied samples shows two main sources: one with Permian ages (maximum peaks between 262 and 252 Ma), and other with Devonian ages (maximum peaks between 399 and 382 Ma). The Jurassic-Cretaceous detrital component is subordinate and has a western provenance from the Mesozoic Andean Arc (Tunik *et al.*, 2010). In addition, the peaks that are related to rocks exposed in the cratonic area are subordinate, resulting on an indirect evidence of the recycling of the zircons, which compose the Jurassic to Lower Cretaceous Neuquén Basin units.

The Permian zircons, one of the most important source rocks in the area, can be linked with the Choiyoi magmatic rocks. These rocks outcrop in the San Rafael Block to the east and in the Malargüe fold and thrust belt to the west (Fig. 1). However, the sedimentological analyses indicate that the source was relatively close and the paleocurrents indicate it was probably located to the west-northwest. Therefore, the Late Cretaceous contraction possibly exhumed the Permian cores of the large anticlines surrounding the study area, such as the Sierra Azul (6), Malargüe (3) and Bardas Blancas (2) anticlines, constituting most likely the main source of these zircons (see Fig. 4).

On the other hand, the origin of the Devonian zircons is more difficult to explain since only a few outcrops of this age are described in the Malargüe fold and thrust belt and adjacent regions. The most likely source could be attributed to the Devonian metamorphic rocks exposed in small outcrops in the Chos Malal fold and thrust belt (Guaraco Norte Formation, Zappettini *et al.*, 2012), located 100 km to the southwest of the study area. Another potential sources, although less likely, could be the Devonian metamorphic and magmatic rocks located 400 km south of the study area (e.g.: Piedra Santa Formation -Ramos *et al.*, 2010b; - and San Martín de los Andes Tonalite -Varela *et al.*, 2005-).

Provenance areas and dimensions of the Late Cretaceous orogen

Identification of growth strata, provenance analysis and U–Pb dating of detrital zircons performed in the Andean and the orogenic front areas, allow partially understanding the evolution and amplitude of the Late Cretaceous orogenic wedge between 35°30′ and 37° S. On the light of these new data, the Bardas Blancas (2), Sierra Azul (6), Malargüe (3), La Batra (4), Sierra de Palaoco (7), Ranquil Co (8), Puntilla de Huincán (11) and Sierra de Cara Cura (12) anticlines are identified as Late Cretaceous growing structures that determined structural highs for these times. High energy fluvial systems would have eroded these growing areas feeding intermontane basins within

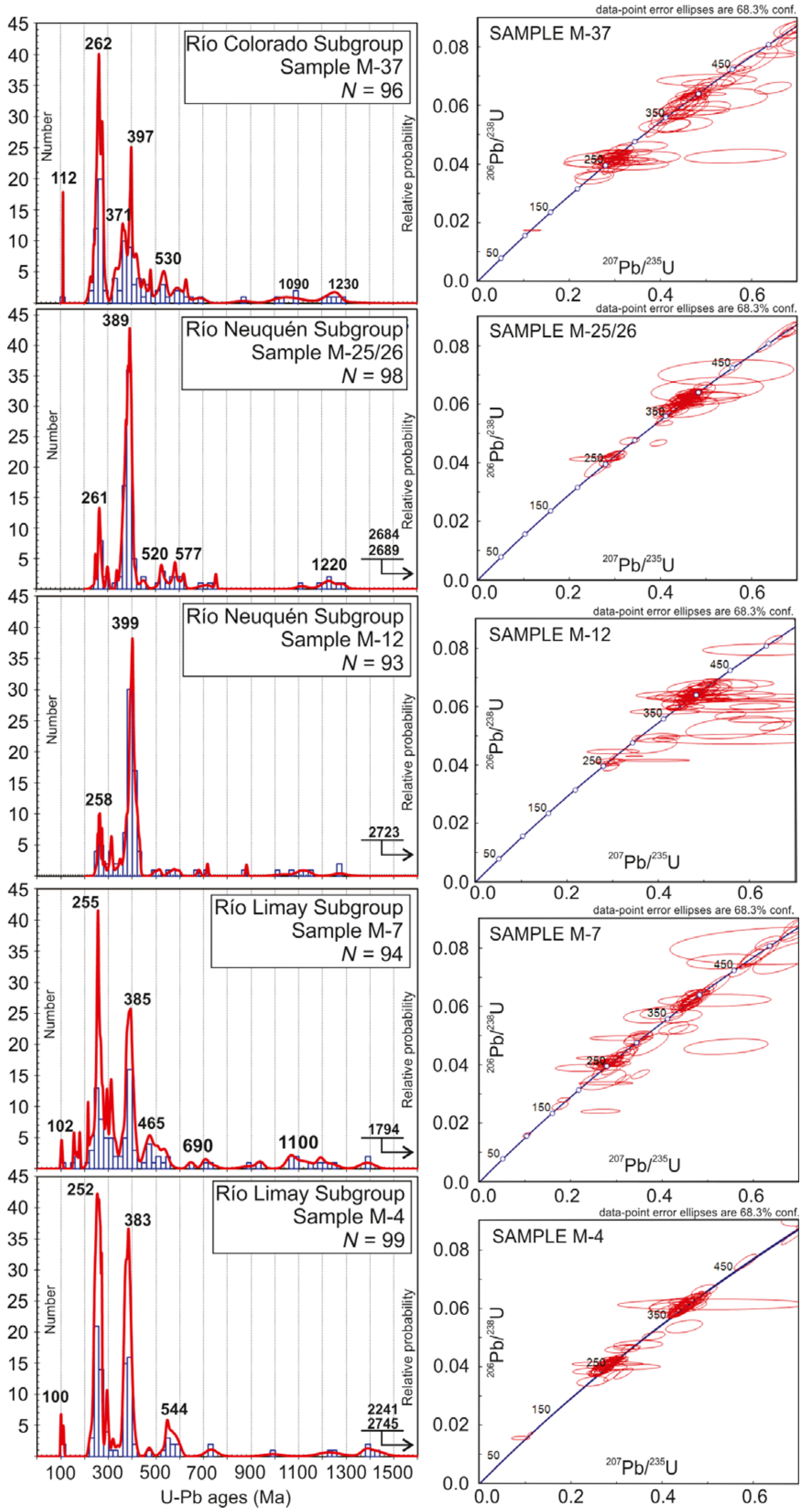

Fig. 12. Frequency histograms, relative probability plots, and concordia plots of U–Pb ages from analysed zircons in five samples of the Neuquén Group located in the Ranquil Co anticline (8) (see Fig. 10 for location of samples).

the wedge top zone of a foreland basin, and the foredeep zone, east of the orogenic front.

Two representative schematic structural cross-sections reflect the dimensions of the Late Cretaceous orogen (Fig. 13), showing the active areas for that time, the direction of the sediment supply, and the location of the intramontane basins (location of the two structural cross-sections is in Fig. 3).

In particular, for the northern section (Fig. 13a), the Sierra Azul (6) in the Andean zone, and the Ranquil Co (8) anticline in the orogenic front zone were uplifted in Late Cretaceous times, defining a broad basin between

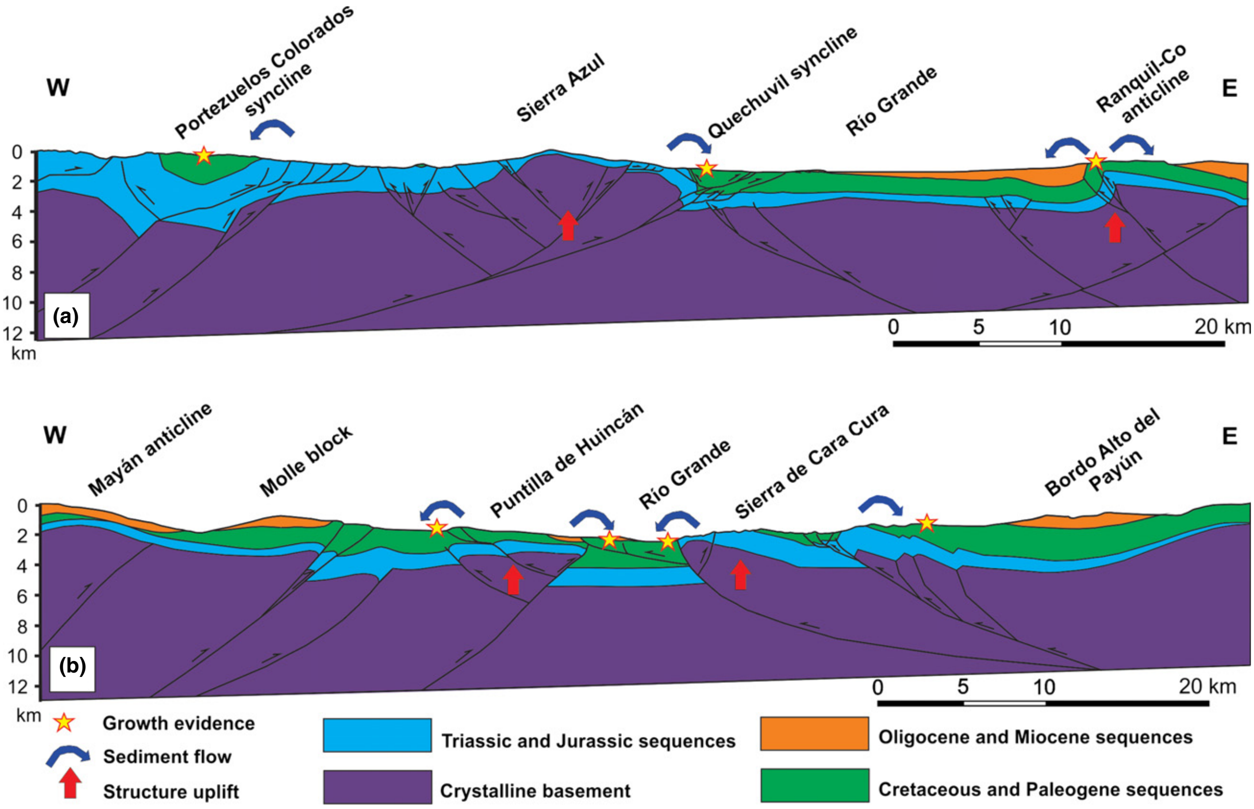

Fig. 13. Schematic cross-sections performed across the study area that show the location of growth evidences provided by other authors (Galarza *et al.*, 2009; Orts *et al.*, 2012a; Sánchez & Asurmendi, 2014) and by this study, along with the main uplifted areas in Late Cretaceous times, paleoflow of sediments and location of intermontane depocenters determined from our present data. Section a. is based on Orts *et al.* (2012a) modified by Ramos *et al.* (2014). The open foredeep in the section b. is based in the borehole data obtained in the Bordo Alto del Payún from Sánchez & Asurmendi (2014).

them, where the Río Grande flows nowadays. The Sierra Azul (6) was the source for the sediments deposited in the Portezuelos Colorados syncline (5) to the west, presently exhumed at the drainage divide area and the Quechuvil syncline to the east. In the orogenic front zone, the Ranquil Co structure (8) was uplifted, but with a shallower level of exposure, acting as a source for the wedge top and foredeep zones located immediately to the east. Taking in consideration new data provided in this work, the maximum advance of the Late Cretaceous orogenic front is, at least, up to the Ranquil Co anticline (8) at these latitudes. This scenario is similar for the structures located to the north of these sections, Sierra de Palaoco (7), Malargüe (3) and La Batra (4) anticlines, constituting the easternmost advance of the orogenic front, and the Bardas Blancas anticline (2) uplifted in the internal part of the orogen.

In the southern section (Fig. 13b), a similar configuration can be observed. The Puntilla de Huincán structure (11) was uplifted during these times, based on Galarza *et al.* (2009), who present a seismic line that shows thickness variation in the Neuquén Group narrowing to the top of the structure, defining two intermontane basins. The eastern intermontane basin coincides with the depocenter that recorded the uplift of the Sierra de Cara Cura (12) in the orogenic front in the Late Cretaceous. East of the Sierra de Cara Cura (12), Sánchez & Asurmendi (2014), based on systematic measurements of thickness of the Cerro Lisandro Formation, derived from borehole data, interpret the geometry of a Late Cretaceous foredeep and corresponding forebulge, indicating this structure as the point of easternmost advance of the orogenic front and main source for the sediments. These authors show how the different orogenic pulses resulted in a large inflow of sediments into the foredeep depocenter, being registered as Gilbert-type delta deposits interrupting lacustrine sedimentation.

In the Agrio and Chos Malal fold and thrust belts, the Cretaceous orogenic front was set based on good stratigraphical, structural and thermocronological evidences (Cobbold & Rosello, 2003; Corbella *et al.*, 2004; Ramos & Folguera, 2005). The advance and main activity of this belt mostly ceased in the Late Cretaceous, being slightly reactivated from the Miocene onwards. In this context, the Cretaceous orogenic front was set in the limit of the deformation, while the foredeep was inferred to be where the Neuquén Group is subhorizonal, being its surficial expression the Chihuidos High (Zamora Valcarce *et al.*, 2009).

On the other hand, in the northern Malargüe fold and thrust belt, the only work that has tentatively identified the Cretaceous orogenic front and set the position of the forebulge was based on facial variations (Mescua *et al.*,

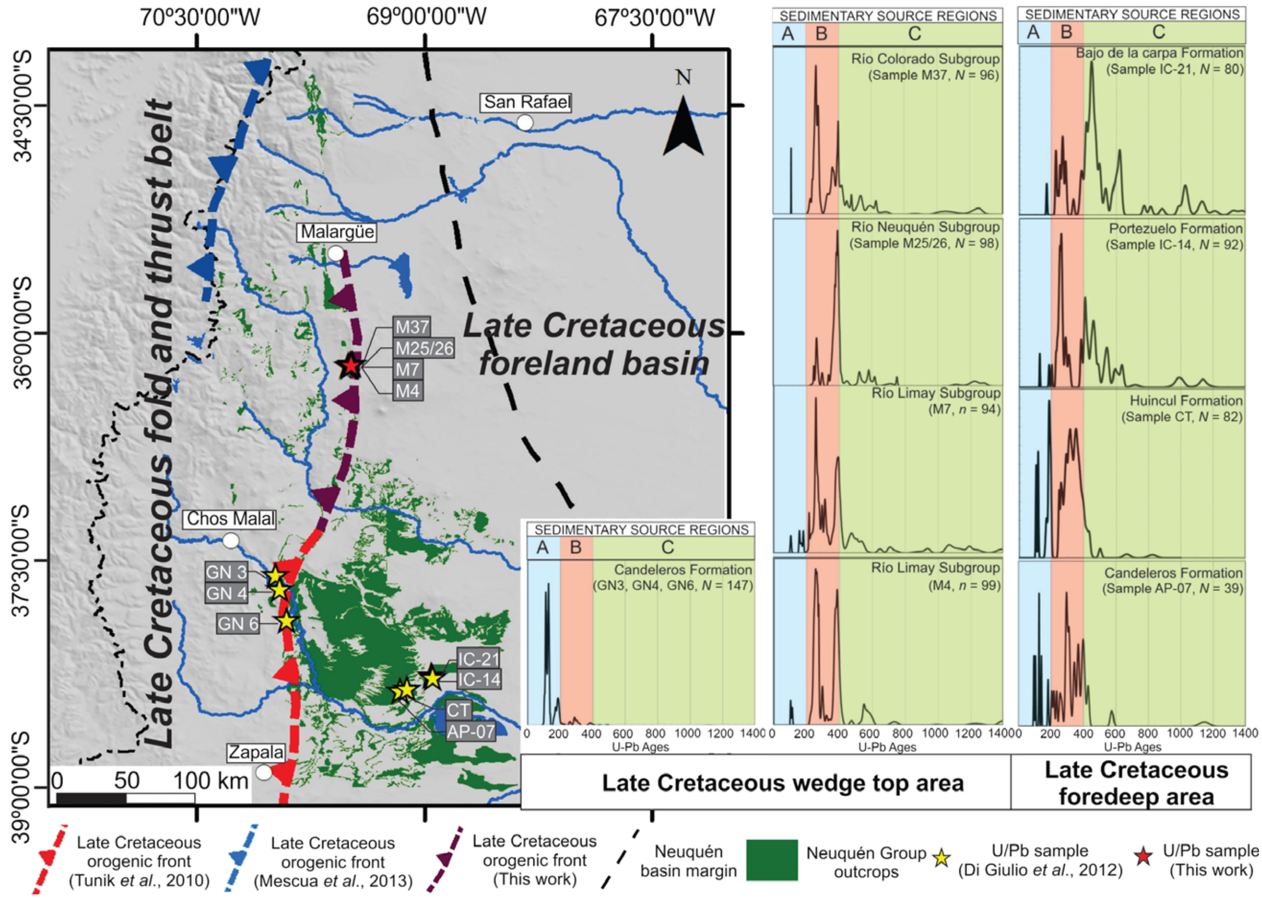

Fig. 14. Late Cretaceous orogenic front between 35° 30′ and 37° S identified in this work and previous proposals. Comparison between detrital zircon age patterns for samples located in the wedge top area vs. the foredeep. Note that the cratonic populations (column C) are inhibited in the wedge top zone indicating progressive uplift of the western intermontane depocenters, while in the foredeep zone these appear towards the youngest terms, implying the uplift of the peripheral bulge to the east. Also, note that the population of zircons coming from the Jurassic-Cretaceous arc rocks (column A) is inhibited towards the top of the foredeep area samples, reflecting the development of the fold and thrust belt to the west. Populations of zircons from Choiyoi and Precuyano rocks (column B) remain constant in both areas, since their sources are located both in the foreland and in the hinterland zones.

2013). These authors assign the orogenic front to an inverted Jurassic normal fault located in the international limit, the Río del Cobre fault, and recognise a proximal sector to the orogenic front and a distal sector with sediment provenance from the forebulge.

In this study, the Cretaceous orogenic front was set also in the limit of maximum advance of the deformation, without taking into account the San Rafael block, interpreted entirely as a Neogene structure (Bastías *et al.*, 1993). The Neogene reactivation was more important in the study area, but did not generate new long wave length structures. Foredeep and forebulge geometries were recently interpreted by Sánchez & Asurmendi (2014) in the Altiplanicie del Payún, but are only visible through indirect methods, since thick layers of Cenozoic volcanism cover the area.

In this way, the Late Cretaceous orogenic front for the area between 35°30′ and 37° S can be defined with more precision (Fig. 14). This orogenic front shows differences regarding the other proposals defined by Mescua *et al.* (2013) and Tunik *et al.* (2010), implying a wider Late Cretaceous orogen. At least, this Late Cretaceous deformational front advanced 50 km eastwards respect to the one proposed for the Agrio and Chos Malal fold and thrust belts to the south (37–39° S), while respect to the northern Malargüe fold and thrust belt (34–35° 30′S) the location is even further to the east, at least 100 km more.

A quick comparison between the three areas shows that the intensity of the Cretaceous deformation, based on the different exposed structural levels, would have been slightly higher towards the south, in the Agrio and Chos Malal fold and thrust belts, in spite of a wider Cretaceous orogen in the study area.

Taking into account the orogenic front proposed in this work, the Ranquil Co (8) depocenter falls in the Late Cretaceous wedge top area. Therefore, a comparison can be made between the detrital zircon age patterns of the Neuquén Group sampled in the Ranquil Co area (wedge top), western (wedge top) and eastern sampling zones (foredeep) of Di Giulio *et al.* (2012), showing some remarkable differences (Fig. 14).

Although both areas are located in different fold and thrust belts, their stratigraphy, structural style and geological history are alike, so the processes that affected them are similar, allowing a comparison. The correlation table in Fig. 2 was used to adequately contrast both zircon U–Pb age patterns, since the Neuquén Group in this work is divided into subgroups and in Di Giulio *et al.* (2012)'s work it is divided into formations. The sample M12 was not taken into account since it is in the same stratigraphic level and has a similar age pattern to M25/26.

Zircons sampled in the Neuquén Group located in the Late Cretaceous wedge top zone (Di Giulio *et al.*, 2012 western sampling zone and this work samples) show high populations that come from the Jurassic-Cretaceous arc roots to the west and from the Choiyoi and Precuyano cycle rocks, located within the cores of the long wavelength anticlines present in the Malargüe, Chos Malal and Agrio fold and thrust belts (Fig. 14). Zircon populations that belong to source areas located in the cratonic area are low, and can be considered as second cycle zircons, being the recycling of the Jurassic and Lower Cretaceous Neuquén Basin units the most plausible source area, as discussed before.

On the other hand, zircons sampled in the Neuquén Group located in the Late Cretaceous foredeep zone (Di Giulio *et al.*, 2012 eastern sampling zone) show that during the Cenomanian, when the Neuquén Group started its deposition, the sediments came from the Jurassic-Cretaceous volcanic arc located to the west. With the progressive development of the Late Cretaceous fold and thrust belt, this contribution was inhibited, and the clastic systems started to be fed from the cratonic area, probably due to the uplift of the peripheral bulge as a consequence of the Late Creteaceous fold and thrust belt lateral growth. The contribution to the foredeep of the Choiyoi and the Precuyano cycle rocks has remained unaltered, since these outcrops are widely represented both in the cratonic region and in the structures located in the fold and thrust belt.

Geodynamic context of the Late Cretaceous orogen and foreland basin

Recent plate tectonic reconstructions have shown that during Cretaceous times the eruption in the paleo-Pacific ocean floor of a suite of Large Igneous Provinces, known as Ontong-Java, Manihiki and Hikurangi Plateaus, was associated with the redefinition of some plate tectonic boundaries (Taylor, 2006; Seton *et al.*, 2012). These series of events took place since 120 Ma, and led to the fragmentation of the Phoenix Plate into four new plates: the Hikurangi, Manihiki, Chasca and Catequil plates. As the boundary between the Chasca and Catequil plates developed (Chasca/Catequil mid-ocean ridge, CCMOR), it interacted with the South American margin at present 43° S (Fig. 15c) in a context of westward acceleration of the continent after its breakup from the rest of western Gondwana (Somoza & Zaffarana, 2008). This initial event would have been associated with a slab shallowing, followed by an arc migration and a deformational stage, as depicted by Gianni *et al.* (2015) for those latitudes. Afterwards, the CCMOR migrated northwards, reaching the paleolatitudes of the southern Malargüe fold and thrust belt at around 93 Ma, in a context of high absolute upper plate velocity (Fig. 15b) (Maloney *et al.*, 2013). The subduction of young, anhydrous, buoyant lithosphere (enclosed by the 10 Ma isochrones in Fig. 15a) attached to the CCMOR could be the responsible for a potential arc waning/gap at the Chilean side of the Andes described by Charrier *et al.* (2007) (Fig. 15a). In this line, Tunik *et al.* (2010), based on the analysis of the Mesozoic detrital zircons from the Neuquén Group, showed that there are two important peaks in the volcanic arc activity developed at 110 and 125 Ma respectively, followed by a gradual decrease, interpreted as a waning in the arc production. Detrital zircon data shown by Di Giulio *et al.* (2012) and data of this work agree with this waning in arc activity between *ca.* 100 Ma and *ca.* 85 Ma.

Coevally to this arc waning/gap, contractional deformation at the Neuquén Basin described for the 35° 30′–37° S area, took place, when the synorogenic Neuquén Group accumulated in a foreland basin (Fig. 15a and b).

Following plate reconstructions, the CCMOR continued its northward migration, becoming extinct at *ca.* 80 Ma, immediately after a new tectonic boundary, corresponding to the Farallon/Antarctic mid-ocean ridge (FAMOR), impacted the margin at 42° S (Fig. 15c). Contrast to the previous ridge collision, the FAMOR remained rather static respect to the margin since its impact at *ca.* 86 Ma. It is remarkable that during this period, Cretaceous volcanic rocks in the Argentinian Andean slope, have ages between *ca.* 85 Ma and *ca.* 60 Ma (Muñizaga *et al.*, 1988; Franchini *et al.*, 2003), with similar ages in the Chilean slope (Charrier *et al.*, 2007). This fact has been used to propose an arc shifting in Late Cretaceous times (Ramos & Folguera, 2005; García Morabito & Ramos, 2012; Spagnuolo *et al.*, 2012). This migration would have reached a maximum advance at the Río Grande area during *ca.* 67 Ma (Spagnuolo *et al.*, 2012), coevally with the uppermost terms of the Neuquén and Malargüe Groups (Llambías & Aragón, 2011).

The deformational processes described in this study could have been caused by the subduction of anomalously young lithosphere, associated with the subduction of two consecutive mid-ocean ridges according to current models, in a context of fast westward motion of the South American continent. The arc waning/gap and later arc migration could be related to these processes, where subduction of anhydrous and buoyant oceanic lithosphere, would have induced changes in the geometry of the subduction zone. The Neuquén Group would be the synorogenic sedimentary unit associated with an early Andean orogen, produced by a shallow subduction regime, which is one of the likely effects of the collision of mid-ocean ridges, as contemplated in the pioneer work of Nelson & Forsythe (1989).

In the light of these recent plate reconstructions and the new evidences shown in this work, it is worth reviewing along the strike of the Andes the areas that have been

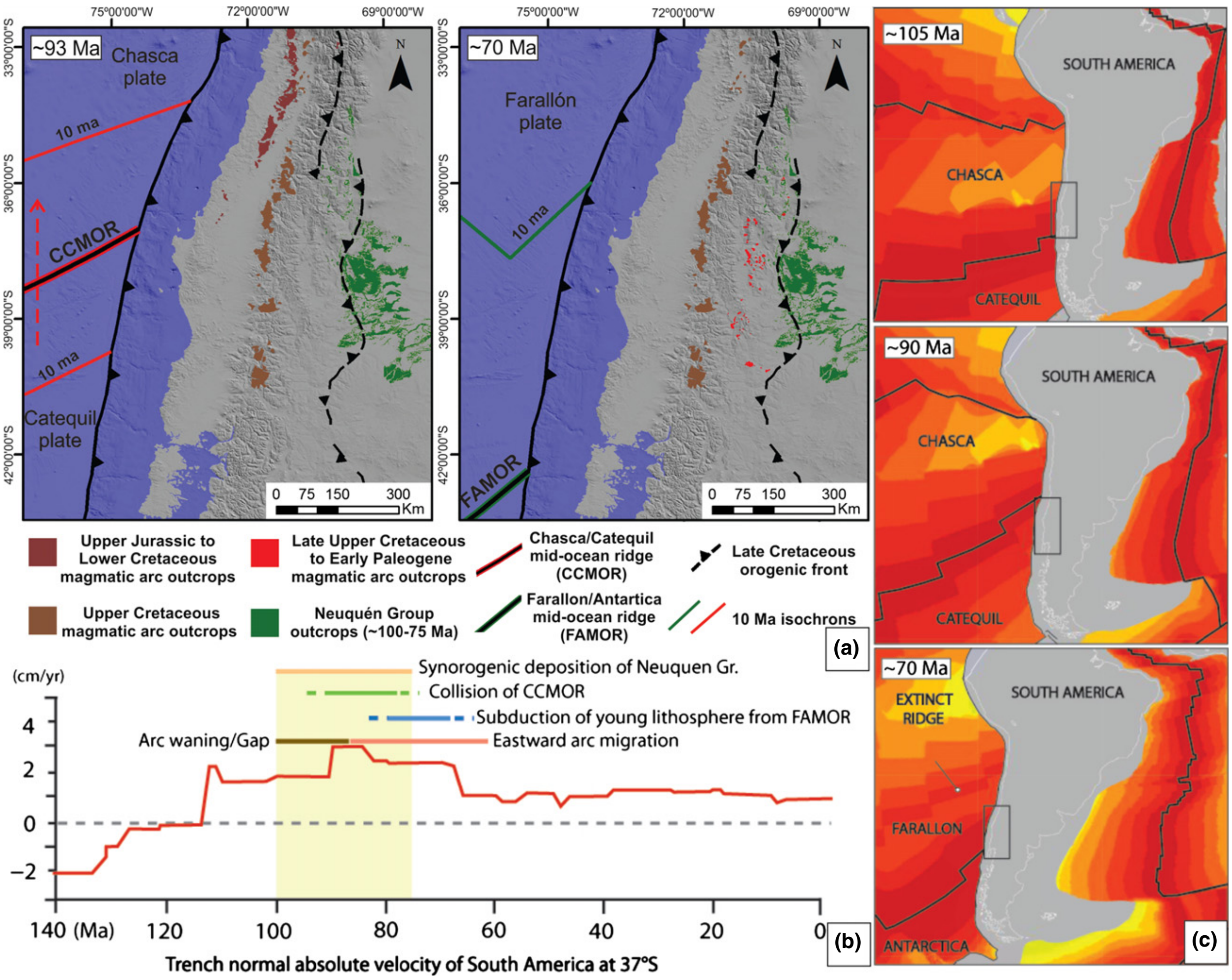

Fig. 15. (a) Paleoreconstructions of the study area in the southern Central Andes margin. Two episodes of young lithosphere subduction were associated with the subduction of two mid-ocean ridges as predicted by Seton *et al.* (2012)'s model. Note a progressive eastward shifting of the arc front during these episodes of ridge subduction (after Muñizaga *et al.*, 1988; Franchini *et al.*, 2003; Charrier *et al.*, 2007; Spagnuolo *et al.*, 2012; García Morabito & Ramos, 2012). The Neuquén Group is coeval with both episodes of ridge collisions. The Late Cretaceous orogenic front is based in Tunik *et al.* (2010), García Morabito & Ramos (2012), Orts *et al.* (2012b), Mescua *et al.* (2013) and this work. (b) Trench normal absolute velocity of South America at 37°S, modified from Maloney *et al.* (2013), and the different geological episodes occurred during its westward migration. Note how the synorogenic deposition of the Neuquén Group is coeval with the subduction of two consecutive mid-ocean ridges, an arc waning/gap and finally an eastward arc migration. (c) Paleoreconstructions of the South American Plate for three different stages since the opening of the Atlantic Ocean, after Seton *et al.* (2012).

considered entirely uplifted in Neogene times, but may have been affected by this Late Cretaceous deformational stage. Taking into account the CCMOR's northward migration from 43° S (120 Ma) until its extinction at 30° S (80 Ma), some potential areas have been recognised: the Frontal Cordillera, with peaks that reach *ca.* 6000 m high, has been exhumed in Late Miocene times, related to the present Pampean flat-slab segment. However, some hypothesis claim that it could have been initially uplifted in Late Cretaceous times (Schiller, 1912; Vicente *et al.*, 1973; Vicente, 2000). In this sense, evidence of growth strata in the Cretaceous Diamante Formation has been found on its back limb, in the Principal Cordillera by Orts & Ramos (2006) that indicates this older uplift stage.

To the south, the San Bernardo fold and thrust belt, between 42° and 48°, is a feature that has been considered to be entirely Neogene in age. Recent studies by Echaurren *et al.* (2014) and Gianni *et al.* (2015) show synorogenic strata in the Cretaceous Chubut Group, resuming the idea of a Cretaceous orogen known as the Patagonides, defined initially by Keidel (1921).

Not only the length but also the width of this Cretaceous orogen are issues yet to be resolved. To understand the real dimensions of this Late Cretaceous orogen, more work has to be done and classic areas should be revisited in search for synorogenic evidences in Cretaceous units.

CONCLUSIONS

After the description of different kind of data and discussion performed in this work, we can draw a series of conclusions. First of all, the Neuquén Group represents the infill of a Late Cretaceous foreland basin, located east to the recognised early Andean orogen that evolved at least since *ca*. 100 Ma, maximum age of the detrital zircons. This orogen was the main source for the sediments in a wedge top area, infilling intermontane basins, and also, during its initial stages, feeding a foredeep zone. This foredeep area would have had its main source in the peripheral bulge, being more important towards the final stages, once the orogen would have gained its maximum dimensions, creating barriers to the eastward dispersion of the Jurassic to Cretaceous Andean sources located to the west and changing the regional slope due to the orogenic load.

The limit between these two areas can be determined with relative precision, by the Late Cretaceous orogenic front, defined in this work by the occurrence of growth strata in the Neuquén Group. This orogenic front is located approximately 400–500 km east from the present trench, reaching 69°30′ W. In comparison with other proposals in neighbour segments, this deformational front is located further to the east reaching the eastern Malargüe fold and thrust belt and showing that Neogene mountain morphology resembles the one reached in Late Cretaceous times. In this context, Permian detrital components indicate that main basement structures were incised up to its present level of erosion, constituting the main sources for this age, defining a structural level similar to the present one.

The sedimentation of the Neuquén Group occurred in a particular geodynamic context, when the South American continent drifted to the west after its break up from the rest of western Gondwana, and when its western margin was impacted by two consecutive mid-ocean ridges. This would have resulted in an arc waning/gap in early Upper Cretaceous times, and a subsequent arc migration in late Upper Cretaceous times, that reached the foreland area, coeval with the Neuquén Group deposition. This arc migration, the deformational processes described and their respective foreland basin deposits would be the product of a shallow subduction regime.

The dimensions of this orogen are yet to be studied, but this work constitutes evidence that Cretaceous deformation in the Andes is more important than previous assumptions.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Data S1. Analytical methods.
Table S1. U-Pb geochronologic analyses.

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