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Neuquén Group (Upper Cretaceous): A case of underfilled-overfilled cycles in an Andean foreland basin, Neuquén basin, Argentina

Estefanía Asurmendi [a, b, *], María Lidia Sánchez [b], Lucas Fennell [c]

[a] *CONICET- Consejo Nacional de Investigaciones Científicas y Técnicas, ruta nacional N°36, Km 603, Río Cuarto, Córdoba, Argentina*

[b] *UNRC - Departamento de Geología, Universidad Nacional de Río Cuarto, ruta nacional N°36, Km 603, Río Cuarto, Córdoba, Argentina*

[c] *Laboratorio de Tectonica Andina, Instituto de Estudios Andinos Don Pablo Groeber, CONICET-Universidad de Buenos Aires, Ciudad Autónoma de Buenos Aires, Argentina*

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A B S T R A C T

The Nenquén Group was deposited during a period dominated by the Cretaceous Greenhouse and can be divided in three cycles correlated with large-scale changes in the evolution of the Andean foreland basin. The filling of the Neuquén Group is constituted by a complete cycle and two incomplete cycles of underfilled-overfilled, separated by first-order discontinuities assigned to the uplift of the Agrio fold-and-thrust belt during the Chasca/Catequil, Mid Ocean Ridge (CCMOR) collision, coinciding with first-order climatic changes within the Cretaceous greenhouse cycle.

The Candeleros Formation in the base of this group was deposited in late underfilled conditions, showing prominent forebulge zones. It is demonstrated that during the Albian, with the cratonward migration of the uplifting forebulge zones, the axis of backbulge zones also migrated cratonwards and a wide uplifted forebulge zone was formed. On top, the Huincul Formation was deposited in an overfilled period without orogenic load, while the Cerro Lisandro Formation was deposited in early underfilled conditions with orogenic load. The Río Neuquén Subgroup started with a late underfilled period (Portezuelo Formation -second-order discontinuity), and after wards the Plottier Formation was deposited in an overfilled period without orogenic load. Finally, the Río Colorado Subgroup was deposited under late and early underfilled conditions (Bajo de la Carpa and Anacleto Formations respectively).

1. Introduction

The Neuquén Basin lies in north-western Patagonia, on the eastern foreland of the Andes (Fig. 1). The Neuquén Basin started as a northwest-rifting system during the Triassic and evolved from a back-arc basin during the Mesozoic with a complex tectonic history (Digregorio et al. , 1984; Legarreta and Uliana, 1999) to a foreland basin during the Late Cretaceous (Ramos, 1981; Tunik et al., 2010). The geometry of a foreland basin is the product of a complex dynamic balance between the orogenic loading, erosion and sedimentation, and lithospheric flexural response.

In foreland basin system, unconformities and their correlative paraconcordances with internal arrangements are the response to the complex interplay of thrust tectonics and regional dynamic topography which dominate the logic of the analysis of its filling. In the case of the Neuquén Group, the consideration of tectonic activity during its synorogenic deposition is critical, because of its relation with the geometry of its depocenters and the variations of its filling. Tectonic is the cause of the vertical movements of large amplitude in the deep basin, near the thrust front, generating an accommodation space that contrasts with more subtle evidence of subsidence in the neighbor region the craton (Liu et al., 2005).

A direct correlation between orogenesis and basin styles has been generally accepted, i.e., orogenic loading (synorogenic) and unloading (postorogenic) periods correlating with and underfilled overfilled basin, respectively (Yang and Miall, 2010; Yang, 2011). Jordan and Flemings (1991) suggested that during episodes of tectonic quiescence, sediment loading in the proximal foredeep zone causes cratonward migration of the foredeep and forebulge. High resolution stratigraphic studies should take into account the basic concepts of accommodation/supply (Martinsen et al., 1999; Catuneanu et al., 2009) for the resolution of paleoenvironmental models, since they define the underfilled and overfilled conditions in the basin (Yang and Miall, 2010; Yang, 2011; Sánchez and

* Corresponding author. Universidad Nacional de Río Cuarto, CONICET – Departamento de Geología, Facultad de Ciencias Exactas Fco.- Qcas y Naturales, Ruta Nac. N° 36 km 603, Río Cuarto, Córdoba, Cod. Postal 5800, Argentina.

E-mail address: easurmendi@exa.unrc.edu.ar (E. Asurmendi).

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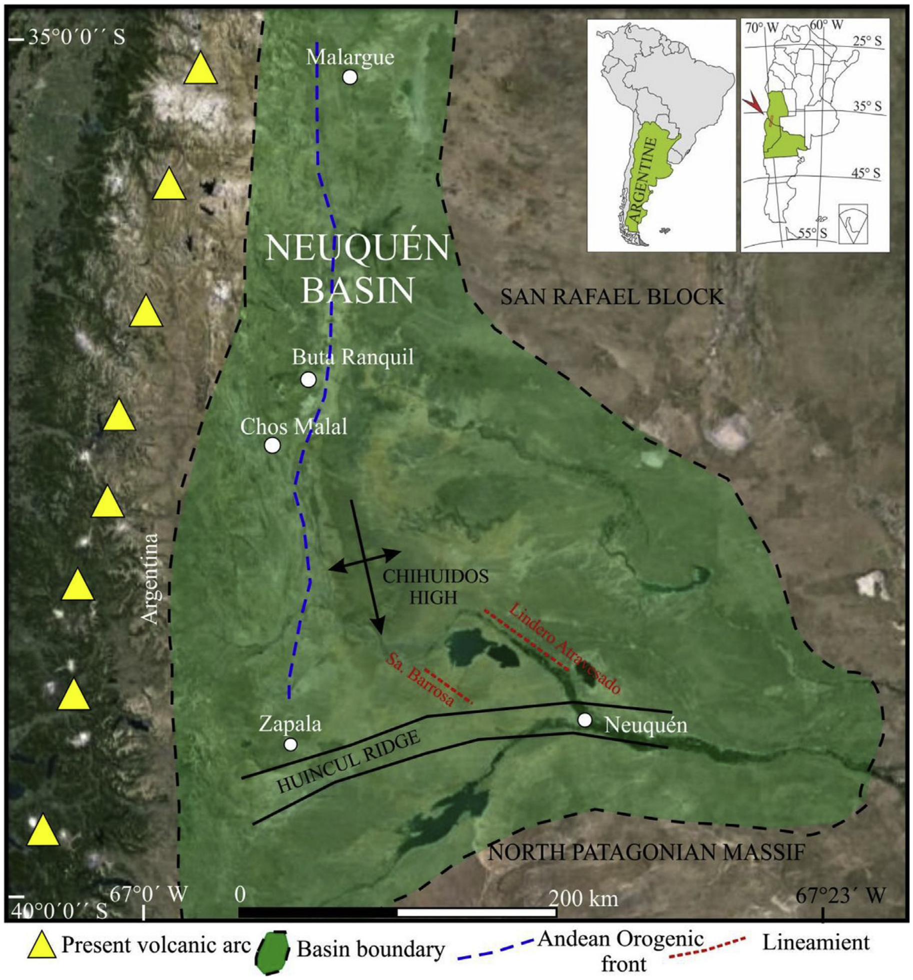


Fig. 1. Location map of the Neuquén basin with the main morphotectonic features.

Asurmendi, 2011, 2016; Sánchez and Asurmendi, 2015; Asurmendi, 2016). The identification of stratigraphically significant discontinuities (unconformities), which in most cases, are diachronic along basins and observed on a large scale and, facilitate the understanding of the evolution of the basin filling. In recent years, the advance in the knowledge of the dynamics and kinematics of the Neuquén Group foreland basin system has improved considerably, due to the multiplicity of scientific approaches applied to its study. The geotectonic framework of the basin has been defined quite accurately by many authors, and much is known about the implication of the tectonics in the dynamics and kinematics of the deformation once generated the Andean foreland basin (Cobbold and Rossello, 2003; Ramos and Folguera, 2005; Sánchez et al., 2008a,b; 2013, 2014; Sánchez and Asurmendi, 2014, 2015; Fennell et al., 2015). This includes detailed studies of the orogenic front, the Huincul ridge and the Chihuidos High (Vergani et al., 1995; Franzese and Spalletti, 2001; Cobbold and Rossello, 2003; Ramos and Folguera, 2005; Franseze et al., 2006; Mosquera and Ramos, 2006; Silvestro and Zubiri, 2008; Zamora Valcarce et al., 2009; Pángaro et al., 2009; Folguera and Ramos, 2011) and some studies of zircon U-Pb dating have also contributed (Aguirre Urreta et al., 2011; Tunik et al., 2010; Fennell et al., 2015; Di Giulio et al., 2012, 2015). However, the detailed evolution of this foreland basin remains unsolved.

In this paper we propose a geological model of the evolution of the filling of the Andean foreland basin for the period of deposition of the Neuquén Group, taking into account the stratigraphic studies of high resolution (Sánchez et al., 2005, 2008a,b,c; 2010a,b, 2013; Sánchez and Asurmendi, 2014, 2015) and the evaluation of the allocyclic factors (tectonics and paleoclimate). Also, we will present the first detailed geological map of the Neuquén Group in the central region of the Neuquén basin (Figs. 1 and 2).

2. Methodology

For this work, the stratigraphically significant surface (unconformities – Martinsen et al., 1999) were analyzed using a different approach, from high resolution stratigraphy studies (Sánchez et al., 2005, 2008a,b,c; 2013; Sánchez and Asurmendi, 2014, 2015; Armas, 2012; Asurmendi, 2016), where tectonics and climate are important controls. Also, the results of the dynamics of the of foreland basin system were contrasted with theoretical models related to the migration of the peripheral bulge (Sigismondi, 2012), which resulted an efficient support for the definition of the stratigraphic sequence and the dynamics of the different depozones.

Little has been taken into account and scarce is the consideration of one of the first-order allocyclic controls, the paleoclimate. This control has been referred only as part of paleoecological or taphonomic analyses (Salgado et al., 2007), or from the sedimentological and stratigraphic point of view, based on the functioning of the depositional systems that integrate the Neuquén Group and its sequence stratigraphic relations (Sánchez et al., 2006a,b, 2008a,b,c, 2009, 2010a, 2014; Armas, 2012; Sánchez and Asurmendi, 2014, 2015; Asurmendi, 2016).

The tectonic processes, which result in the variation of the size and distribution of the continental masses, are useful to explain the paleoclimatic records, since they operate in a suitable time scale and generate large relative changes in the surface of the earth that correlate with the first order cycles (Donnadieu et al., 2006). Tectonics is an allocyclic control related to paleoclimatic changes and is essential in the definition of high resolution stratigraphy to define cycles in the Neuquén Group.

The Cretaceous is a period characterized by high mobility of the plates resulting from the Pangea breakup (McElwain et al., 2005). In particular, rapid expansion initiated in the Aptian (124 Ma) and reached to the Albian (83 Ma), resulting in changes in the continental configuration and a significant increase in the production of oceanic crust.

3. Geological setting

The Neuquén Basin is located on the eastern side of the Andes in Argentina and central Chile, between 32° and 40°S latitude (Fig. 1). This comprises a Late Triassic to Early Cenozoic succession including continental and marine siliciclastics, carbonates and evaporites that accumulated under a variety of basin styles (Uliana et al., 1995; Legarreta and Uliana, 1999). The majority of the basin's hydrocarbon fields are located in the Neuquén Embayment (Bracaccini, 1970) where most of the Mesozoic sedimentary record is in subsurface and the strata are relatively undeformed. On the other hand, in the Andean region, Late Cretaceous and Cenozoic deformation has resulted in the development of a series of N-trending fold and thrust belts (i.e Marlargüe and Agrio fold-and-thrust belts – Yrigoyen, 1972; Rojas Vera et al., 2014). This geotectonic framework and the highly complex history of the basin are largely controlled by changes in the tectonic regime on the western margin of Gondwana in the Cenomanian and in the Miocene, two periods of shallow dipping subduction zone resulted (Spagnuolo et al., 2012; Ramos and Folguera, 2005; Folguera and Ramos, 2011) resulted in compression and flexural subsidence, associated with 55–11 km of crustal shortening (Giambiagi et al., 2012; Rojas Vera et al., 2014) and cannibalization of the foreland basin. The Andean foreland basin comprises a continuous stratigraphic record up to 1300 m of synorogenic sediments, including the Neuquén Group deposits. The Late Cretaceous stage was characterized by eastward contraction in the Agrio fold-and-thrust belt, which caused the low-angle intra-Cenomanian unconformity at the top of the Rayoso Formation and the synorogenic deposition of Neuquén Group (Legarreta and Uliana, 1998). The U/Pb age of detrital zircons of the Candeleros Formation (98 Ma; Tunik et al., 2010; Di Giulio et al., 2012) suggests that the deformation of the Agrio fold-and-thrust belt began after 98 Ma Knowledge over the last years about the Agrio fold-and-thrust belt dynamics and kynematics and zircon dating studies have provided abundant information (Cobbold and Rossello, 2003; Corbella et al., 2004; Ramos and Folguera, 2005; Zamora Valcarce et al., 2009).

The Upper Cretaceous strata (Neuquén Group) in the Cordilleran foreland basin has been subdivided into underfilled and overfilled cycles generated during repeated changes in the tectonic load (Sánchez and Asurmendi, 2016). The Neuquén Group (Table 1) is subdivided into the Río Limay, the Río Neuquén and the Río Colorado Subgroups (Ramos, 1981). The Río Limay Subgroup represents the initial stage of the sedimentation of the Neuquén Group, its thickness extends for 350 m, its age is Cenomanian-early Turonian (Rodríguez et al. 2007), and its composed by the Candeleros, Huincul and Cerro Lisandro Formations. The Río Limay Subgroup consists of fluvial, aeolian, lacustrine and deltaic deposits accumulated in the Neuquén foreland basin (Sánchez et al., 2009, 2008a,b,c, 2010a; Sánchez and Asurmendi, 2011, 2014, 2015; Asurmendi and Sánchez, 2014a; 2014b).

The Candeleros Formation has its type locality east of the Cerro Lotena in the southern province of Neuquén and its maximum thickness is approximately 300 m. The sequence in the type locality is interpreted as deposits of braided fluvial systems associated with muddy floodplain deposits with development of paleosols (Herrero Duclox, 1946; Leanza and Hugo, 1997; Garrido, 2000) and terminal fan deposits (Sánchez and Cardozo, 2002; Sánchez and Asurmendi, 2014). Whereas, near the El Chocon dam Spalletti and Gazzera (1994) mentioned the presence of aeolian and beach-lake deposits.

The Huincul Formation has its type locality is in Plaza Huincul and its thickness varies between 50 and 250 m. The formation overlaps concordantly with the Candeleros Formation, presenting a net and markedly erosive contact (Rodríguez et al. 2007; Garrido, 2010). The Huincul Formation has been characterized by low sinuosity fluvial system with sandy and gravel-sandy for the upper section, while for the lower one it has been interpreted as meandering muddy-load river systems (Gazzera and Spalletti, 1990).

The Cerro Lisandro Formation presents its type locality in the Cerro Lisandro in the vicinity of Senillosa and its thickness varies between 35 and 75 m. The Cerro Lisandro Formation is arranged in conformable relation on the underlying Huincul Formation, being overlapped transitional by deposits of the Portezuelo Formation. Cazau and Uliana (1973) indicate for this formation condition of alluvial deposit of moderate to low energy. Leanza and Hugo (2001) indicate a connection with distal mud flats of fluvial systems. The predominance of fangolites in the deposits of the Cerro Lisandro Formation suggests, then, a low energy fluvial environment; where the sandy intercalations reflect the sporadic action of stronger currents, which towards the top of the unit acquire greater relevance (Rodríguez et al. 2007).

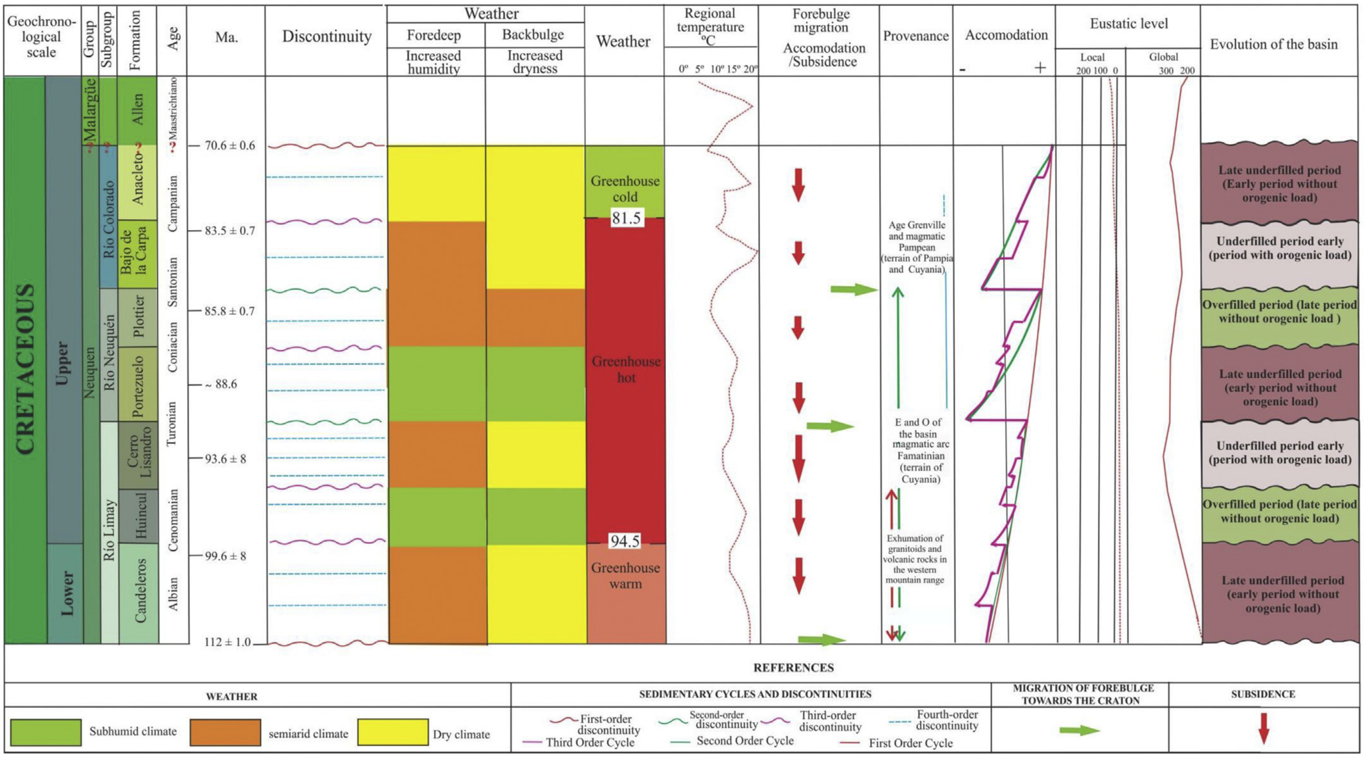
The Río Neuquén Subgroup consists of fluvial deposits accumulated in the Neuquén foreland basin (Sánchez and Heredia, 2006; Sánchez et al., 2010b, 2005, 2008d; Sanchez et al., 2014).

The Portezuelo Formation presents its type locality in the Sierra de Portezuelo western of the city of Plaza Huincul and is in concordance and transitional with the underlying Cerro Lisandro Formation (Rodríguez et al. 2007; Garrido, 2010). The Portezuelo Formation is made up of deposits of fluvial origin, dominated by lithology in the eastern sector of the basin and greater proportion of shales towards the western, in more central positions (Cazau and Uliana, 1973). The installation of a river system with these characteristics points to a rejuvenation of the eastern sector, where a wide descent was developed in the distal part of which deposited the pelitic facies in an extensive alluvial plain (Ramos, 1981), while Danderfer and Vera (1992) interpreted the environment as an anastomosed fluvial system, which gradually becomes alluvial plain sediments. On the other hand, Garrido (2000) interpreted for this unit a typical meandriform fluvial system of sandy load.

The Plottier Formation, with a thickness of 25 m and is type's locality has been established in the proximities of the city of Plottier on the bardas located to the north of this locality. The Plottier Formation relies on transitional contact on the sandstones of the Portezuelo Formation (Rodríguez et al. 2007; Garrido, 2010). The sedimentary rocks of the Plottier Formation respond in their origin to low energy conditions (Cazau and Uliana, 1973), while Ramos (1981) interpreted that the pelitic facies of this unit reflect deposition in a broad alluvial plain with little relief.

The Río Colorado Subgroup consists of fluvial, Aeolian and estuaric deposits accumulated in the Neuquén foreland basin (Sánchez and Gómez, 2005; Sánchez and Armas, 2008; Armas and

Table 1
Chronostratigraphic table of the Neuquén Group compiled from the data of Huber et al. (2002); Ramos and Folguera (2005); Ramos (2008); Aguirre-Urreta et al. (2011); Tunik et al. (2010) and Di Giulio et al. (2012).



Sánchez, 2011; Sánchez et al., 2006a, 2008a; 2011; 2013; 2016). The Bajo de la Carpa Formation, its type locality is located in the Bajo (or Aguada) de la Carpa, the outcrops are approximately 50 m thick and are located in the upper part of the fence, supported in conformable relation on the fangolites of the Plottier Formation. The unit has been interpreted as the result of the deposition of river systems with low sinuosity and abundant sandy bedload (Garrido, 2000). However, in the outcrops of the city of Neuquén the inferior sandy packages have an aeolian origin. Heredia and Calvo (2002) interpreted these same rocks as dune facies and interdune wet of distal floodplain with the presence of ephemeral interlaced fluvial systems associated with aeolian dune deposits.

The Anacleto Formation presents its type locality in the hill Senillosa, in the vicinity of the Aguada de Anacleto with a thickness of 42 m (Rodríguez et al. 2007). The upper limit of the formation and therefore of the Neuquén Group, was defined as a surface of erosive stratigraphic discontinuity (Andreis et al., 1974; Digregorio and Uliana, 1980; Uliana and Delapé, 1981; Legarreta et al., 1989), attributed to a process of marked subsidence that allowed the development of the first Atlantic transgression in the Neuquén basin (Uliana and Dellapé, 1981; Uliana and Biddle, 1988). This discontinuity was called Huantráiquica (Rodríguez et al., 2007) and the erosive effects of it tend to decrease towards the center of the basin (Uliana and Dellapé, 1981). The Anacleto Formation is interpreted as low energy river systems, with river courses diverting from extensive alluvial plains (Cazau and Uliana, 1973; Ramos, 1981; Hugo and Leanza, 2001; Rodríguez et al. 2007). In the top of the formation have been identified estuaric deposits, associated to the first Atlantic transgression (Andreis et al., 1974; Barrio, 1990; Rodríguez et al. 2007).

4. Paleoenvironments of the Neuquen group

The deposits of the Neuquén Group corresponding to the wedge top within the foreland basin system (DeCelles and Giles, 1996) were identified in the north of the Neuquén basin, near Ranquil Co, Sierra de Palaoco and Bardas Blancas; in the south of the province of Mendoza. The Neuquén Group here presents wedge geometries forming growth strata associated with levels of seismites (Tunik et al., 2010; Fennell et al., 2015).

At the N-W of the Huincul ridge (Figs. 1 and 2), the sequence begins with the deposits of the Río Limay Subgroup (Late Albian-Early Turonian), which lies on an first-order angular discontinuity on top of the Rayoso Formation, representing an excellent exposure at the foot of the Agrio fold and thrust belt. The development of growth strata has been identifies with dips that vary from 45° in the base to 29° in the Candeleros Formation (Sánchez and Asurmendi, 2014). On the other hand, in the NNW sector (southern Mendoza province), the basal unit of the subgroup is absent and the Huincul Formation is in contact with the Rayoso Formation. In contrast, in the Chihuidos High, a forebulge region, the Candeleros Formation is in contact with the Rayoso Formation through an angular discordance of 20° (Fig. 1).

The Candeleros Formation shows relative variations of thickness, varying from 35 m in the Chihuidos High, 367 m to the west and 102 m to the north and south of the Huincul Ridge (Figs. 1 and 2). In the zone of the Payún volcanic plateau subsurface date show, the Candeleros Formation lying on top of Rayoso Formation. Here, its thickness oscillates between 92 and 203 m in a 15 km N-S directed section, and between 92 and 72 m in a E-W direction (Asurmendi and Sánchez, 2014a,b; Sánchez and Asurmendi, 2015).

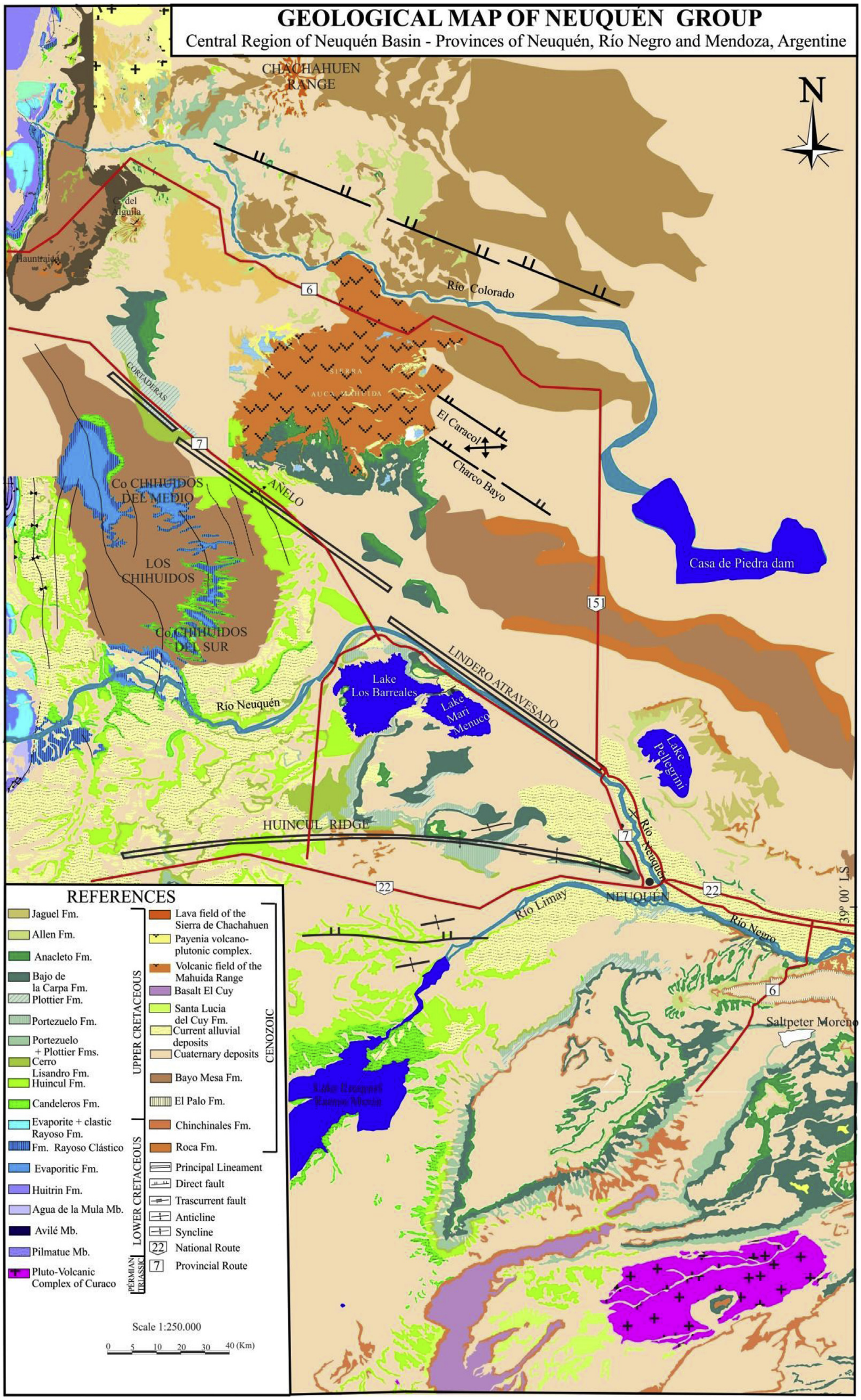


Fig. 2. Geological map of the central region of Neuquén basin with special detail in the Neuquén Group.

The Candeleros Formation depositional paleoenvironments are represented mainly by terminal fans with fields of barchan dunes (Sánchez, 2004; Sánchez and Cardozo, 2002; Sánchez and Asurmendi, 2015, 2016). On top of the Candeleros Formation, a regional third-order discontinuity is identified, over which the Huincul Formation is deposited (Table 1). This discontinuity is highlighted, marked by profuse erosion, a sharp increase in the participation of coarser facies compared to the channel fillings of the lower units and intense nesting of the channel belts. These changes are related to a period of tectonic stability and a notable increase in precipitation (Sellwood and Valdes, 2006; Carvalho et al., 2010; Hu et al., 2012) that induced drastic changes in the depositional systems as a consequence of a decrease in the Accommodation/Supply (A/S) ratio.

In the western sector of the basin the contact with the Huincul Formation is through discordance, whereas towards the boundary of the craton and the vicinity of the forebulge, this discordance has erosive character. Tectonic activity during the deposition of the Huincul Formation is evidenced by the presence of growth strata, whose dips vary in inclination from 28° to 18° towards ENE and E. The Huincul Formation shows variations in thickness in different sectors of the basin, from 150 m to the north and west of the Chihuidos High, 27 m in the region of the High and 36 m to the south of the Huincul ridge.

The depositional systems that integrate the Huincul Formation are dominated by high sinuosity fluvial systems with strong aggradation channel belts. These belts frequently preserve the roof and the style of avulsion at the base is gradational, generally affecting large overflow fans. The system shows stacking of the channel units, slight multilateral relationship and poor preservation of floodplain deposits. The local preservation of the surfaces of the scrolls and the bedsforms that migrate in the floor of the channel, together with the deformation of the frontal surfaces of the mesoforms, suggest highly aggradational channels and high discharge of water (Sánchez et al., 2006a,b, 2008a; 2009; Sánchez and Asurmendi, 2011).

Over a fourth-order discontinuity identified in the middle section of the Huincul Formation (Table 1) an increase in floodplain deposits generated by decantation is observed, marking a change in the fluvial system towards an abrupt stratigraphic style of avulsion with oblique aggradation and relation of multilateralism and, locally, stacking. This is associated with a noticeable decrease in the A/S ratio due to the increase in the channel/flood ratio. It is represented by channels of high sinuosity aggradation with an increase in the contribution of volcaniclastic material and the development of thick successions of flood plain.

At the end of the deposition of the Huincul Formation there must have been a strong re-accommodation of the base level of the basin, which is inferred from the identification of marked areas of erosion and profuse incision of valleys in the eastern sector of the basin (Fig. 1). The Cerro Lisandro Formation is deposited over this extensive erosive third-order discontinuity (Table 1), which is identified throughout the basin, west of the Chihuidos High and near the craton. The thickness of the formation varies from the foredeep to the forebulge and backbukge basin from 86 m to 18 m–44 m, respectively.

Three fourth-order discontinuities associated with autocyclical factors of the depository systems have been identified (Table 1). The Cerro Lisandro Formation records the peak of subsidence during the deposition of the Río Limay Subgroup, since during this period there was a sharp change in the base level in the western sector of the basin (foredeep). In this sector, an increase in the accommodation space generated an ENE-WSW lacustrine catchment basin at a regional level, whose mínimum extensión, corroborated by surface and subsurface data, reached 75 km in a N-S direction and 17 km in a E-W direction. Outcrops of the marginal facies of the lake have been observed in the Colorado River area, represented by important levels of calcretes, gypsum and development of paleosols. The development of this lacustrine system constituted a local base level for river systems draining large areas in the zone of greater subsidence of the foreland. This perennial lacustrine system underwent repeated contraction and expansion events and Gilbert-type deltas were developed, preserving the tripartite depositional architecture (top, front and base), and extensive mouth lobes on its western and southern edge. The deltaic system presents a lobed morphology, which registers numerous phases of aggradation and progradation towards the E and N-E (Sanchez and Asurmendi, 2014).

In the eastern area, the Cerro Lisandro Formation presents a radical change in the depositional style. Although the basal third-order discontinuity is planar (Table 1), an erosive contact surface has been locally between the Huincul and Cerro Lisandro Formations, both in subhorizontal position, indicating a profuse incision and expansion of the wind dune field. In the sector closest to the craton, the Cerro Lisandro Formation begins with the development of a terminal fan system. The first deposits of this fan system correspond to a medium distributary plain environment. Afterwards, a fluvial flood surface is interpreted as a discontinuity, which points to the expansion of the system associated with an abrupt increase in the space of accommodation and rapid progradation of the distal facies. On the other hand, in the Huincul ridge a low sinuosity fluvial system was being developed, which suggests an increase in the subsidence rate during the beginning of the deposition of the Cerro Lisandro Formation, which is also evidenced, although diachronic, in the western edge.

The terminal fan deposits are covered with a humid aeolian system (Sánchez and Cardozo, 2002). The development of a field of parabolic dunes associated with environments of dry, wet and flooded interdunes indicates a progressive rise in the water table, which eventually remained above the depositional surface generating very shallow lagoons. Short-term climatic changes related to an increase in precipitation and the relative water table position controlled the development of stabilization and growth surfaces (Kocurek and Havholm, 1993) and the migration of wind forms.

A fourth-order discontinuity (Table 1), identified as Super-Superperfaces (Kocurek and Havholm, 1993) is associated with dune field migration, which can be assigned to periods related to an increase in the supply or availability of climatically conditioned sediments. Periodically, interdune corridors were invaded by ephemeral rivers during flood events. They are associated with flood basin environments of the terminal fan system. The characteristics of the systems involved, dune field and terminal fan, suggest a climatic change to semi-arid and low gradient conditions in the depositional environment (Sánchez and Cardozo, 2002; Sánchez et al., 2016).

A new major fluvial flood event interbedded with the aeolian deposits is evidenced by terminal fan deposits in facies from flood basin to distal distributary plain with development of interlaced channels, indicating the progradation of the system. The identification of tabular strata, which represent the stacking of channel units with multiepisodic filling, are gradually replaced towards the top by thick low sinuosity channels of that reflect a greater proximity to the trunk network of the system and correspond to a progradation event of the terminal fan (Sánchez and Cardozo, 2002; Sánchez et al., 2016).

These deposits are covered by a new field of transverse dunes in which two Super-Surfaces (two fourth-Order discontinuity) are identified (Table 1). The succession is covered by a fluvial flood surface on which a progradant terminal fan sequence is identified. It is considered that the semiarid climatic conditions remained stable during the deposition of the Cerro Lisandro Formation.

The Río Neuquén Subgroup lies on an erosive regional second-order discontinuity the Río Limay Subgroup (Table 1) that is recognized in the whole basin. This subgroup presents thicknesses that vary from 183 to 92 m to the north and east of the Huincul ridge, while in subsurface in wells located to the south of the locality of Malargüe, the thicknesses vary from 114 m to 57 m from north to south.

The Río Neuquén Subgroup begins with the deposition of the Portezuelo Formation and it is characterized in the eastern sector of the basin by to the existence of progressive unconformities that also affect the overlying Plottier Formation (Sánchez et al., 2008c, 2014). It comprises fluvial deposits characterized by a general tendency towards avulsion deposits, high complexity of the high and low sinuosity channel belts with notable changes in the lateral to oblique aggradation style (Sánchez et al., 2014; Rajchl and Uličný, 2005).

The basal section of the Portezuelo Formation is dominated by conglomerate and subordinately sandy systems with high sinuosity. These are aggradant systems with a lateral aggradation towards the ENE (to the east of the Huincul ridge) in a general sense probably controlled by the depositional gradient of the basin (Sanchez et al., 2014).

Towards the roof of the Portezuelo Formation there is a fourth-order discontinuity (Table 1) related to a notorious decrease in the relation between channel deposits and floodplain. The channel belts correspond to gravel and sandy low sinuosity river systems, being the first dominant along the succession. The Portezuelo Formation represents a stage of changes in the source area, showing a substantial increase in the proportion of coarse clastics with respect to the infra and overlying units, possibly associated with the migration and erosion of the forebulge (Sanchez et al., 2014).

A erosive third-order discontinuity (Table 1), in some cases of high relief to the east of the Huincul ridge and a radical change in the depository system signal the beginning of the Plottier Formation. This unit is represented by sandy-conglomerate/sandy low-sinuous systems, which shows an oblique aggradation style with high connectivity (Rajchl and Uličný, 2005), where the floodplain was affected by numerous flood events. These fluvial systems were characterized by a strong aggradation of fine deposits in the floodplain with periodic events of flow in mantle and the development of shallow channels, limited in their migration by the cohesion of the banks. Avulsion deposits were related to a great magnitude flood events (Sánchez et al., 2014).

The river systems in the vicinity of the craton show similarities, although the vertical aggradation of the systems is characterized by extensive lapses of inactivity during which the colonization and activity of organisms generated in some cases the mixture of materials in the deposits and obliteration of the primary sedimentary structures of complete channel units.

A fourth-order discontinuity is observed towards the top of Plottier Formation (Table 1), given by a change in the conditions of water supply and sediments, which the development of more extensive and powerful channels with avulsion events, possibly related to changes in the slope of the main channel for fast aggradation. In the top sandy high-sinuosity systems dominate, where the channel belt stacking and the sparse preservation of flood plain deposits suggest a progressive increase in the sediment supply/accommodation space ratio.

The Río Colorado Subgroup is deposited above a second-order regional discontinuity over the roof of the Río Neuquén Subgroup (Table 1). This discontinuity presents planar geometry to the north of the Huincul ridge, while to the east of the ridge it is erosive. The Río Colorado subgroup begins with the Bajo de la Carpa Formation, with thickness ranging from 80 m to 40 m north of the Huincul ridge and decreasing to 35 m in the vicinity of the craton. In subsurface, in wells to the south of the locality of Malargüe the thickness varies from 67 m to 41 m from north to south.

The base of the Bajo de la Carpa Formation begins with fluvial deposits where the channel belts near the Chihuidos High developed of avulsion abrupt stratigraphic style with low connectivity of the units configuring a system with characteristics comparable to ephemeral fluvial systems and a pattern of oblique aggradation with low connectivity.

To the north of the Huincul ridge, the Bajo de la Carpa Formation is represented by an ephemeral fluvial system in proximal facies characterized by the development of a network of shallow channels related to high energy and low frequency flows that alternate with floodplain deposits, with permanent interference by flow events in sheets. The identification of compound paleosols and numerous mantle flow events in the floodplain confirm conditions of rapid aggradation. This fluvial style is characteristic of regions with semi-arid climate (Sánchez et al., 2006a,b; Marshall, 2000).

To the east of the Huincul ridge, the channels of high sinuosity dominate, and the floodplain does not present without changes in the avulsion pattern but with a remarkable increase in the connectivity of the channel bodies. The channel deposits are strongly bioturbated and preserve rhizoconcresions. The preserved floodplain is constituted by an alternation of very fine sandstones and sandstones in which levels of overflow and volcaniclastics are interbedded. The meandering belt extended for more than 200 m and the meander cut mechanism was dominant. Overflow deposits extend for more than 50 m. A level of seismites is recognized at the base of the Bajo de la Carpa Formation (Sánchez et al., 2013).

An ESE directed transect, north of the Huincul ridge that extends for about 70 km, periodically affected by the action of ephemeral fluvial currents. The dune field remained stationary, while the periods of expansion and contraction of the margins were controlled by short term climatic variations, sediment supply or river system interference. Data suggesting that dune deposits have been characterized by long periods of migration include the consistent orientation of their interlocking strata and the overlapping of successive dune deposits over extensive truncation surfaces with paleosols.

Towards the craton, the deposits of high sinuosity fluvial systems are dominant. The channel bodies are relatively narrow (little more than 300 m wide), stacked to form the belt that represents the individual migration of each of them through time and space. The bodies are linear, extending with a general NE-SW orientation within floodplain deposits with a lateral migration pattern. The overflow fans extend for more than 300 m, developing an abrupt stratigraphic style that is attributed to regional avulsions and to the re-localization of the channels in topographical depressions from the periods of expansion of the flow on the floodplain. A fourth-order discontinuity of the is evidenced by a new cycle within the Bajo de la Carpa Formation (Table 1), which is marked by a change in the avulsion pattern of the fluvial systems and erosion surface of in the aeolian deposits considered as Super-Surface (Kocurek and Havholm, 1993) or a limiting surface of regional character (Sánchez and Gómez, 2005; Sánchez et al., 2016).

Near the of Huincul ridge, the records of evolution stages of the channel belts appear isolated within an environment dominated by deposits of floodplain. The fluvial system has aggradation pattern migration and the channels are not very powerful (2 m thickness). Overflow fans strongly affect the substrate and have a lateral extension of more than 400 m, with triangular forms that are rapidly thinning. A second level of seismites) is recognized in the top of the formation associated with the migration of the orogenic front (Sánchez et al., 2013).

A second-order discontinuity of is recognized in the top of the Bajo de la Carpa Formation of the on which lies the Anacleto Formation (Table 1). This unit has thicknesses between 40 and 50 m approximately in the north area of the Huincul ridge and decreases between 33 and 9 m to the east of the ridge. In general the sequence presents a dip of 4° to the east. In the subsurface, to the south of the locality of Malargüe, the thicknesses vary from 88 m to 45 m from north to south.

The Anacleto Formation in the northern region of the Huincul ridge presents a marked differentiation with respect to the great scale architecture and the fluvial design of the deposits of the Bajo de la Carpa Formation. The unit is formed by a succession of conglomerate-sandy high sinuosity channels, nested and with frequent overflows. During the floods the parental channel, downstream of the avulsion, narrowed as the flow diverged in the fan complex. As the flow expanded into overflow lobes, the large channels of the distributary spread in the floodplain. It is estimated that the processes of high discharge were seasonal and in pulses, followed by the reinstallation of the channel. The result is a series of individual overlapping channel units with reduced width of the active belt, which is immersed in successive overflow fan deposits and with little preservation of the fine grain deposits of the floodplain. The stratigraphic style of avulsion is gradual and the migration pattern of the channel belts is lateral.

To the east of the Huincul ridge, this formation is characterized by a highly aggradation, low-sinuous, sandy-conglomerate fluvial system that exhibits a high channel/flood ratio that results from the strong stacking of the channel units. The conspicuous erosion of the river courses in the pre-existing deposits is reflected by the strong variations in the thickness of the succession. The initial fluvial erosion affecting different levels of the Bajo de la Carpa Formation was extremely deep, removing early cemented dunes and older systems representing an episode of base-level change and assigned to surface flood fluvial. Downstream towards the NE, this system can be correlated with a high-sinuosity fluvial system (Sánchez and Armas, 2008; Armas and Sánchez, 2011).

A fourth-order discontinuity (Table 1) evidenced by a marked climatic seasonality, which gave rise to successions with different styles of aggradation, transitional or abrupt, which correlate with regional or local floods in the basin, respectively (Jones and Hajek, 2007) and the lateral migration patterns of the channel belts were the result of the variations in the accommodation space (Martinsen et al., 1999; Rajchl and Uličný, 2005).

The WNW of the basin suffers an increase in floodplain deposits but there are no changes in fluvial design, a particular feature is the identification of fine-grained successions with important levels of intercalated paleosols and few small channels suggesting a distributary system that is associated with a low topographic flood that eventually was fed by overflows of the main channels.

To the east of the Huincul ridge, there is a sudden change in the fluvial style towards a sandy-muddy low-sinuosity system, of rapid aggradation, which presents a low channel/floodplain ratio. The subsidence foreland basin under conditions of base-level rise or changes in climate regime, are considered ideal frameworks for anastomosed fluvial systems (Makaske, 2001). An increase in the subsidence rate coupled with a rise in the baselevel under more humid climatic conditions could be responsible for the installation of the new fluvial design.

To the NNW of the locality of Neuquén province thick deposits of muddy supratidal plain environments of are observed, assignable to the head of a proximal estuaric system. This is evidence of the migration of the depositional environments of the estuary towards the continent, generating the classic expansive overlap that characterizes transgressive sequences (Armas and Sánchez, 2011; Armas, 2012).

It is inferred that an increase in the rate of subsidence, accentuated by the eustatic rise, allowed acceleration in the advance of the estuary towards the continent. The increase in the accommodation space, due to the combined effects of tectonics and eustasia, reaches its maximum expression in the development of a transverse ravinement surface that constitutes the boundary between the Neuquén Group and the Malargüe Group (first-order discontinuity-Table 1).

5. Geological model of the foreland basin system

During the Cretaceous, a suite of large igneous provinces was developed in the Paleo-Pacific Ocean, known as the Ontong-Java, Manihiki and Hikurangi plateau, associated with the redefinition of plate boundaries (Taylor, 2006; Seton et al., 2012; Fennell et al., 2015). This event resulted in the fragmentation of the Phoenix plate during the Aptian generating four new plates: Hikurangi, Manihiki, Chasca and Catequil. The interaction between the westward accelerating South American plate after the opening of the Atlantic Ocean, and the boundary between the Chasca and Cachequil plates (Chasca/Catequil, Mid Ocean Ridge - CCMOR) induced the shallowing of the slab and the consequent migration of the volcanic arc and orogenic front to the east. As a consequence, there was a decrease in volcanic arc activity and an increase in the contractional deformation between 35°30′-37°S. The installation of this strain-field together with the CCMOR collision at 105 Ma, established two important aspects: (i) extensive volcanic activity south of the horizontal segment of flat subduction, ii) rapid migration and/or shifting of the Agrio fold and thrust belt orogenic front. The result of these processes was the generation of a first order unconformity, known as the Patagonidic or Intersenonian unconformity (Albian/Cenomanian boundary; Groeber, 1929; Suero, 1951; Herrero Duclox, 1946; Ramos, 1988; Roll, 1941; Stipanicic et al., 1968; Leanza, 2009) and the formation of a system of well differentiated depozones in the foreland. The configuration and geometry of this basin system is the product of a complex dynamic balance between orogenic loading, erosion, sedimentation and lithospheric flexural response, generating a foredeep in the western part of the Neuquén basin, between the Chihuidos High and the Agrio fold-and-thrust belt, a forebulge, constituted by the Chihuidos High, and a backbulge in the eastern end of the Neuquén basin, onlapping over the stable craton to the east (Asurmendi, 2016 - Fig. 3).

The synorogenic deposition of the Neuquén Group took place above the first order unconformity in the top of the Rayoso Formation in most of the foreland basin system (Table 1; Fig. 3). The angular character of this unconformity is observable to the north and the west of the Chihuidos High. On the other hand, in southern Mendoza, southern Neuquén and near the Ezequiel Ramos Mexia lake, it constitutes an erosive unconformity.

The deposition of the Neuquén Group began with the extensive development of terminal fan and aeolian systems in the Albian (Candeleros Formation - Figs. 3 and 4, Table 1- Sanchez and Cardozo, 2002; Sánchez, 2004; Sánchez et al., 2004; Sánchez and Asurmendi, 2014). The depositional model is representative of the sedimentary record of a basin with discrete evidence of the presence of a forebulge, developed in overfilled conditions, after the first event of uplift in the fold and thrust belt. During the middle Albian, fluvial systems showed a very low gradient topography developed in extreme paleoclimatic conditions during smaller cycles, in which the dune fields operated under the control of occasional or episodic flood cycles.

The development of fluvial and aeolian systems was controlled by paleogeography and paleoclimate at the moment of its deposition. During this period, western Gondwana was characterized by

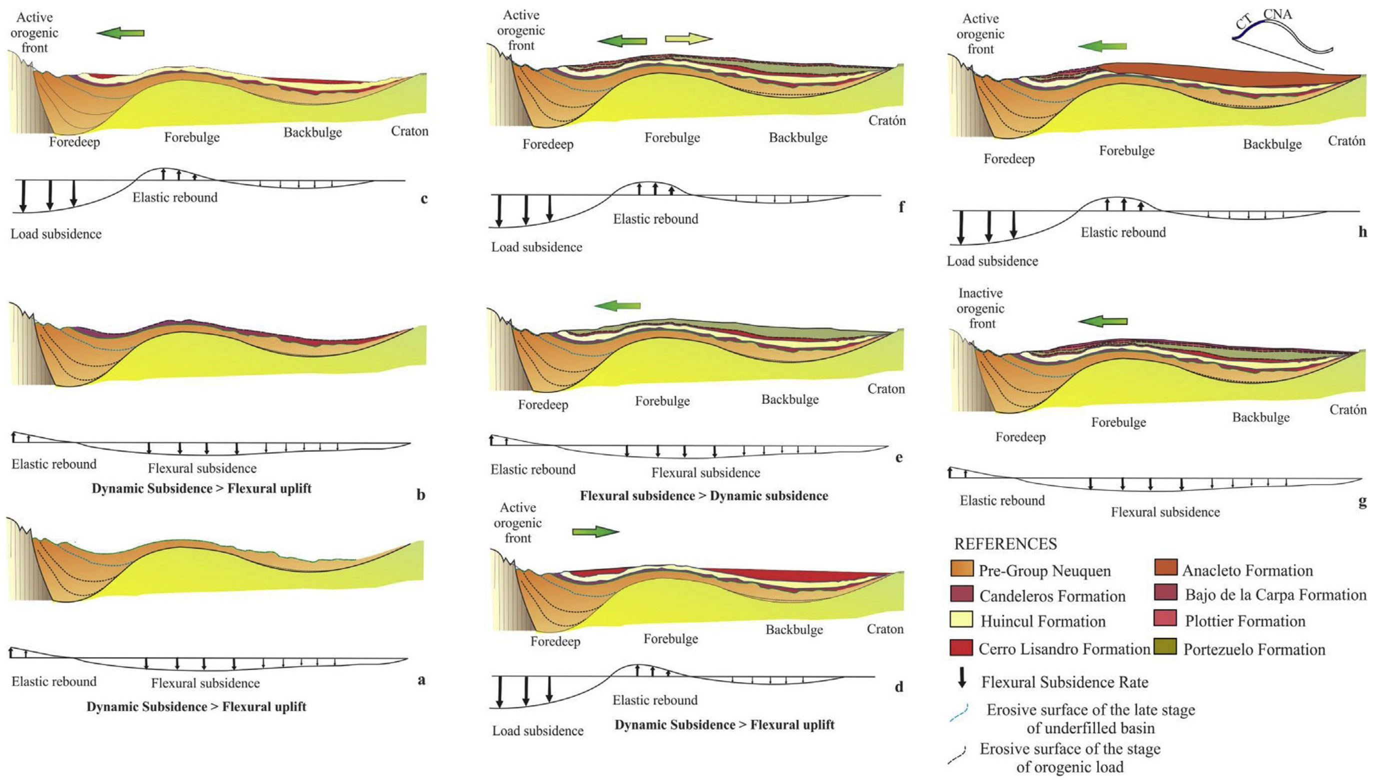


Fig. 3. Geological model of the Neuquén Group deposition.

the presence of a subduction margin towards the Pacific Ocean with an active volcanic arc, the development of a foreland basin in its initial stages and a mosaic of cratons bounded to the east by the Atlantic Ocean (Quattrocchio et al., 2011). Therefore, aridity was influenced by the distribution of continental masses and topography, which defined the distribution of paleoprecipitations and the location of deserts. The wide extent of the continental masses of Gondwana, at the beginning of its dismemberment, produced a more arid continental interior (Table 1). Even in the absence of mountains, the hot winds that flowed to the earth lost moisture, due to the warming propelled by the masses of upwarding air (Carvalho et al., 2010). There was a strong dependence on the water vapor content at the surface due to the high temperatures, in this manner, the increase in the evaporation capacity of the warmer air on the ground could not be compensated by the available humidity, which produced an overall heating and increased in continental aridity as a result (Wolfe and Upchurch, 1987; Hay, 1996; Price et al., 1998; Carvalho et al., 2010; Sánchez et al., 2005, 2006a,b; 2009). These climatic variations in the continental interior represent second-order climatic cycles, where the depositional systems were subjected to sporadic seasonal flood regimes, alternating periods of rain and drought along with a more arid continental interior (Ortega et al., 2000; Carvalho et al., 2010).

On a third-order regional discontinuity (Table 1), high and low sinuosity fluvial systems (Sánchez et al., 2006a,b, 2009; 2010a,b; Sanchez and Asurmendi, 2011, 2016) dominated the deposition dynamics during the Cenomanian (Huincul Formation - Figs. 3 and 5), both in the foredeep as in the forebulge and the backbulge. Here, the contemporary volcanic activity generated an

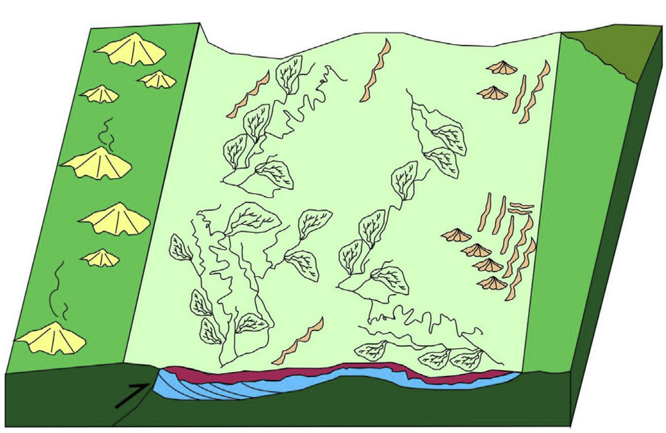


Fig. 4. Geological model of the Candeleros Formation. In the area of the foredeep this formation is represented by terminal fan systems and in the area of the backbulge it is a dominated by aeolian and fluvial systems.

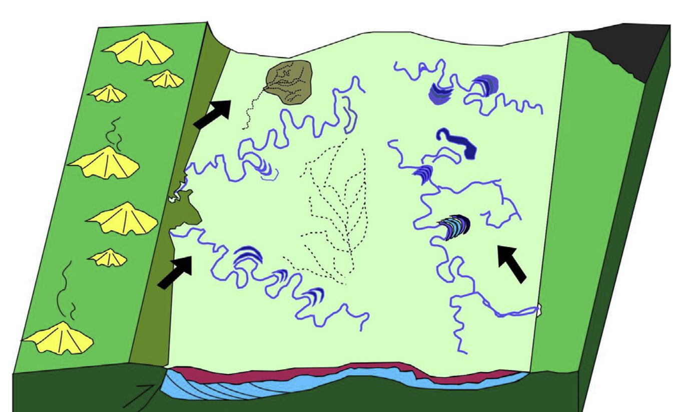


Fig. 5. Geological model of the Huincul Formation, represented by high and low sinuosity fluvial systems throughout the entire foreland basin.

important contribution of pyroclastic components in channel and intrachannel deposits and the development of volcaniclastic floodplains. The orogenic load and a slow advance of the Agrio fold and thrust belt flexured the lithosphere and controlled the dynamic subsidence, resulting in a third-order discontinuity (Table 1). At this stage the area of the forebulge locally ascended under the effect of erosion, the sediments were then deposited on the foredeep and backbulge (Huincul Formation). High supply of sediment allowed the accumulation and the progressive onlap on the forebulge under conditions of filled basin (Sanchez and Asurmendi, 2011, 2016, Figs. 3 and 5; Table 1).

During the late Cenomanian, an abrupt increase in subsidence forced the development of an ENE-OSO elongated lacustrine system in the deep basin over an erosive and regional discontinuity, (third-order discontinuity -Table 1), after wards in the early Turonian, large fluvial distributary systems developed Gilbert-type deltas (Sanchez et al., 2008a,b,c; Sanchez and Asurmendi, 2014; Cerro Lisandro Formation - Fig. 6, Table 1) in the west and north of the forebulge (Chihuidos High). In the Huincul ridge, fluvial systems of low sinuosity developed with important bars. Meanwhile, in the area of the backbulge (east and south of the Huincul ridge), a humid wind system resulted in the development of wet and flooded dunes and interdunes, with local establishment of lagoons in the windward of the large parabolic dunes in the marginal sectors of the erg. In its last stages it underwent an abrupt expansion and interacted with influenced the underlying fluvial deposits (Huincul Fomation) excavating extensive paleovalleys. This was the consequence of a progressive decrease in availability, possibly due to a climatic improvement. This scenario shows a substantial change in the configuration of the foreland basin system, with a clear differentiation of the depozones and a greater definition of the forebulge (Fig. 3). During this orogenic phase, the accommodation space migrated from the distal region of the basin to the proximal sector of the Agrio fold and thrust belt and this, leading to underfilled basin conditions (Table 1). With a decrease in the tectonic activity, a late period of underfilled basin began. The erosion of the fold and thrust belt and a small amplitude elastic rebound in the basin forced the migration of the accommodation space towards the foredeep region (Fig. 3). Therefore, the axis of subsidence migrated towards the craton, and the forebulge and backbulge areas advanced quickly in the same direction. This migration of the forebulge continued towards the craton and resulted in a strong erosion and cannibalization of the deposits previous of the backbulge basin, generating a diachronic erosion surface (second-order unconformity) in the basin.

Over this erosion surface, the fluvial activity generated thick deposits characterized by the dominance of thick clastics and the extensive development of fluvial networks, where the generation of crevasse splay was intense and frequent (Portezuelo Formation - Sanchez et al., 2008c; 2010b; 2014 - Table 1; Figs. 3 and 7). During this stage of underfilled basin (late Turonian), fluvial sedimentation spread fairly uniformly in the depositional dynamics along all areas of the foreland, as a consequence of the migration of the forebulge and the subsequent high deposition rate of sediments in the backbulge. When contrasted, the migration of the forebulge is in agreement with the empirical subsurface data of Sigismondi (2012). At this stage, the configuration of the foreland basin resulted in slow but continuous subsidence in the backbulge area (Table 1), due to high sedimentary supply and periodic paleoprecipitation. The high supply of sediments is the result of the erosion of paleotopography established in previous wetter climate which would have favored the development of more vigorous fluvial systems due to the base level change originated by the new topography and the migration of the dynamic load to the west, towards the foredeep. In this framework, the extensive erosion in the region and changes in paleogeomorphology are corroborated by U-Pb detrital zircon ages (Di Giulio et al., 2012) and the modification of sandstone provenance, confirming a notorious shifting of the source areas after the active tectonic load period (Asurmendi et al., 2016; Asurmendi, 2016). The deposits of this period incorporated detrital zircons from the Pampean magmatic arc (640-514 Ma), preserved in the Grenvillian terranes of Pampia and Cuyania (1200–1000 Ma), derived from the basement of the Andes or the Cuyania terrane, confirming a reversal in source areas of contribution (Di Giulio et al., 2012; Naipauer and Ramos, 2016).

In the Coniacian, the foredeep was filled with sediments (Fig. 3, Table 1) and the basin entered into overfilled conditions, with the accommodation space migrating towards the forebulge of the previous underfilled basin period (Sánchez and Asurmendi, 2011, 2016; Asurmendi, 2016). A large peripheral sag basin developed where the strata in the distal basin overlapped over the craton (Plottier Formation - Fig. 8). During this stage, the climate played a preponderant role, considering the high supply due to the continuous erosion of the fold-and-thrust belt (Fig. 3). It is inferred that there was a shift towards more restricted, semi-arid paleoclimatic conditions, which contributed to a decrease in the discharge and in intermittent activity of some channel belts of low sinuosity fluvial systems, generating extensive floodplains.

In the Santonian an early stage of underfilled basin started, marked by a second-order regional discontinuity and high sinuosity fluvial systems with paleocurrent directions to the NE

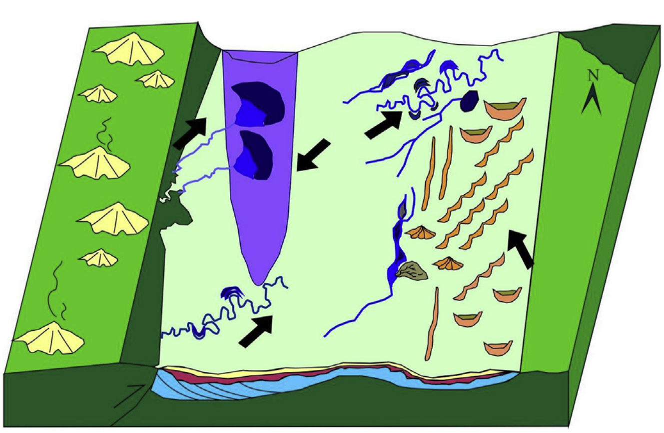


Fig. 6. Geological model of the Cerro Lisandro Formation. While in the foredeep zone it is represented by lacustrine systems interrupted by Gilbert-type delta deposits, in the backbulge zone to the east it is represented mainly by aeolian systems.

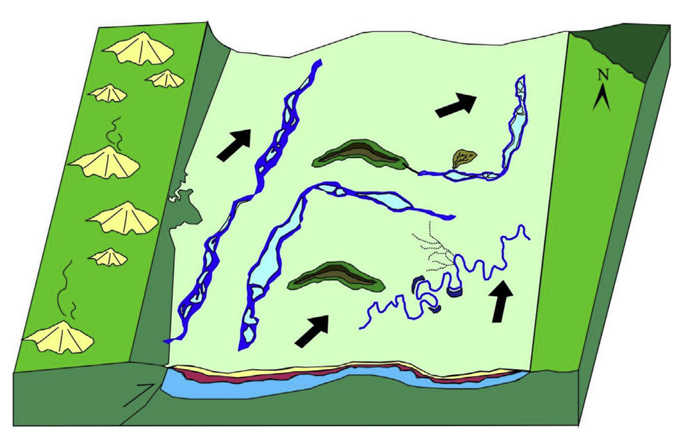


Fig. 7. Geologic deposital model of the Portezuelo Formation, represented by fluvial systems in all areas of the basin.

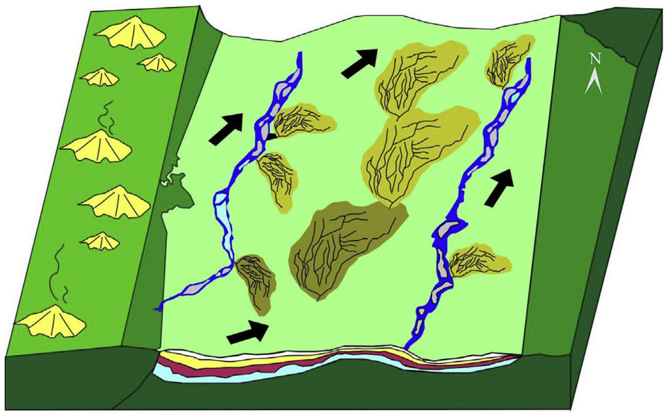


Fig. 8. Geologic depositional model of the Plottier Formation, represented by fluvial systems with large overflows all along the basin.

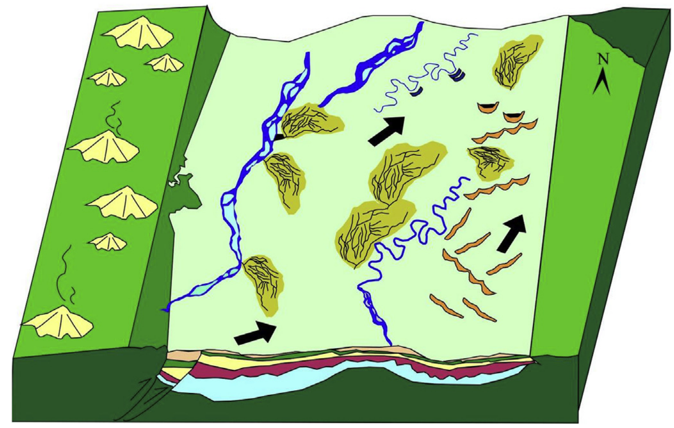


Fig. 9. Geological model of the Bajo de la Carpa Formation. In the area of the foredeep this formation is represented by fluvial, while in the backbulge area it is dominated by aeolian and fluvial systems.

(Sánchez et al., 2006a,b, 2008c; 2011; 2014; 2013 - Bajo de la Carpa Formation - Table 1, 3 and 9). Therefore, it is assumed that the gradients of the basin floor were low with a general slope towards the NE-ENE. A period of tectonic activity was reflected by the identification of levels of seismites at its base, in the deposits of the Bajo de la Carpa Formation (Sánchez et al., 2013). Therefore, deposition was initiated under tectonically active conditions, in an area bounded to the west by the Agrio fold-and-thrust belts and the Chihuidos High, to the north by the NO-SE Lindero Atravesado lineament, and to the south by the Sierra Barrosa lineament and the Huincul Ridge (Fig. 1). Several deformational events that resulted in seismic shocks with an inferred magnitude of up to 6 on Richter scale were recorded at stratigraphic levels that exceed 18 km of regional extension, constituting excellent guide horizons (Sánchez et al., 2013).

Forebulge, the tendency to an oblique aggradation (Rajchl and Uličný, 2005) is assumed to be influenced by the general gradient of the basin under conditions of high accommodation space with a slow rise in water level in the channels, which was balanced by the sediment input and aggradation rate of the channel belts. The floodplain registered gradual avulsion of crevasse-splay. The most severe climatic conditions were reflected by the development of dune fields towards the continental interior (Fig. 9), affected by a great aridization, and in conditions of high sediment supply, correlated with topographic modifications and subsequent renewal of the source areas. In the sectors near of the Huincul High, towards the craton, the channels had periods of high discharge of water and sediments that generated regional floods.

The progressive advance of the Agrio fold-and-thrust belt generated a change in the base level and a third-order discontinuity manifested throughout the backbulge basin conditioning the change in the geometry of the basin fill. At WNW, the subsidence in the backbulge increased slowly and allowed the expansion of the systems and a greater development of the floodplain. Extense levels of paleosols were developed, suggesting long periods of stability in the plain that generated crevasse-splay during periods of flooding concentrated mainly in the rainy season. The arid continental conditions favored the development of an extensive erg (1500 km^2; Sánchez et al., 2016) with a continuous supply of sand and formation of composite transversal dunes, according to the paleogeographic location. The establishment of monsoon conditions progressively decreased the availability of sand, and the previous dunes were reworked and redeposited as parabolic forms with wet interdunes on the avalanch faces. The almost stationary wind field suffered a restriction of the clastic input as a consequence of the development of extensive floodplains in the source area, while the high capacity of sand transport controlled the erosion and remobilization of the underlying dunes. A high water table combined with the high frequency of interference of fluvial systems in the interdune affected the advance of the dunes.

In the proximity to the craton and the Huincul ridge a low rate of subsidence conditioned the availability of accommodation space and the fluvial systems generated regional floods, under a regime of high precipitations concentrated in the warmer months. The levels of seismites and volcanoclastic deposits present in the Bajo de la Carpa Formation (Sanchez et al., 2013) confirm the pulsating activity of the orogenic front and the volcanic arc.

During the Campanian, the activity and erosion of the Agrio fold-and-thrust belt induced the migration of the subsidence center rapidly towards the craton, indicating the beginning of a late stage of underfilled basin (Anacleto Formation - Figs. 3 and 10; Table 1). The erosion of the forebulge and the reworking of the sediments deposited previously in the backbulge basin generated abundant supply of clastic material. The characteristics of the fluvial systems were conditioned by the high accommodation space and high rate of sediment supply (Sanchez et al., 2014). To the WSW of the backbulge, an abundant supply of sediments from the fluvial courses generated a relative decrease of the accommodation space, while the high frequency climatic cycles generated multiple crevasse-splay events during large floods, eroding floodplain

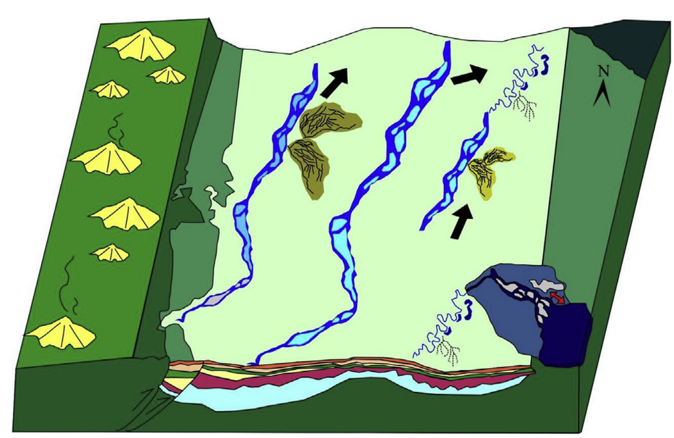


Fig. 10. Geological model of the Anacleto Formation. While in the foredeep area it is represented by fluvial systems, in the backbulge area it is dominated by continental and transitional to shallow marine deposits.

deposits. Towards the craton, the sedimentation was dominated by coarse clastics in high aggradation rate conditions, generating abundant crevasse during periods of high discharge, both of high frequency and low duration.

The tectonic reactivation of the thrust belt had its correlation not only in the in the generation of a first-order unconformity (Table 1), but also in the generation of earthquakes, translated as a level of seismites (top Anacleto Formation) of regional extension (Sanchez et al., 2013).

The first marine Atlantic Ocean transgression in the Maastrichtian (Figs. 1 and 2) further complexing the distribution of continental and transitional paleoenvironments to shallow marine in the eastern sector of the basin. As a consequence, conditions of high relative accommodation space were maintained over time despite the low subsidence rate in the central sector towards east of the backbulge, due to eustatic processes. In the ESE, the fluvial systems adjusted to the new base level, developing anastomosed fluvial systems to WNW, more than 100 km away from the coast, the main controls were tectonics, in the first place, and climate, in the second. Fluvial systems were developed in an area affected by progressive decrease in the A/S ratio (accommodation/supply), registering repeated flood events due to cyclical variations in the discharge.

The paleoprecipitations were controlled by a zonal pattern and were more intense in the windward of the orogenic barriers, where the marine airflow affected the continent, associated with the first Atlantic marine transgression (Armas and Sanchez, 2008). Both temperature and precipitation must have fluctuated strongly with the seasons due to the insulation of the continental interior and the influence of the surrounding ocean. The climatic seasonality was marked by long dry periods interrupted by periods of intense precipitation, where fluvial systems produced intense overflows and flooded the floodplain (Sánchez, 2004; Sánchez et al., 2006a,b, 2008a,b,c; 2014; Sánchez and Asurmendi, 2014).

The depositional model of the basin filling ends with an overfilled foreland basin stage (Fig. 3), marked by the development of a first-order discontinuity between the end of the Neuquén Group depositional period and the beginning of the deposition of the Allen Formation (Malargüe Group). This coincides with the collision of the Farallon/Antarctic mid-ocean ridge (FAMOR) in the western margin of Gondwana (Fennell et al., 2015).

6. Discussion

6.1. Paleoclimatic considerations

The Cretaceous was a period dominated by a climatic greenhouse with marine and terrestrial paleotemperatures higher than the present (McElwain et al., 2005), that can be divided in three cycles correlated with large-scale changes in the evolution of the Andean foreland basin (Table 1). The first one corresponds to the coldest Early Cretaceous, followed by a continuous warming through the Albian-Cenomanian, with a a marked warming peak in the Turonian and a general tendency to colder climates in the Santonian-Campanian, along with subcycles within each period (Huber et al., 2002; McElwain et al., 2005; Souza Carvalho et al., 2010). The wet periods were associated with the increase of the monsoon conditions and the arid ones with strong winds causing an intense evapotranspiration (Frakes et al., 1992; McElwain et al., 2005; Barron, 1983). This process together with volcanic activity is considered as the primary responsible or global high temperatures in the middle Cretaceous, as they indirectly increased the release of gases (CO_2 and methane) from the greenhouse (McElwain et al., 2005). From the Albian to late Campanian-Maastrichtian the volcanic activity was intense with a decrease during the Turonian-Santonian (Table 1). Since volcanism is a substantial source of CO_2 for the atmosphere, significant warming in the climate during episodes of increased volcanic activity should be expected (Frakes et al., 1992). The records of these events have been recognized in different units of the Neuquén Group (Sanchez et al., 2008a,b,c; 2009, 2013; 2014; Sánchez and Asurmendi, 2014, 2015). The Coniacian and Campanian were warm intervals that correlate with an increase in volcanic activity (Frakes et al., 1992). The geological evolution of the western margin of Gondwana during the deposition of the Neuquén Group shows a paleogeography characterized by active subduction of the paleo-Pacific plates, generating an active volcanic arc and foreland basin, bounded to the east with a mosaic of cratons moving westwards due to the opening of Atlantic-Ocean. Aridity was controlled by the distribution of continental masses and orogens, influencing the distribution of paleoprecipitations and deserts in the paleogeography. Since there is a strong dependence of the surface temperature in water vapor content, the increase in the evaporation capacity of the warmer air on the earth was not satisfied by the available humidity, giving as a result of global warming and increase in the aridity in the continental interior.

Stratigraphic definitions have varied since Herrero Duclox (1946); Digregorio (1972); Cazau and Uliana (1973); Hugo and Leanza (2001). Recently, Garrido (2010) proposed the designation of two new stratigraphic units and modifications in the conformation of the Subgroups previously established on the basis of *"the Portezuelo Formation presents a transitional character of its deposits, which in many cases makes it difficult to precisely define their contacts"*. From the formal point of view, the definitions of Cazau and Uliana (1973) and Hugo and Leanza (2001) are the most adequate for the stratigraphic definition of Neuquén Group. However, the application of high resolution sequential stratigraphy allows establishing a general pattern confirming that the first-order discontinuities are associated with tectonic movements at the base and top of the Neuquén Group, and the resolution of three incomplete filling cycles in the Neuquén Group foreland basin system (Table 1).

Taking into account the relevance of the discontinuity at the base of the Cerro Lisandro Formation (Table 1), it is clear that a complete underfilled-overfilled cycle comprising the Cerro Lisandro, Portezuelo and Plottier Formations can be defined, bounded by another second-order regional discontinuity (Table 1). This proposal, besides of being considered fit to the requirements of the Argentine Code of Stratigraphy and the International Code (IUGS), opens the pertinent debate about the two incomplete cycles in the base and top of Neuquén Group.

Two lines of debate and their possibilities must be satisfied in future investigations: i) the beginning of the compressive tectonics has been proposed in a coincident way by several researchers (Ramos and Folguera, 2005; Cobbold and Rossello, 2003; Zamora Valcarce et al., 2009; Franseze et al., 2006; Fennell et al., 2015) in the Late Cretaceous. There is no discussion regarding the regional extent and importance of the Patagonidic unconformity. However, there is a significant gap in the base, and wedge top foreland basin deposits have only been recognized by Fennell et al. (2015), also, the differentiation with the upper terms of the Rayoso Formation is not easy, due to subtle regarding geometry, facies and relations, both in surface and in well logs (Ponce et al., 2002; Zavala et al., 2006). However, the conditions are homologous to an underfilled basin stage in a period of tectonically active basin containing syntectonic deposition. (ii) the Río Colorado Subgroup proposes: ii-a) the existence of an incomplete foreland basin cycle which some researchers (Tunik et al., 2010; Armas, 2012; Sánchez and Armas, 2008; Armas and Sánchez, 2011, 2013), although agreeing on the existence of a first-order discordance, recognize a continuous sequence from the Anacleto to Allen Formation or its homonymous within Andean foreland basin. The first-order unconformity has been defined as a ravinement surface (Sánchez and Armas, 2008; Armas and Sánchez, 2011, 2013), which is the result of the combination of both tectonic and eustatic effects (Fig. 3) and in an exclusively continental area constitutes a profuse surface of erosion. In the some sectors, like in the Colorado river, the backbulge is represented by incised valley (Sánchez et al., 2016), whereas in the western border, near the craton (north of the Huincul Ridge) it generates a profuse unconformity between different units of the Rio Neuquén and Río Colorado Subgroups. iib) the lack of concordance between the age on the first Atlantic transgression (Maastrichtian) and the age assigned to the Río Colorado Subgroup, which in the eastern sector of the basin exhibits features that pre-announce the transgression in the Bajo de la Carpa Formation (Sánchez and Gómez, 2005; Gómez et al., 2005; Gómez et al., 2005), while the definition of coastal to shallow seas from the Anacleto Formation remains undisputed in the backbulge, to the northwest of the Huincul Ridge.

7. Conclusions

In this work, the integration of surface and subsurface data and the evaluation of allocyclic and autocyclic factors have been the key to elaborate a proposal of the evolutionary of basin from the Albian to the Maastrichtian. The filling of the basin consists in a complete cycle and two incomplete cycles of underfilled-overfilled, separated by first-order discontinuities assigned to the uplift of the Agrio fold-and-thrust belt during the Chasca/Catequil, Mid Ocean Ridge (CCMOR) collision, coinciding with first-order climatic changes within the Cretaceous greenhouse cycle. These are found at the base and roof of the Neuquén Group, this last case including the eustasy as a third variable, related to the Maastrichtian transgression.

The Candeleros Formation was deposited after the collision of the CCMOR, which generated the angular Patagonidican unconformity, recognized throughout the Neuquén basin, both in the foredeep and in the forebulge of the foreland basin system under conditions of late underfilled. The Huincul Formation corresponds to the overfilled basin stage in a period of low to none tectonic activity and strong arc activity. Extensive high sinuosity fluvial systems that suffered regional or local flooding covered all the foreland basin. A second-order discontinuity, related to the tectonic subsidence peak in response to the reactivation of the fold-and-thrust belt, limits the Rio Limay and Río Neuquén Subgroups. On the other hand, the Cerro Lisandro Formation was deposited in conditions of underfilled basin. An extensive lake system with Gilbert-type delta development occupied the foredeep, whereas in the backbulge an extensive erg with permanent interference of ephemeral fluvial systems demonstrates the extreme climate near the transition with the carton. The Portezuelo Formation corresponds to a late underfilled basin stage, where the erosion of the forebulge and a change in the source area suggest that there was active erosion and contribution of new uplifted areas to the west. Extensive fluvial systems were dominated by avulsion during regional floods, while the river courses suffered strong incision and variations in the design from high to low sinuosity fluvial system. The Plottier Formation was developed in overfilled basin cycle conditions. In several sectors of the basin the stacking of channel and the cannibalization of their deposits is notorious. This unit has the best development of paleosols in channels and in floodplains, dominated by numerous records of Bk horizons (Retallack, 1999). The activity of the orogenic belt generated underfilled basin conditions, period in which the Rio Colorado Subgroup was deposited. The Bajo de la Carpa Formation was characterized by the development of extensive river networks of varied designs, with the predominance of a more arid climatic regime in the central sector of the Neuquén basin, evidence by the development of new ergs and incision of numerous valleys throughout the lower units of the of the Neuquén Group along the basin. The Anacleto Formation ends with the depositional period of the Neuquén Groups, culminating in an early underfilled basin cycle, where the combination of eustasia and climate generated a radical change in the basin filling. A strong incision of the fluvial systems and the early development of an estuary evidenced the marine influence on the eastern edge of the basin.

We also propose the inclusion of the Cerro Lisandro Formation as the base of the Rio Neuquén Subgroup in the new stratigraphic chart of the Neuquén Group, since the regional importance of the discontinuity at its base clearly defines a complete underfilled-overfilled cycle integrated by the Lisandro, Portezuelo and Plottier Formations, limited at the top by another second-order regional discontinuity.

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