Late Cretaceous Uplift in the Malargüe fold-and-thrust belt (35°S), southern Central Andes of Argentina and Chile

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ABSTRACT. The Cordillera de los Andes is the typical example of a subduction-related orogen. Its present topography is the result of post-Miocene uplift, however, Andean compressional deformation and uplift started in the Late Cretaceous, as increasingly recognized in different sectors of the mountain belt. We present evidences of a Late Cretaceous event of compressional deformation in the southern Central Andes (35°S), reflected in syn-orogenic foreland basin deposits assigned to the Neuquén Group in Argentina and the Brownish-Red Clastic Unit in Chile. Comparison of the facies of these units allows us to recognize a sector proximal to the Late Cretaceous orogenic front, a distal sector with sediment provenance from the forebulge and a western sector where the sediments where deposited within the Late Cretaceous mountain belt. On this basis, we assign the orogenic front to an inverted Jurassic normal fault, the Río del Cobre fault, and reconstruct the structure of the easternmost Late Cretaceous Andes at this latitude. The change in the location of the orogenic front north and south of 35°S allows us to recognize a long-lived change in behavior in Andean evolution in this sector, which correlates with a change in the shape and the deposits of Mesozoic Neuquén basin.

Keywords: Andes, Orogeny, Cretaceous, Foreland basin.

RESUMEN. La Cordillera de los Andes es el ejemplo típico de un orógeno asociado a subducción. Su topografía actual es el resultado del levantamiento posterior al Mioceno, la deformación y el levantamiento ándicos comenzaron a partir del Cretáceo Tardío, como se reconoce actualmente en diversos sectores de la faja montañosa. En este trabajo se presentan evidencias de un evento de deformación compresiva durante el Cretácico Tardío en los Andes Centrales del sur (35°S), reconocidos a partir de los depósitos sinorogénicos asociados, que se asignan al Grupo Neuquén en Argentina y la ‘Unidad Clásica Café-Rojiza’ (BRCU) en Chile. Mediante las variaciones de facies en estos depósitos se pueden reconocer un sector proximal cercano al frente orogénico Cretácico Tardío, un sector distal con aporte desde el dorso periférico, y un sector occidental en el que los depósitos se produjeron dentro del cordón montañoso. De esta manera, se puede ubicar el frente orogénico Cretácico Tardío, el que asignamos a la inversión tectónica de una falla normal jurásica, la falla Río del Cobre. El cambio en la ubicación del frente orogénico Cretácico al norte y sur de 35°S permite reconocer a este sector como un limite entre sectores con diferencias en su evolución andina, que se interpreta como heredado de la evolución de la cuenca Neuquina.

Palabras clave: Andes, Orogenia, Cretácico, Cuenca de antepaís.
1. Introduction

The Cordillera de los Andes is one of the most extensive mountain ranges in the world, extending for more than 8,000 km along the western margin of South America. In its central portion, it is the result of the subduction of the oceanic Nazca plate below the continental South America plate, being the typical example of a subduction-related orogen (Dewey and Bird, 1970; Oncken et al., 2006). The present configuration of the range is mostly the result of Cenozoic deformation and uplift (e.g., Jordan et al., 1983; Mégard, 1984; Ramos, 1999; Vicente, 2005). However, in many sectors of the Andes, the first stage of Andean uplift took place in the Late Cretaceous. This stage has been recognized in the Peruvian Andes (Steinmann, 1929; Aubouin et al., 1973; Vicente et al., 1979; Mégard, 1984); the north Andes of Ecuador, Colombia and Venezuela (Aspden et al., 1992; Jaimes and de Freitas, 2006; Martin-Gombojav and Winkler, 2008), the Central Andes in Bolivia (Sempere, 1995), and the Patagonian Andes (Biddle et al., 1986; Fildani et al., 2003).

In the southern Central Andes, the intense Cenozoic deformation overprinted previous events, making their recognition difficult. However, south of 36°S, Upper Cretaceous continental deposits known as the Neuquén Group have recently been interpreted as syn-orogenic strata corresponding to a Cretaceous foreland basin (Cobbold and Rossello, 2003; Ramos and Folguera, 2005). Based on detrital zircon ages, Tunik et al. (2010) dated the beginning of the exhumation in the Cordillera Principal and the maximum age of deposition of syn-orogenic strata in this basin as taking place in the early Cenomanian. In this contribution, we will present evidence for a Late Cretaceous age for the beginning of Andean uplift and deformation at 35°S, and we will address the issue of the location of the Late Cretaceous orogenic front north of 36°S. This will allow us to discuss some of the characteristics of this deformational event.

2. Geologic setting: the Neuquén basin

The Neuquén basin is a Mesozoic retroarc basin developed in the western edge of the Gondwana continent, sporadically open to the Pacific Ocean at its western margin (Fig. 1). Its infill comprises a thick succession of sediments, with the interplay between tectonics, sea level and activity in the volcanic arc controlling the development of marine versus continental conditions (Legarreta and Uliana, 1996). The basin presents two distinct sectors: north of ~35°S, it comprises a narrow north-south trough (90 km wide), while south of this latitude it extends eastwards in the so-called Neuquén embayment, where it reaches a width of 300 km (Fig. 1). The history of the basin starts in the Late Triassic with the development of isolated hemigrabens, controlled by normal faults (Legarreta and Gulisano, 1989; Cristallini et al., 2009; Giambiagi et al., 2009; Fig. 1). Triassic-Jurassic synrift deposits consist of more than 2,000 m of fluvio-lacustrine and fan-delta deposits in the northern sector, and over 4,000 m of volcanic and volcanioclastic rocks in the Neuquén embayment (Gulisano and Gutiérrez-Pleimling, 1994; Manceda and Figueroa, 1995; Giambiagi et al., 2009; Bechis et al., 2010). Marine rift sequences unconformably overlay these continental deposits (Legarreta and Uliana, 1996; Lanés et al., 2008). Since the Pliensbachian, when the depocenters were connected during a generalized marine transgression, the infill of the basin consisted in an alternance of continental and marine deposits (Legarreta and Uliana, 1999; Veiga et al., 2005). Figure 2 shows the units of the infill at 35°S. Eventually, the beginning of widespread contractional deformation and the rise of the Andes led to the development of a foreland basin setting. Traditionally, this was interpreted as taking place during the latest Cretaceous to Paleogene, as evidenced in the deposits of the Malargüe Group which record the first Atlantic transgression in the Neuquén basin (Weaver, 1927), pointing out the change of the basin slope associated with the Andean uplift (Barrio, 1990; Aguirre-Urreta et al., 2011). In recent investigations, it has been proposed that the foreland basin stage began earlier, in the early Late Cretaceous, with the deposition of the Neuquén Group (see section 3 below).

3. The Neuquén Group: syn-orogenic deposits of the initial Cretaceous uplift of the Andes

The Neuquén Group (Digregorio, 1972; Cazau and Uliana, 1973) corresponds to a Late Cretaceous sedimentary succession of clastic continental deposits which presents a maximum thickness of 1,500 m (Legarreta and Gulisano, 1989; Legarreta and Uliana, 1999). It crops out in the eastern sector of the Andes of southern Mendoza and Neuquén. Red sandstones
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and shales predominate, though intercalations of grey conglomerates and conglomeratic sandstones are found in the base of the succession at many localities, giving place to an upward-fining arrangement (Gerth, 1925, 1931; Cruz et al., 1989; Legarreta and Gulisano, 1989). The basal contact with the underlying units is uncomformable (Keidel, 1925; Gerth, 1931; Legarreta and Gulisano, 1989; Barrio, 1990; Leanza, 2009; Tunik et al., 2010).

A fluvial environment is interpreted for this unit (Cazau and Uliana, 1973), including braided and meandering fluvial environments (Cruz et al., 1989; Legarreta and Gulisano, 1989). In the eastern part of the basin, Armas and Sánchez (2011) have reported estuarine deposits in this unit, which could be related to the high sea-level which characterized the Late Cretaceous (Muller et al., 2008).

According to Legarreta and Gulisano (1989), the age of the Neuquén Group is Cenomanian to Campanian (94 to 80 Ma). In the southern part of the Neuquén basin, in the locality of Cerro Policía (39ºS), Corbella et al. (2004) obtained a zircon fission-track age of 88±3,9 Ma for a tuff interbedded in the lower section of the Neuquén Group, which confirms the Late Cretaceous age of this unit.

The interpretation of the Neuquén Group deposits as syn-orogenic foreland basin deposits has been advanced by Keidel (1925) in the Neuquén province. This view was supported by other pioneer investigators such as Groeber (1929) and Wichmann (1934). However, in later works some authors interpreted that the deposition of the Neuquén Group took place during a period of tectonic quiescence, with thermal subsidence or magmatic load generating the accom-

FIG. 1. Geologic setting of the Neuquén basin. Inset shows the location of the basin during the break-up of Gondwana in the Albian (paleogeographic map from Blakey, 2010). Main figure over GTOPO30 digital elevation model (available at http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info (last accessed 24/10/2012)). The white box shows the location of figure 3. Limits of the Neuquén basin marked by the grey line. The fault-controlled isolated depocenters of Late Triassic to Early Jurassic age are also shown (according to Cristallini et al., 2009 and Giambiagi et al., 2009). The generalized location of the Mesozoic magmatic arc is also indicated.
moderation space (Uliana and Biddle, 1988; Legarreta and Gulisano, 1989; Legarreta and Uliana, 1998), while others followed Keidel’s proposal of a Late Cretaceous orogenic phase (Stipanicic and Rodrigo, 1970; Ramos, 1988). Recent works focused on the outcrops of the Neuquén Group south of 36ºS have strengthened the idea of interpreting these beds as syn-orogenic foreland basin deposits (Zapata et al., 2002; Cobbold and Rossello, 2003; Ramos and Folguera, 2005; Zamora Valcarce et al., 2006; Tunik et al., 2010; Di Giulio et al., 2010).

In particular, Tunik et al. (2010) have shown that there is a change in the provenance areas between the Neuquén Group and the underlying units through U-Pb dating of detrital zircons. The Aptian to Albian Rayoso Formation presents zircons derived from the cratonic basement located to the east and southeast of the Neuquén basin. In contrast, samples from the Neuquén Group present zircons with Early Cretaceous ages, which can only be attributed to the exhumation of the Andean magmatic arc located to the west (Figs. 1 and 7), indicating a period of compressional deformation and uplift.

4. The Neuquén Group at 35ºS

At 35ºS latitude, the Andes of Argentina correspond to the Malargüe fold-and-thrust belt, a mountain range with altitudes between 2,000 and 4,500 m, uplifted between the Early Miocene and the present (Kozlowski et al., 1993; Giambiagi et al., 2008; Silvestro et al., 2005). Figure 3 shows a simplified geologic map of the Andes at 35ºS, with the distribution of the outcrops of the Neuquén Group. During the Cenozoic uplift (Combina and Nullo 1997, 2011; Mescua, 2011), the Mesozoic rocks were exposed and eroded. As a result of its stratigraphical position, high in the Mesozoic succession, the Neuquén Group was eroded away in many areas of the Malargüe fold-and-thrust belt, and at 35ºS only minor relict exposures of this unit are found in two sectors of the Argentinean Andes.
FIG. 3. Simplified geologic map of the Andes at 35ºS, based on Mescua (2011). The rectangle in the inset shows the location of the study area, in the northern part of the Neuquén basin. Outcrops of the Neuquén Group and BRCU are shown in black. The numbers indicate the main localities mentioned in the text: 1. Eastern outcrops of the Neuquén Group; 2. Western outcrops of the Neuquén Group; 3. Rio del Cobre fault; 4. Outcrops of the BRCU in Termas del Flaco.
A western sector of outcrops is located in the area of the classic geological locality of Portezuelo Ancho, where a partial column of 350 m of the lower part of the unit is found (Legarreta and Kozlowski, 1984); while the top of the Neuquén Group was eroded. The succession corresponds to an upward-finining package, with grey sandstones and conglomerates in the base which grade upwards to red sandstones and shales. The eastern outcrops are found in the easternmost Malargüe fold-and-thrust belt, near the Cenozoic orogenic front. Most of this sector is covered by Quaternary lavas and alluvial and colluvial deposits, and the Neuquén Group is poorly exposed, with isolated patches of red sandstones (Dajczgewand, 2002).

The base of the succession of the Neuquén Group in the western outcrops, as observed 3 km north of Portezuelo Ancho, is composed by 150 m of grey conglomerates. The beds are lenticular, 1 to 3 m thick, and the conglomerates are clast-supported, with subrounded clasts of up to 30 cm (Fig. 4a). Clast composition is polymictic (Fig. 4b): andesites predominate, and red sandstones and limestones are also abundant. This suggests a provenance from the Late Jurassic and Cretaceous units which were deposited in this sector of the Neuquén basin. In particular, andesites are one of the dominant lithologies of the Kimmeridgian Río Damas Formation, limestones are derived from the marine rocks of the Tithonian to Hauterivian Men doza Group, and red sandstones are interpreted to be derived from the Kimmeridgian Tordillo Formation or from the erosion of older deposits from the same Neuquén Group. The succession grades to a sandstone predominant section, composed of 1 m-thick lenticular beds of red sandstones with through cross-bedding,
parallel lamination and climbing ripples (Fig. 4c). Shale content increases upwards, giving place to a section composed by red shales which contains fossilized trunks of 30 cm of diameter (Fig. 4d).

In Portezuelo Ancho, the succession has been described by Legarreta and Kozłowski (1984). The fining-upward tendency is also observed in this locality, though conglomerates in the base are slightly finer (maximum clast size is 20 cm), and clasts of fossiliferous limestones of the Mendoza Group are dominant.

Therefore, the composition of the clasts of the conglomerates indicates the exhumation and erosion of the Late Jurassic and Early Cretaceous units of the Neuquén basin.

The eastern outcrops of the Neuquén Group correspond to a much finer grained succession, composed by red sandstones and minor intercalations of gravelly sandstones. Dajczgewand (2002) characterized these sandstones as derived from a clastic source of pre-Jurassic basement located towards the east. South of 36ºS, Di Giulio et al. (2010) applied U-Pb dating of detrital zircons in the eastern outcrops of the Neuquén Group, and also observed a basement clastic source, which they interpreted as the result of the erosion of a peripheral bulge located further east. The eastern outcrops at 35ºS confirm this interpretation.

5. The Brownish-Red Clastic Unit and the Mesozoic-Cenozoic unconformity in Chile

The Brownish-Red Clastic Unit (BRCU) was defined by Charrier et al. (1996) in the locality of Termas del Flaco in Chile (marked as 4 in figure 3). It corresponds to a succession of continental rocks with a thickness of 250 m, composed of a basal breccia, conglomerates and sandstones showing an upward-fining arrangement. It is covered unconformably by volcanic and volcanioclastic deposits of the Late Eocene-Miocene Abanico Formation (Charrier et al., 1996; Flynn et al., 2003). Charrier et al. (1996) suggest a correlation with the Neuquén Group based on the lithological characteristics of both units and the finding of dinosaur remains in the BRCU which constrain its age to the Cretaceous. U-Pb dating of detrital zircons from this unit provided ages around 90 Ma (80-118 Ma, Aguirre et al., 2009), which indicate a Late Cretaceous maximum age for this unit. Our observations in the Portezuelo Ancho area support the correlation with the Neuquén Group, since the lithological characteristics, the upward-fining sedimentary pattern and the stratigraphic position of the Neuquén Group in that area are similar to those of the BRCU. Furthermore, Charrier et al. (1996) state that ‘the coarse basal breccia of the BRCU is difficult to account for in the context of any simple regression model. Irrespective of the true correlations involved, faulting along the basin margin must have contributed to the abrupt transition observed’. This agrees with the hypothesis of a Cretaceous deformation event and therefore the BRCU is interpreted as deposited when thrusting was taking place west of the present locality of Termas del Flaco. It should be noted, however, that zircon fission track dating of samples from the BRCU was carried out by Waite (2005), obtaining ages between 90.5±10.9 and 62.8±5.4 Ma. The younger ages indicate a Paleocene minimum age for deposition of part of the BRCU, which suggests that: i. the BRCU deposited over a longer timespan than the Neuquén Group, and ii. that the Cretaceous deformation in the Termas del Flaco area might have extended into the Paleogene.

The unconformity between the Mesozoic units (Baños del Flaco Formation and BRCU) and the Late Eocene to Miocene Abanico Formation is of only a few degrees in the Termas del Flaco area (Charrier et al., 1996). It is remarkable, however, that in less than 2 km of distance, the Abanico Formation presents different stratigraphic relations: it covers the BRCU in the northern sector of the area, and the Baños del Flaco Formation towards the south (Fig. 5). This implies that the 250 m of thickness of the BRCU were eroded prior to the late Eocene in this last sector - or that this unit was not deposited, which seems unlikely given the short distance. Based on the information presented in the previous sections, we conclude that the erosional event is related to the Late Cretaceous to Paleogene activity of a fault located to the east of the Termas del Flaco locality, the Rio del Cobre fault (indicated in figure 3), which could have generated a large anticline with harpoon geometry (McClay, 1995). Erosion of part of the the BRCU might have taken place in part of the low-dipping backlimb of the anticline, whereas erosion of the frontal limb of the anticline provided the sediments which were deposited in the Portezuelo Ancho area (Fig. 6). It is worth noting that the sector where the BRCU was eroded corresponds to the location of maximum displacement of the Rio del Cobre fault, and that the reverse throw of this structure decreases rapidly to the north (Mescua, 2011), coincidently with
the preservation of the BRCU in the backlimb of the anticline. In Oligocene times, the extensional Abanico basin was developed, and deposition of the Abanico Formation preserved the erosional surface carved on the Mesozoic rocks. Since the Miocene, the compressional deformation of the Abanico basin took place, and the generation of the El Fierro fault resulted in the complex geometry observed at present (Fig. 5).

6. Discussion and conclusions

Our results are consistent with the interpretation of the Neuquén Group as foreland basin deposits. An important relief contrast between the clastic source area and the basin, as well as a short distance of transport, is needed to provide large clasts (diameters of 30 cm) as those found in the basal conglomerates at Portezuelo Ancho. Furthermore, clast compositions indicate the exhumation of Late Jurassic and Early Cretaceous units. The regional geometry of the Neuquén Group, without abrupt thickness changes or evidence of syn-sedimentary faulting, and with uniformly spaced isopach trends in the Neuquén embayment (Legarreta and Uliana, 1998) prevents the interpretation of the basin as extensionally controlled in the period of deposition of this unit. Therefore our interpretation is that the Neuquén Group deposited at 35°S in a foreland basin setting, during a Late Cretaceous phase of compressional deformation, in agreement with other work focused south of this latitude (Tunik et al., 2010; Di Giulio et al., 2010). The Cretaceous orogenic front at this latitude can be related to the Río del Cobre fault, located 5 km to the west of the outcrops of the Neuquén Group at Portezuelo Ancho (Fig. 3). This structure is a Jurassic normal fault which was inverted during Andean compression, as indicated by thickness and facies changes of the Jurassic units at both sides of the structure. Age constraints for Andean tectonics east of the Portezuelo Ancho area suggest a beginning of deformation in the Middle Miocene (Combina and Nullo, 1997, 2011; Mescua, 2011). Our data suggest that the Río del Cobre fault was inverted in the Late Cretaceous and probably again in the Paleogene. The reactivation of the same structure in the Miocene makes it difficult to estimate the Cretaceous displacement. The Neuquén Group conglomerates include clasts of the Río Damas Formation. The exhumation of this unit requires the previous exposure of the 150 m of overlying Lower Cretaceous rocks, which can be taken as a minimum Late Cretaceous displacement. The great thickness of the partially exhumed Río Damas Formation (between 3,000 and 5,000 m, Klohn, 1960) prevents an accurate estimation of the pre-Miocene displacement, which could be as much as 5,000 m. However, an important Miocene reactivation of this structure can be inferred from the present structural
relations (Mescua, 2011), which suggests that the Late Cretaceous displacement was not that large.

The local characteristics of the structure in this part of the Andes, which corresponds to the inversion of the Río del Cobre fault and the formation of an anticline with a harpoon geometry, have resulted in a low angle unconformity between the Mesozoic strata and Cenozoic rocks in the backlimb of the anticline. In spite of this low angle, in part of the study area at least 250 m of the BRCU were eroded before the deposition of the Abanico Formation. South of the study area, the contact between the Mesozoic beds and the Abanico Formation is covered by Pliocene and Quaternary volcanic rocks. If the Late Cretaceous compressional phase of deformation extended further north, as proposed by Orts and Ramos (2006), the unconformity between the Mesozoic strata and the Abanico Formation (and equivalent units) should be a major feature of the Andes in its western slope, where Oligocene and Early Miocene units were deposited. At the Cachapoal River (34°20'S), an important unconformity was proposed by Charrier (1973, 1982) and Charrier et al. (2002). In contrast, Godoy (1991) and Godoy et al. (1999) interpreted the contact as tectonic. Further complications arise from the difficulty in differentiating the Cretaceous and Cenozoic units in this sector of the Andes, since lithologically, units of both ages are very similar. Future investigations are needed to verify if the Mesozoic-Cenozoic (pre-Miocene) unconformity can be recognized at a regional scale.

Figure 7 shows the extent of Late Cretaceous deformation recognized in the Southern Central
Andes between 33ºS and 39ºS. We have extended the orogenic front towards the north of the study area based on a compilation of the scarce information available. The description of syn-tectonic unconformities in beds of the Neuquén Group in the Río del Plomo area (Orts and Ramos, 2006) is the only known evidence of Late Cretaceous deformation for this northern region. On the other hand, the presence of marine Maastrichtian deposits resulting from an Atlantic ingression in some sectors of the high Andes of Mendoza (Tunik, 2003; Pose et al., 2011) can be taken as indicative of areas which were part of the foredeep of the foreland basin (Aguirre-Urreta et al., 2011), and therefore not uplifted in the Late
Cretaceous, which allows to outline the approximate location of the orogenic front.

The data available so far indicates an important change in the location of the orogenic front. The orogenic front south of 36ºS is located 40 km to the east of the orogenic front north of 35ºS. At the longitude of 69º45'W, Late Cretaceous structures have been identified in the south, while in the north the Maastrichtian deposits of the marine ingressation indicate an area that was not uplifted.

It is important to mention that this sector of the Andes also presents particular characteristics during its Cenozoic evolution. Anomalous low values of shortening and crustal thickness at 35ºS (Giambiagi et al., 2012), and changes in exhumation amounts north and south of this latitude (Spikings et al., 2008) have been reported for the post-Miocene Andean history.

Therefore, the change in the location of the orogenic front observed for the Late Cretaceous orogenic event suggests that this sector has been a long-lived transitional area separating zones of different behaviour in the Andean orogen. It is particularly noteworthy that this latitude also coincides with the change between the narrow basin of the northern sector and the wider southern embayment of the Neuquén basin (Fig. 1). Furthermore, the change in the infill of the Triassic–Early Jurassic extensional depocenters of the Neuquén basin, from a sedimentary infill in the north to a volcanic and volcanoclastic infill in the south, indicates a transition between passive and active rifting behaviors. This contrast can have a long-standing effect on the composition and strength of the crust, which can influence the post-Mesozoic geologic history, and be reflected in variations in the behavior of the segments north and south of 35ºS during the Andean orogeny.

As a final remark, it should be mentioned that the widespread recognition throughout the Andes of a Late Cretaceous start of the compressional deformation suggests that the initiation of the Andean orogeny was related to global or at least continental-scale processes. A link between the initiation of compressional tectonics in the Andes and the final disconnection between South America and Africa during the opening of the South Atlantic ocean has been proposed by several authors (e.g., Mpodozis and Ramos, 1989; Jaillard et al., 2000). Furthermore, according to Somoza and Zaffarana (2008), the change from extensional to compressional conditions in the present Andean region would be related to a global plate reorganization which took place in the Mid-Cretaceous and resulted in an increase in the westward drift of South America since Late Cretaceous times. The scenario which arises from investigations across the whole Andean range supports this hypothesis.

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