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Evolution of the Neogene Andean foreland basins of the Southern Pampas and Northern Patagonia (34°–41°S), Argentina

Alicia Folguera [a,*], Marcelo Zárate [b], Ana Tedesco [a], Federico Dávila [c], Victor A. Ramos [d]

[a] Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino, Colectora de Avenida General Paz 5445, edificio 25, piso 2, oficina 201, San Martín, Buenos Aires, 1650, Argentina
[b] Instituto de Ciencias de la Tierra y Ambientales de La Pampa, Universidad Nacional de La Pampa-Conicet, Avenida Uruguay 151, 6300, Santa Rosa, La Pampa, Argentina
[c] CICTERRA, CONICET-Universidad Nacional de Córdoba, Av. V. Sarsfield 1611, Córdoba, 5016, Argentina
[d] Instituto de Estudios Andinos- CONICET, Universidad de Buenos Aires, Ciudad Universitaria, Pabellón 2, Buenos Aires, Argentina

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ABSTRACT

The Pampas plain (30°–41°S) has historically been considered as a sector that evolved independently from the adjacent Andean ranges. Nevertheless, the study of the Pampas showed that it is reasonable to expect an important influence from the Andes into the extraandean area. The Pampas plain can be divided into two sectors: the northern portion, adjacent to the Pampean Ranges, has been studied by Davila (2005, 2007, 2010). The southern sector (34°–41°S) is the objective of the present work. The study of this area allowed to characterize two separate foreland basins: the Southern Pampa basin and the Northern Patagonian basin. The infill is composed of Late Miocene and Pliocene units, interpreted as distal synorogenic sequences associated with the late Cenozoic Andean uplift at this latitudinal range. These foreland basins have been defined based on facies changes, distinct depositional styles, along with the analysis of sedimentary and isopach maps. The basins geometries are proposed following De Celles and Gilles (1996) taking into account the infill geometry, distribution and grain size. In both cases, these depocenters are located remarkably far away from the Andean tectonics loads. Therefore they cannot be explained with short-wave subsidence patterns. Elastic models explain the tectonic subsidence in the proximal depocenters but fail to replicate the complete distal basins. These characteristics show that dynamic subsidence is controlling the subsidence in the Southern Pampas and Northern Patagonian basins.

1. Introduction

The Andean foreland of central Argentina (~30°–41°S) comprises the geomorphological domains of Sierras Pampeanas (Pampean Ranges), the extensive Pampean plain, and the northernmost part of the Patagonian plateau. In the Pampean plain, a vast foreland sedimentary system developed during the Neogene characterized by its relatively reduced and constant thickness (e.g. Dávila et al., 2010; Folguera and Zárate, 2009, 2011; Nivière et al., 2013). Considering the general geological and structural setting, as well as the Neogene stratigraphic record, two main foreland basins here called Southern Pampa basin and Northern Patagonia basin have been identified between 34° and 41°S, a region bounded by Sierras Pampeanas to the north and the Northern Patagonian massif to the south (Fig. 1). The southern Pampa basin (34°–38°S), south of Sierras Pampeanas, is a large area that covers most of La Pampa province and southern Buenos Aires province mainly; it is characterized by a main phase of sedimentation in the late Miocene with up to 200–300 m of thickness widely distributed (Folguera and Zárate, 2009). The Northern Patagonian basin (38°–41°S) extends between the Colorado-Curacó fluvial system and the North Patagonian massif comprising the northern part of Río Negro province, eastern Neuquén province and the southernmost part of La Pampa and Buenos Aires provinces. The sedimentary record is dominantly composed of fluvial conglomerates and sandstones of late Miocene and Pliocene age. The filling of both basins is made up of synorogenic deposits derived from the Andes (Folguera and Zárate, 2009).

* Corresponding author.
E-mail addresses: alifolguera@gmail.com (A. Folguera), fmdavila@efn.uncor.edu (F. Dávila).

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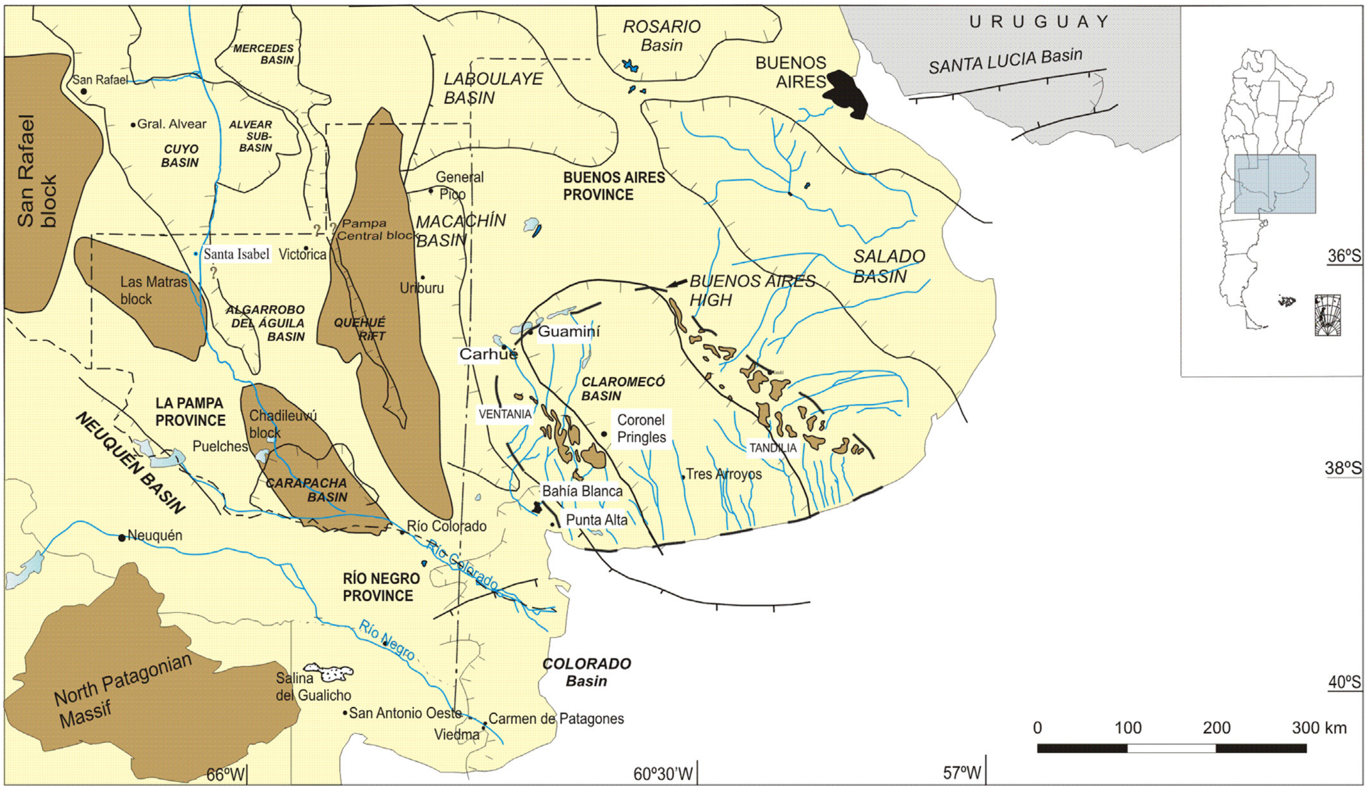

Fig. 1. Pampean region and its surrounding areas. Morphostructural units mapped.

Because of the significant areal extension of the basins, and the distance from the orogenic front, the resulting basin geometry and the maximum thickness of the sedimentary record cannot be only reproduced by topographic loading (see Dávila et al., 2005, 2007; 2010; Dávila and Lithgow-Bertelloni, 2013). In this respect, east of Sierras Pampeanas, subsidence was interpreted as a combination of sub-lithospheric and supra-lithospheric mechanisms driven by both tectonic and dynamic loads (Dávila et al., 2010; Dávila and Lithgow-Bertelloni, 2013); dynamic subsidence was thought to take place at the location of the slab leading edge associated with the flat subduction dynamic; major subsidence may have taken place during the late Miocene, migrating westwards later, during the Pliocene retreating phase of the slab (Dávila et al., 2010). Further south (36°–38°S) at the latitudinal fringe of the Southern Pampa basin, flat slabs occurred during the late Miocene (13–5 Ma, see Ramos and Folguera, 2005), likely followed by rollback and foreland extension since the Pliocene to the present (Folguera et al., 2005a,b).

The main objective of this contribution is to analyze and compare the Neogene evolution of the two foreland basins of central Argentina and the plausible mechanisms involved in the generation of subsidence and the resulting accommodation space. With this purpose in mind, the general infill history is reviewed, including the lithological characteristics of the stratigraphic units, and the description of the basins geometry. Finally, the overall subsidence patterns and the possible relationship of these features to regional tectonic events are discussed.

2. Methods

The analysis of the study region was mainly based on field work that included the reconnaissance, description, and mapping of the Neogene stratigraphic units in the study region. Digital elevation models and Google earth images were also used to map the units and place the stratigraphic sections in the regional geological and geomorphological setting. Sedimentological sections were described based on the identification of lithofacies.

Due to the general lithological homogeneity of the Northern Patagonian Basin deposits, informal allostratigraphic units were defined following the criteria of the North American Commission of Stratigraphic Nomenclature (1983). Morphological features (*i.e.* topographic altitudes, gradient, relative degree of dissection) were qualitatively considered as complementary criteria to attribute relative ages. Isopach maps were made using information from outcrop measurements as well as borehole data recovered by federal institutions of Argentina (YPF, Ministerio de Agricultura, Ministerio de Industria y Comercio de la Nación, Ministerio de Obras Públicas, Secretaría de Industria y Comercio) The information on the areal extension, thickness, lithology, and chronology of the sedimentary units were integrated to analyze the basin geometry, the temporal and spatial thickness of the deposits, and the subsidence history of the basins.

3. Tectonic and geological setting

The western limit of the study region is the Andean orogenic belt, a typical orogen with subduction of oceanic crust, without participation of collisions during the Mesozoic–Cenozoic, absence of Andean age metamorphism, maximum tectonic stacking and crustal shortening (Ramos, 1999). The geometry of the Andean segment west of the study area (34°–41°S) is within the zone of normal subduction characterized by a plate inclination of 30°, that generates a volcanic system in the cordillera (Ramos, 1999). Northwards, between 33° and 34° S is the transition from normal to subhorizontal subduction (28°–33° S), associated with the subhorizontalization of the oceanic Nazca plate, that constitutes the western limit of the northern Pampa basin.

3.1. Southern Pampa basin (~34°–38°S)

The basin is developed across several major morphostructural units including blocks (Pampa Central, some areas of the Chadileuvú, the Chical-có plain at the southeastern part of the San Rafael Block, the Bonaerian High *(Positivo Bonaerense sensu* Yrigoyen, 1975) along with subsurface tectonic basins, Alvear-Algarrobo del Aguila, Salado and Macachín, (Yrigoyen, 1993; Criado Roqué and Ibañez, 1979; Kostadinoff et al., 2002; Kostadinoff and Gregori, 2004; Kostadinoff et al., 2006; de Elorriaga y Camilletti, 1999; Kostadinoff and Llambías, 2002) (Fig. 1).

The Pampa Central Block, in the center of La Pampa province (Folguera and Zárate, 2011), is an east-dipping plain (0.08%) with altitudes ranging from ~400 m westwards (Valle Daza) to ~180–200 m eastwards. It is characterized by deep depressions (up to ~100 m deep) of debatable origin (tectonics vs fluvial erosion) with variable trends, NE in the north, EW in the central part, and SE in the southern portion. The block is bordered by double vergent fault systems, the Valle Daza and Uriburu faults (Folguera and Zárate, 2009) (Fig. 2). The NNW-trending Uriburu fault is related to the suture between the Pampia terrane and Río de la Plata craton, and/or the southward extension of Trans-Brasiliano lineament (Rapela et al. 2007; Rapalini, 2012). The Neogene sedimentary cover is affected by both fault systems, suggesting a structural reactivation after ca. 6.8 Ma (Folguera and Zárate, 2011). Southwards, it grades into the Chadileuvú Block composed of a Precambrian–Paleozoic bedrock with a significant record of Permian–Triassic magmatic activity (Choiyoi Group) and outcrops of late Cretaceous deposits; the Neogene mantle occurs in marginal sectors, mainly to the N-NE and NW.

The Bonaerian High (Positivo Bonaerense) (*sensu* Yrigoyen, 1975) includes Ventania and Tandilia ranges and Claromecó tectonic basin (Folguera and Zárate, 2009 and references therein). The area between the ranges is known as inter-range plain (llanura interserrana) or inter-range Pampa (Pampa interserrana). The Neogene cover is thicker near the Ventania range including Huayquerian fossil remains while Pliocene deposits with Montehermosan-Chapadmalalan fossil remains are found in the Tandilia area.

The Macachin basin is a group of north–south asymmetric rifts (De Elorriaga et al., 2013) The Alvear subbasin is a subsurface feature in which most of the formations found in the subsurface were originally defined from outcrops in the Mendoza Andes. It is a tafrogenic basin with 3000 m of infill formed by Mesozoic and terciary sediments.

Algarrobo del Águila basin is an asymmetric rift defined by Kostadinoff and Llambías (2002) based on a gravimetric minimum located in the line between Algarrobo del Aguila and Paso de los

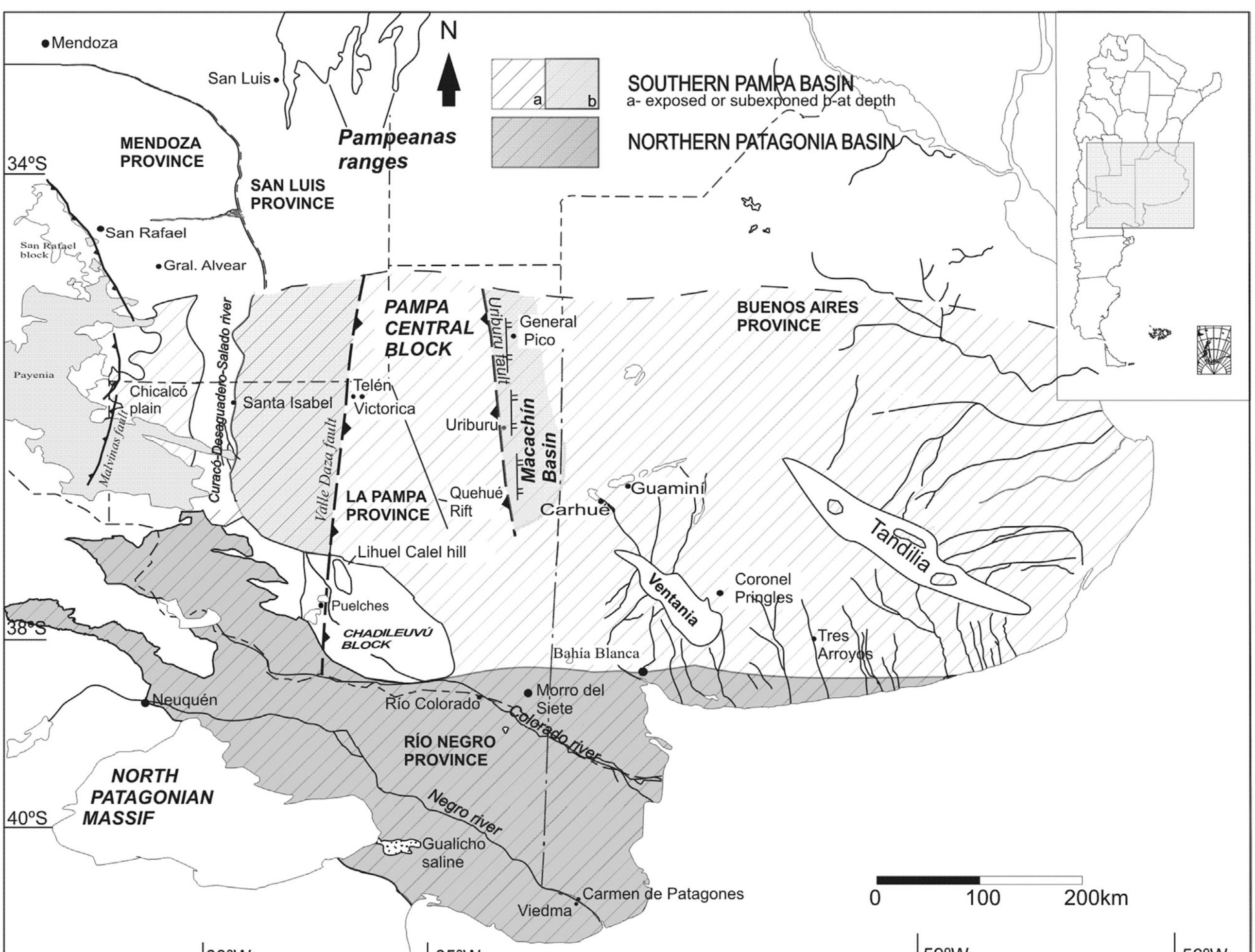

Fig. 2. Distribution of Southern Pampa basin and Northern Patagonia basin in the extra-Andean region.

Algarrobos. The similar azimut to Quehué basin had led to the authors assigned to it a Triassic age.

The Salado basin develops mostly offshore. It evolved during the break of Gondwana in the Late Jurassic - early Cretaceous (Demoulin et al., 2005). It consists of two large tectonic trench, Salado basin and Punta del Este basin, separated by Martin Garcia – del Plata high. It has a thickness of sediments in the order of 7 km.

Westwards of the Southern Pampas basin, the Cordillera Principal basically includes the Malargüe fold and thrust belt formed by thin-skinned structures of 15 to 8 Ma old units (Giambiagi et al., 2008) that also involves basement rocks covered by Jurassic and Cretaceous deposits (Kozlowski et al., 1993; Giambiagi et al., 2008). The belt is bounded by the mid to late Miocene foreland basin of Río Grande characterized by a sedimentary sequence more than 2500 m thick. During the onset of a shallow subduction zone between 34°30′ to 37°S, the basin was partially cannibalized by the uplift of the San Rafael block (Ramos and Folguera, 2005) which was affected by two deformation phases (Ramos and Folguera, 2014). The first took place in the middle-late Miocene related to the shallowing of the subducting Nazca plate (14–10 Ma). The second phase, placed between 5 and 3 Ma, involves the maximum deformation event, and coincides with the maximum shallowing of the subducting oceanic slab (Ramos and Folguera, 2014).

The Chadileuvú-Pampa Central blocks, situated away from the orogenic Andean highlands, may have been uplifted during this flat-slab episode (Folguera and Zárate, 2011). The restoration to a normal-dipping subduction regime and the correspondent roll-back may have occurred since the Pliocene to the present (Ramos and Folguera, 2005; Spagnoulo et al., 2012), as suggested by the volcanic trend retreat and the occurrence of normal faults. Consequently, the main deformation and sedimentation phases in the Southern Pampa basin are thought to be related to the oceanic slab shallowing followed by its progressive steepening (Folguera and Zárate, 2011).

3.2. *Northern Patagonian basin (~38°–41°S)*

The Northern Patagonian basin is mostly developed within the Colorado tectonic basin, and the easternmost part of the Neuquén embayment. It is characterized by a stepped topographic morphology consisting of several plateaux of variable areal distribution dipping to the east. The basin, drained by the Colorado and Negro rivers, is bounded by the Chadileuvú block-Bonaerian High to the north, and the North Patagonian massif to the south. It includes the southernmost fringe of the inter-range Pampean plain (*Pampa interserrana*) between Tandilia and Ventania (Fig. 2).

The Colorado Basin is located in the austral segment of the Western South Atlantic margin. The bigger development is in Argentina offshore, roughly E–W, oblique to the NNE-trending. The infill of the basin is proposed to have a maximum thickness of 7000 m (Fryklund et al., 1996; Juan et al., 1996).

Westwards of the Northern Patagonian basin, the Andes Cordillera segment of Neuquén province comprises the geological provinces of Cordillera Principal, the Neuquén embayment, and Cordillera Patagónica. Cordillera Principal consists of Jurassic-Cretaceous marine deposits, and magmatic arc rocks. The Cenozoic stratigraphic record is represented by Oligocene to Miocene continental deposits. The Neuquén embayment, eastwards of Cordillera Principal, is divided by the Huincul High into a northern sub-basin and a southern (Picún Leufú) sub-basin (Turner and Baldis, 1978). The Neuquén Basin is a retroarc basin that encompasses more than 6000 m of Upper Triassic–Lower Cenozoic sedimentary succession, which records a subsidence varying from a rift stage in the Early Jurassic, a thermal subsidence in a retroarc setting for the Late Jurassic-Early Cretaceous, and a foreland basin during late Mesozoic to Cenozoic times (Legarreta and Uliana, 1991).

The Cordillera Patagónica, situated southwards of Cordillera Principal, is a fold and thrust belt that involved the basement in the deformation (Ramos and Cortés, 1984; Giacosa and Heredia, 2004). According to Ramos et al. (1982) the preservation of the Jurassic-Cretaceous sequences that characterize the Cordillera Principal, is the main criterion to define the boundary between the two mountain ranges. The Cordillera Patagónica is characterized by the predominance of volcanic and plutonic rocks of the Paleogene magmatic arc (Paleocene–Eocene–Oligocene).

There is general consensus that the Late Cretaceous was an uplift period of the Neuquén Andes and the Northern Patagonian Andes (38°–46° S) supported by fission track data, and Ar/Ar ages obtained in Neuquén (Zapata et al., 1999; Kay, 2001; Burns, 2002), and the retroarc sedimentation probably associated with the development of a proximal foreland basin (Neuquén group, 100–70 Ma and Malargüe 70–55 Ma; Barrio, 1990). An Eocene and Late Miocene uplift episodes of the Andes have been inferred on the basis of the synorogenic sedimentation in the Agrio fold and thrust belt (Ramos, 1998), along with fission tracks data yielding ages of 44 Ma and 12 Ma in the Chilean adjacent sector (Burns, 2002).

4. Neogene stratigraphy

4.1. *Southern Pampa basin*

Late Miocene deposits are widespread across the Pampas basin extending from the northernmost part of La Pampa province and Southern of San Luis province to the Colorado river, and from the western margin of the La Pampa central block to the Bonaerian High (*Positivo Bonaerense*) reaching the Atlantic coast (Fig. 2). These deposits which are grouped into the Cerro Azul Formation (see Folguera and Zárate, 2009 and references therein) also cover the easternmost part of the San Rafael block (Chicalcó plain) (Fig. 2). The unit overlies the pre-Cenozoic basement on the blocks areas and late Miocene marine deposits (*Mar Paranense*, Paranense Sea) (Malumián et al., 1998) in the tectonic basins (*e.g.* Macachín, Alvear, Algarrobo del Aguila, Salado). Cerro Azul consists of a relative uniform sedimentary mantle, with a maximum thickness of ~150 m in the Salado-Chadileuvú depression and a minimum of ~50 m in the Pampa Central block and the Bonaerian high, resulting in a huge and shallow depocenter (Fig. 8). In addition, a smaller depocenter is located in the north-northwest of Bahia Blanca city, with a thickness is about 100 m.

The unit is made up of brown silts and sandy silts (loess and loess-like deposits) with common pedogenetic features throughout, and discrete paleosol levels. Carbonate accumulations, including nodules and rhizoconcretions, are common traits (Folguera and Zárate, 2009) (Fig. 3). The lithological composition of the deposits is volcaniclastic including a high percentage of volcanic fragments (Visconti, 2007). The chronology is based on vertebrate fossils (see Folguera and Zárate, 2009 and references therein) and radiometric dates on impactites (scorias; see Folguera and Zárate, 2009 and references therein). The faunistic assemblage of the lower levels is referred to the Chasiquean stage-age (Verzi et al., 2008), whereas fossil remains of the upper part are characteristic of the Huayquerian stage-age (Goin et al., 2000).

The succession is capped by a ~2 m-thick calcrete, including well-rounded pebbles of volcanic and igneous rocks at the Chicalcó plain. In turn it is covered by Late Pleistocene–Holocene aeolian deposits.

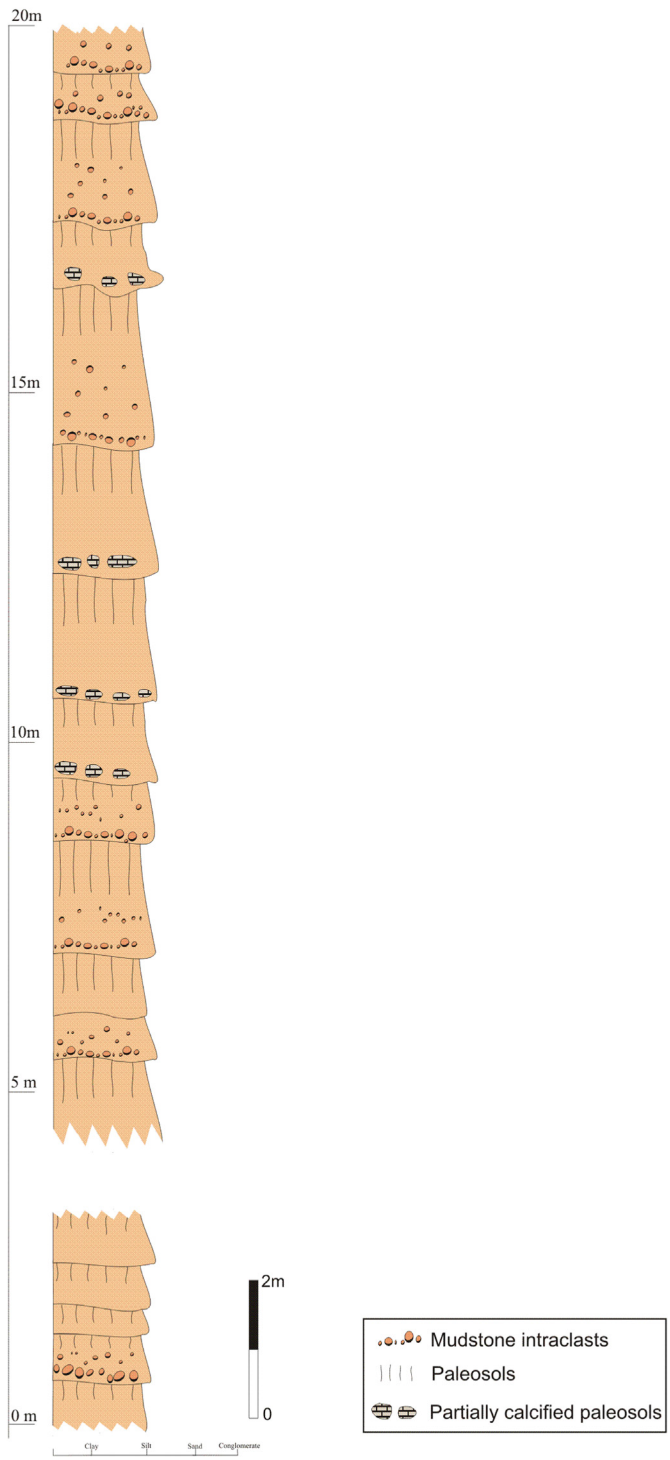

Fig. 3. Schematic late Miocene sequence outcropping in the morro del Siete (Fig. 2), located in the south of La Pampa province.

4.2. Northern Patagonian basin

An extensive apron of Neogene deposits, coarser than those accumulated along the Southern Pampas Basin, spreads from the surroundings of Neuquén city to the Atlantic coast (Folguera and Zárate, 2011). The deposits dominated by fluvial conglomerates and sandstones (Folguera and Zárate, 2011), have been stratigraphically grouped into 5 alloformations (informally named from older to younger I, II, II, IV, V) separated by major erosional episodes. In general, within the uncertainties of the ages assigned to the units (see below), the resulting erosional unconformities between the alloformations are correlatable with the unconformities reported in the Neuquén Andes caused by deformation events (Fig. 4).

Each unit consists of coarsening upwards sequences with a fan shape in plain view (Fig. 5), and similar composition comparable to that of the blue(in the web version) to bluish gray sandstones of the Río Negro Formation (Andreis, 1965) made up of predominant volcanic (rhyolites and basaltic andesites) a volcaniclastic sediments. The isopach map shows an increasing sedimentary thickness from the area of Neuquén city in the west to the Atlantic coast to the east (Fig. 8). The volume of sediment accumulation is estimated at ~11,500 km^3 with the older alloformations developed much closer to the orogenic front in comparison with the younger alloformations, situated ~600 Km to the east. The deepest depocenter is located in the Colorado Basin, far away from the main Andes domain.

Alloformation I with a maximum thickness of 20 m and the apex near the orogenic front (Fig. 5), is situated southwestward of Neuquén city. Originally called *Pedimento Renteria* by Uliana (1979), it was interpreted as an aggradational level and named Renteria Formation (Hugo and Leanza, 2001). Alloformation I unconformably overlies Mesozoic bedrock, and is made up of clastic-supported polymictic conglomerates composed of subrounded clasts of granite and gneiss rocks, quartz, Mesozoic sedimentary rocks, petrified logs and basalts (Hugo and Leanza, 2001); yellow sandstones lenses are frequently intercalated. It is highly dissected and shows a gentle slope with an altitude of 925 m a.s.l. at the SW end to 550 m a.s.l. at the north-easternmost tip. The genesis is likely related to the erosional and sedimentary dynamic of a Neogene precursor of the present Limay river. A Pliocene-early Pleistocene age was originally attributed to the unit (Uliana, 1979; Leanza and Hugo, 1997); however considering its general altitude and erosional dissection, it is here considered much older than Alloformation II (see below), with a tentative age of at least late Miocene.

Alloformation II, situated in the eastern part of the Neuquén embayment, includes the Barranca de Los Loros, El Palo and Bayo Mesa Formations (Fig. 4) (Uliana, 1979); It unconformably overlies a bedrock composed of Cretaceous-early Cenozoic units (Malargüe Group). On the basis of vertebrate fossil remains of Friasian age collected from the lower section, a middle Miocene - early Pliocene age was attributed to the unit (Uliana, 1979*)*. Alloformation II composes a high flat level that slopes eastwards from 400 m a.s.l. at the western end to 360 m a.s.l. at the distal eastern part. It is the present watershed between the Colorado, Neuquén and Negro rivers. The unit is composed of three lithological sedimentary sets genetically linked, which consist of 30 m of reddish silty deposits alternating with light-brown siltstones with stratification, corresponding to a floodplain environment of a major fluvial system. The sequence ends with a 10–15 m thick fluvial conglomerate level composed of basaltic rounded clasts capped by a calcrete crust (Fig. 6).

Alloformation III extends northwards of the Colorado River, and surrounds the Chadileuvú block (Fig. 5); the altitude is ~560 m at the western part, descending progressively to ~60 m eastwards, south of Bahia Blanca. In the type locality area (25 de Mayo locality) Tedesco et al. (2015) subdivided the succession into a lower section and upper section. The lower section, ~45 m thick and predominantly composed of sandy-clay deposits, is interpreted as the result of sandy channels of a braided river that becomes deeper toward the top where the scarce presence of mudstones is explained as a decrease in accommodation space. The upper section, 5–10 m

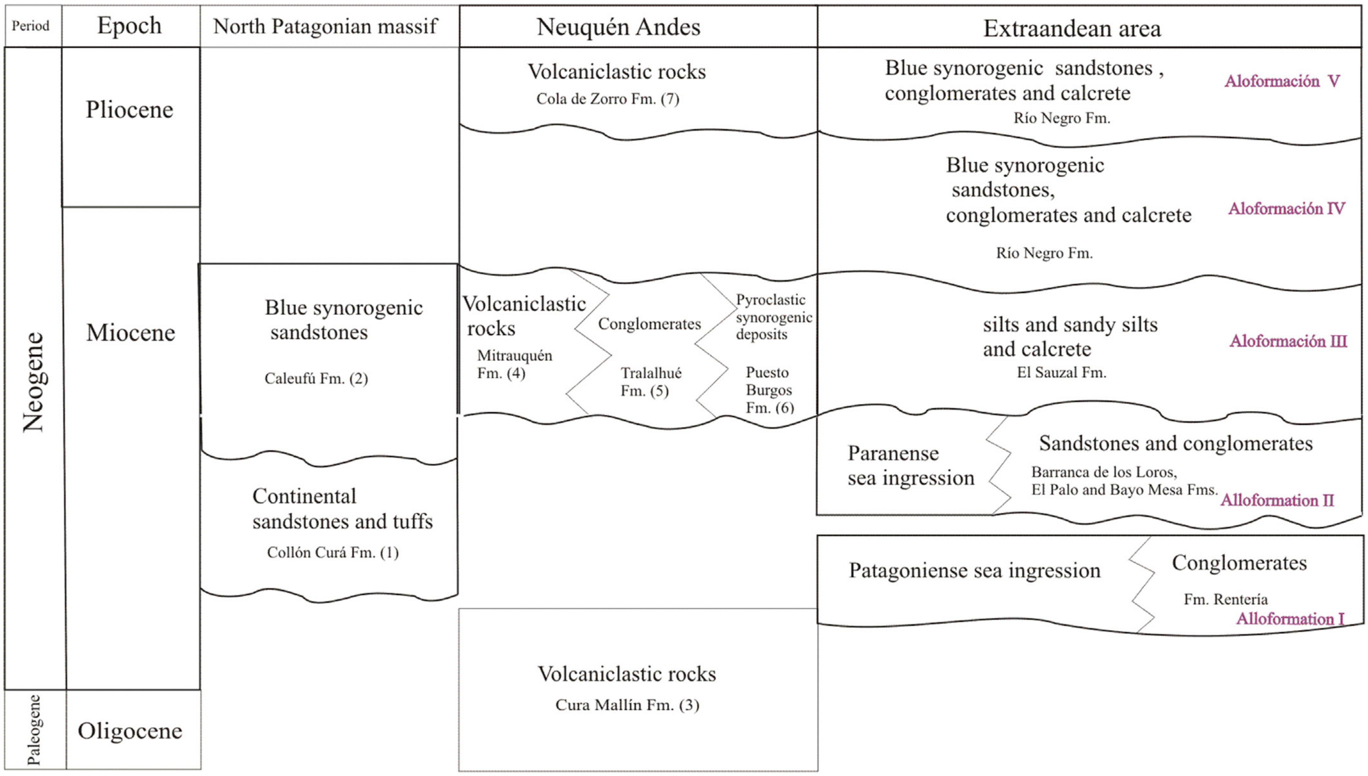

Fig. 4. Correlation among the erosional unconformities between the alloformations and the unconformities reported in the Neuquén Andes and North Patagonian massif. (1) Yrigoyen (1969); (2) González Díaz et al. (1986); (3) Niemeyer et al. (1983), Jordan et al. (2001a,b); (4) Suarez and Emparán (1997); (5) Ramos (1998); (6) Leanza and Hugo (2001); (7) Linares et al. (1999).

thick, is made up of clast-supported conglomerates consisting of well-rounded and imbricated pebbles dominantly composed of intermediate volcanic rocks, and secondarily by red sandstones, acid volcanic rocks and sandstones. The upper section is interpreted as a high energy braided river system within a huge alluvial fan (Tedesco et al., 2015). The uppermost part is strongly cemented with calcium carbonate giving way to a calcrete crust. Vertebrate fossil remains collected from the unit near Puelches, belong to the Huayquerian stage-age (Visconti et al., 1995), and suggest a late Miocene age for the unit. West and northwest of the Chadileuvú Block, the deposits were grouped into El Sauzal Formation (Llambías, 1975); it was also mapped under the name of Colorado River paleofan (Rimoldi and Silva Nieto, 1999), interpreted as synorogenic deposits by Ramos (1999).

Alloformation IV extends across the center and southern part of the Northern Patagonian basin (Fig. 5). It includes the Río Negro Formation, the Río Colorado Gravels (*Rodados del Río Colorado*), and the Calcrete II (Folguera, 2011). The unit has a gentle slope descending from 530 m a.s.l. to 30 m by the Atlantic coast. It is composed of lake and aeolian interbedded deposits (Etcheverría et al., 2006). An early Pliocene minimum age is tentatively attributed on the basis of their general stratigraphic relationships and altitude and relative degree of erosional dissection.

Allostratigraphic unit V is located around the mouth of the Negro river with its apex near General Conesa; the altitudes range from ~320 m in the western part to ~30 m by the Atlantic coast. The succession corresponds to the upper stratigraphic levels of the Río Negro Formation (Andreis, 1965) composed of aeolian sandstones with interbedded fine sediments accumulated in small lakes; volcanic ash layers including one dated at 4.41 ± 0.5 Ma (Alberdi et al., 1997) in the upper section, and paleosols are present throughout the succession.

5. Discussion

5.1. Foreland depocenters (architecture of the basins)

Two foreland basins system of the study region have been identified on the basis of the Neogene stratigraphy, the sedimentological features, the areal distribution of the units, along with the inferred chronology.

5.1.1. Southern Pampas basin

In the Southern Pampas basin, the depocenter of the Chasiquean-Huayquerian fauna bearing deposits is displaced eastwards in relation to the depocenter of the Colloncuran fauna bearing deposits (13.8–15.5; according to SALMA) (Silvestro et al., 2005). This eastwards migration might be associated with the fill up of the foreland basins situated at the foot of the Andes, and a later *by-pass* towards more distal areas. As a result, the late Miocene depocenter is located more than 800 km away from the orogenic front with a fairly constant average thickness of ~200 m across 1000–1500 km along strike (wavelength of >500 km). The volume of synorogenic deposits accumulated is here estimated at ~18,700 km^3. The deposits characteristics, in turn, indicate a low-energy sedimentary environment with gentle gradients across the foreland.

The widely distributed and relatively thin and fine-grained sedimentary successions with paleosol levels (Folguera and Zárate, 2009) suggest a large and uniform accommodation space in the distal Andean foreland (e.g., DeCelles and Giles, 1996; DeCelles and Horton, 2003; Dávila et al., 2007).

The thickness, the tabular geometry, as well as the wide areal extension and the occurrence of paleosols of the late Miocene sedimentary record of the Pampa Central block permit to interpret

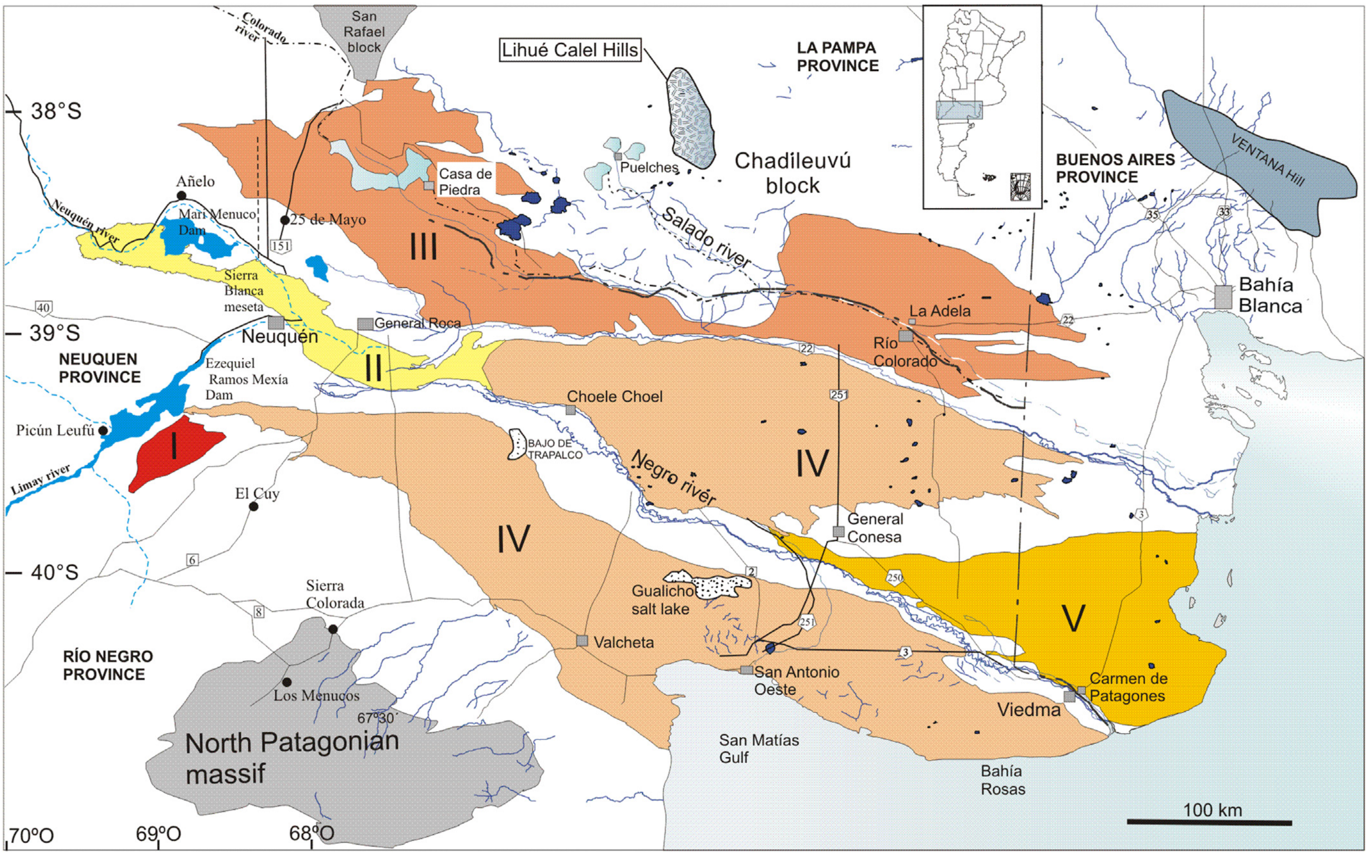

Fig. 5. Scheme of the Northern Patagonian basin showing the distribution of the alloformation I, II, II, IV and V.

this region as a sedimentary setting of reduced accommodation space. The presence of discrete paleosol levels indicates episodic aggradation, which together with the topmost calcrete crust suggest low rates of sedimentation and subsidence.

All these point to the presence of a late Miocene forebulge in the Pampa Central block, although it shows evidences (Folguera and Zárate, 2011) of tectonic reactivation by the end of the Miocene.

So far, no evidences of forebulge migration have been found, suggesting that it might have remained stationary for several million years.

In this scenario, the backbulge might be located eastward of the Macachín Basin, embracing the Bonaerian High (Fig. 7), comprising a shallow trough located between the forebulge and the Río de la Plata craton that accommodates thin distal deposits.

The proximal foredeep depocenter, considering the characteristics and the thickness of the aeolian and fluvial beds of the Cerro Azul formation exposed in the San Rafael block (Figs. 2 and 5) may have been located between the orogenic front that was situated along the Malvinas fault and the Curacó river during the late Miocene. The Alvear Basin with a thicker upper Miocene succession according to the scarce available information (Criado Roqué and Ibañez, 1979) could be considered as part of the foredeep.

On the basis of the analogue of the easternmost Sierras Pampeanas (see Dávila et al., 2010), the Southern Pampas Basin might be considered as a fossil and incipient broken foreland system (cf. Jordan, 1995; Jordan et al., 2001a,b). The basement faults may have served as lines of flexural rigidity that determined the location of the forebulge and back-bulge in response to a change in the Nazca plate geometry. Consequently, the foreland accommodation space might have been limited by the uplift of the forebulge (Pampa Central block) at ~6.8 Ma (Fig. 8) (Folguera and Zárate, 2009, 2011).

5.1.2. Northern Patagonian basin

In the Northern Patagonia basin the older alloformations are developed much closer to the orogenic front in comparison with the younger units, situated ~600 Km to the east. The total volume in this basin is here estimated at ~11500 km^3. The Northern Patagonian Basin characterized by low subsidence shows an anomalous geometry. The deepest depocenter is located in the Colorado Basin, far away from the main Andes domain. This basin exhibits a sinusoidal wavelength profile different from the Southern Pampas basin. It is featured by a long wave, very low sedimentation rate, and a poor development of the foredeep.

The characteristics of the deposits and the thickness of the successions (Alloformations I y II) (Fig. 9) suggest that the foredeep depocenter (cf. DeCelles and Giles, 1996) might have been located between the cities of Neuquén and Choele Choel (Fig. 8). The forebulge, in turn, might be placed near the locality of Choele Choel, as suggested by geophysical studies from Kostadinoff et al. (2005), who pointed out the presence of a subsurface structural high; no sedimentation has been mentioned in this area (Escosteguy et al., 2011). The backbulge depozone might have been located eastwards along the Negro and Colorado rivers, embracing the Negro and Colorado fluvial basins as well as the southern Bonaerian High (Fig. 9). This distal depocenter is filled with sediments generated by a braided river system (e.g., Alloformations III, IV y V).

The Northern Patagonian basin is characterized by the recurrence of Neogene cycles of sedimentation (Allofomations I, II, III, IV and V) that suggest periods of subsidence alternating with intervals of no subsidence (dominant erosion or soils/calcretes development). The scarce sedimentation recorded in the foredeep indicates that the subsidence was not significant during the late Miocene. When the foredeep was active the sedimentation was

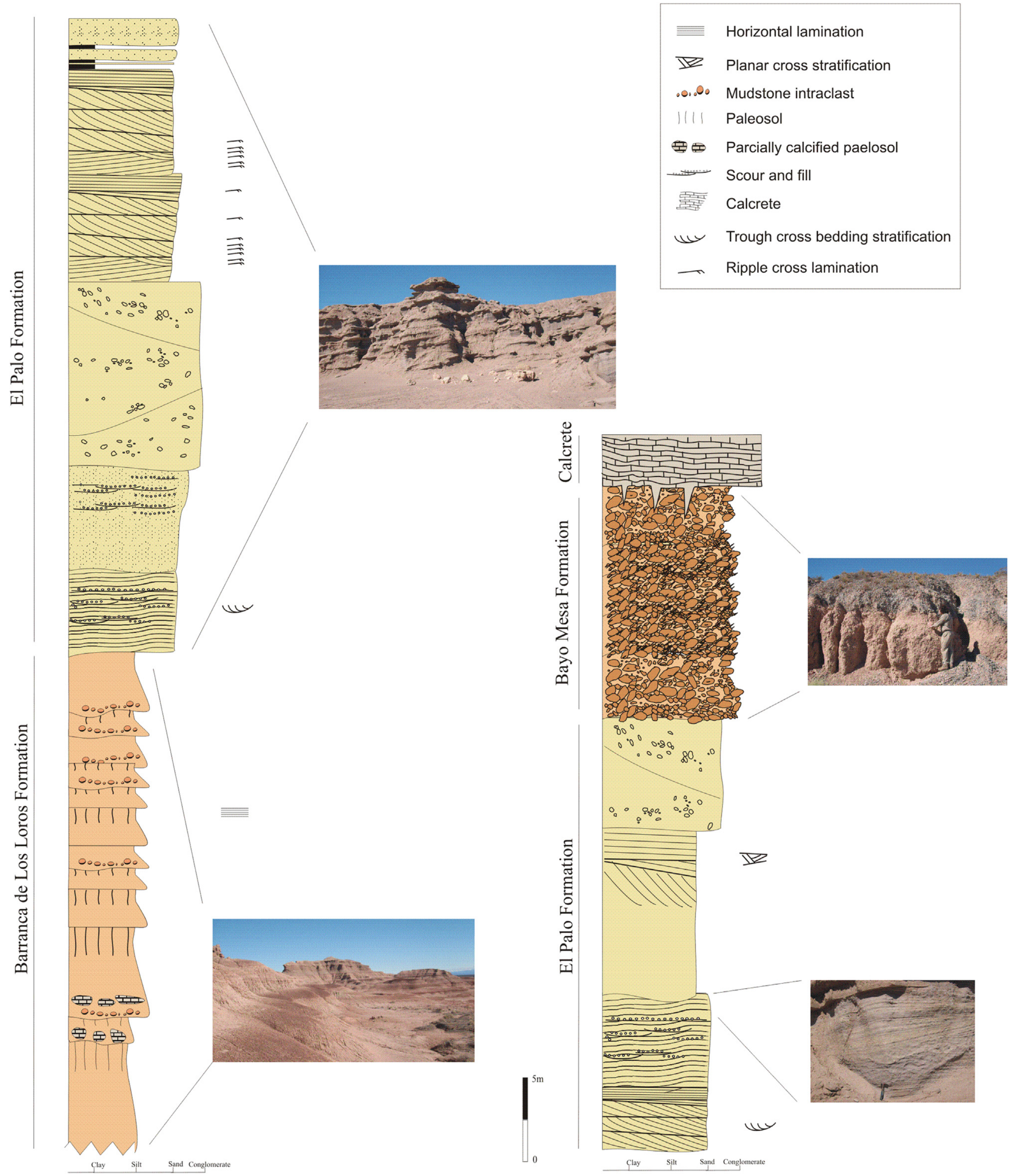

Fig. 6. Schematic Alloformation I unit outcropping in the meseta Sierra Blanca.

very much reduced in the backbulge (Fig. 10). Accommodation space was no more available in the foredeep after El Sauzal deposition, beginning the by-pass sedimentation to the East (backbulge). During the basin activity, the forebulge was not reactivated with increasing migration of the synorogenic sedimentation from the deformation front to more distal sections. The isopach map of the Northern Patagonian basin shows an increasing sedimentary thickness from the area of Neuquén city in the west to the Atlantic coast to the east (Fig. 9). In addition, the typical coarsening and thickening upward successions suggest an eastward migration of the depocenter, consistent with the eastward shifting of the deformation front.

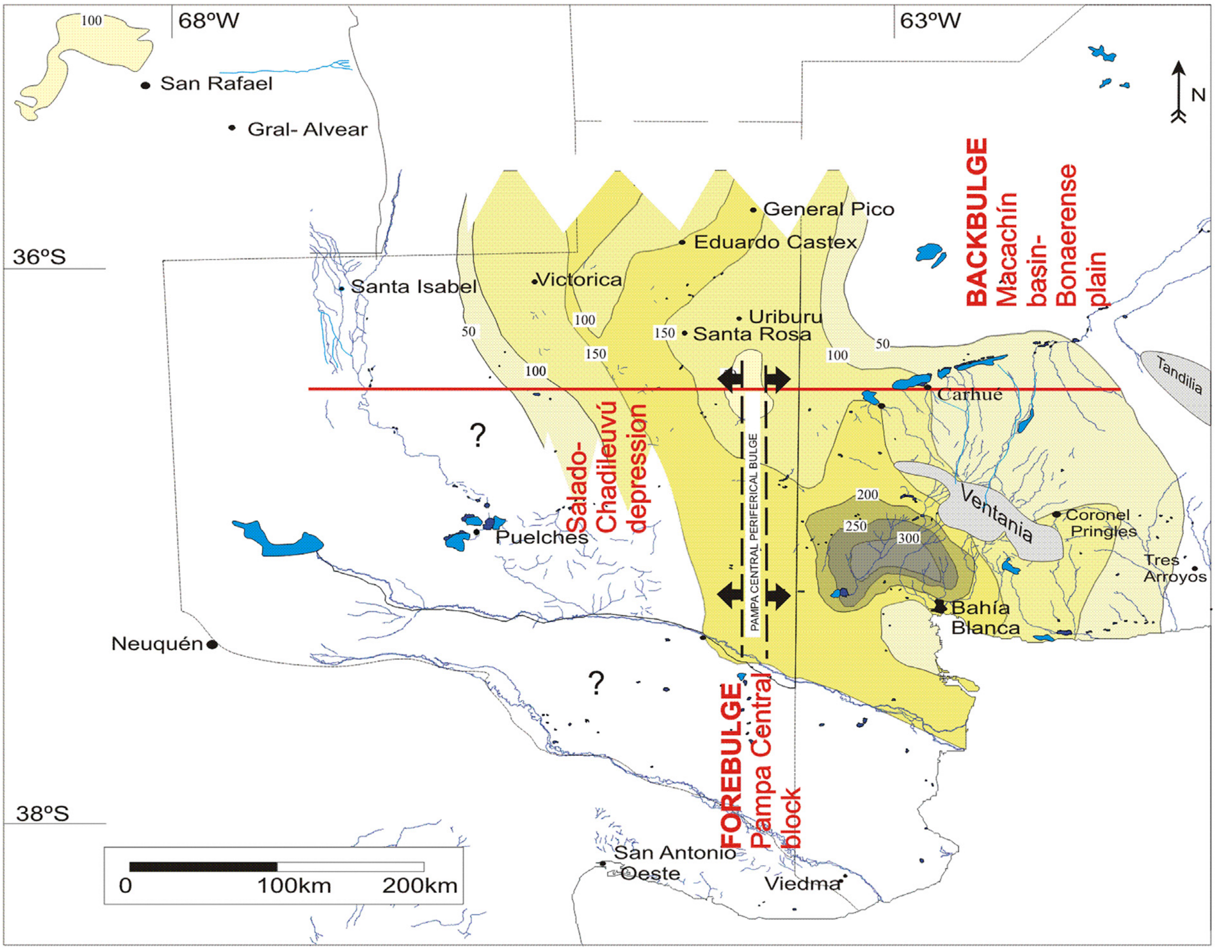

Fig. 7. Isopach map of late Miocene deposits to the Southern Pampa basin and it's proposed geometry.

6. Subsidence mechanisms

6.1. Southern Pampas basin

The shortening and tectonic loading have been considered as the main controls in the subsidence history of the Andes foreland (e.g. DeCelles and Horton, 2003; among many others). However, the mismatching between flexural models and basin observations led some authors to propose a sublithospheric and dynamic contribution in the generation of negative topography -or subsidence-in the Sierras Pampeanas area (e.g., Dávila et al., 2005, 2007; 2010; Dávila and Lithgow-Bertelloni, 2013). This dynamic force is non-isostatic and proportional to convection forces driven by density anomalies introduced into the mantle during subduction (see Mitrovica et al., 1989; Gurnis, 1992; Dávila and Lithgow-Bertelloni, 2013). Dynamic subsidence has been described as a phenomenon affecting large areas, even cratonic belts located at great distances from the orogenic fronts and trenches. Dávila et al. (2005, 2007; 2010) proposed that the dynamic subsidence affected the pericratonic areas of the foreland in the northern Pampas. In that region flat-slab subduction has affected the Argentine foreland from the late Miocene to the Present. In contrast to what it has been previously proposed, these studies suggested that dynamic subsidence in flat-slab settings only occurs from the subducting leading edge of the slab to the mantle wedge. Low subsidence rates are registered along the flat subduction belts. This is consistent with the observations and modeling across South America (Dávila and Lithgow-Bertelloni, 2013).

Niviére et al. (2013) performed a geomorphologic analysis of the Central Pampa (37°S) and proposed a model compatible with a flexural morphology on the basis satellite images and flexural models. The suggested geometry is similar that proposed by Folguera (2011), where the Salado-Chadileuvú river basin represents the foredeep, the Pampa Central block the forebulge and the Pampa Deprimida, the backbulge. Niviére et al. (2013) also suggested that the forebulge has changed from a buried forebulge to an eroded forebulge at Present.

In the Southern Pampas basin, as mentioned above, the basin geometry and deposits distribution cannot be only explained by supracrustal tectonic loading or shortening. Likewise, we propose that dynamic forces might have contributed to the generation of the accommodation spaces, which might have also assisted in the preservation of the forebulge sequences of two hundreds of meters of deposits.

If the hypotheses of dynamic subsidence were correct and valid for the Southern Pampas basin, a flat-slab subduction scenario should be required for the Mio-Pliocene to drive the sublithospheric down-welling forces into the mantle to more than 500 km away from the trench. Based on the volcanic studies, Kay (2001) proposed a flat subduction regime during the Mio-Pliocene along a segment that embraces the study area. This flat subduction and basin history correlate with the deformation history across the

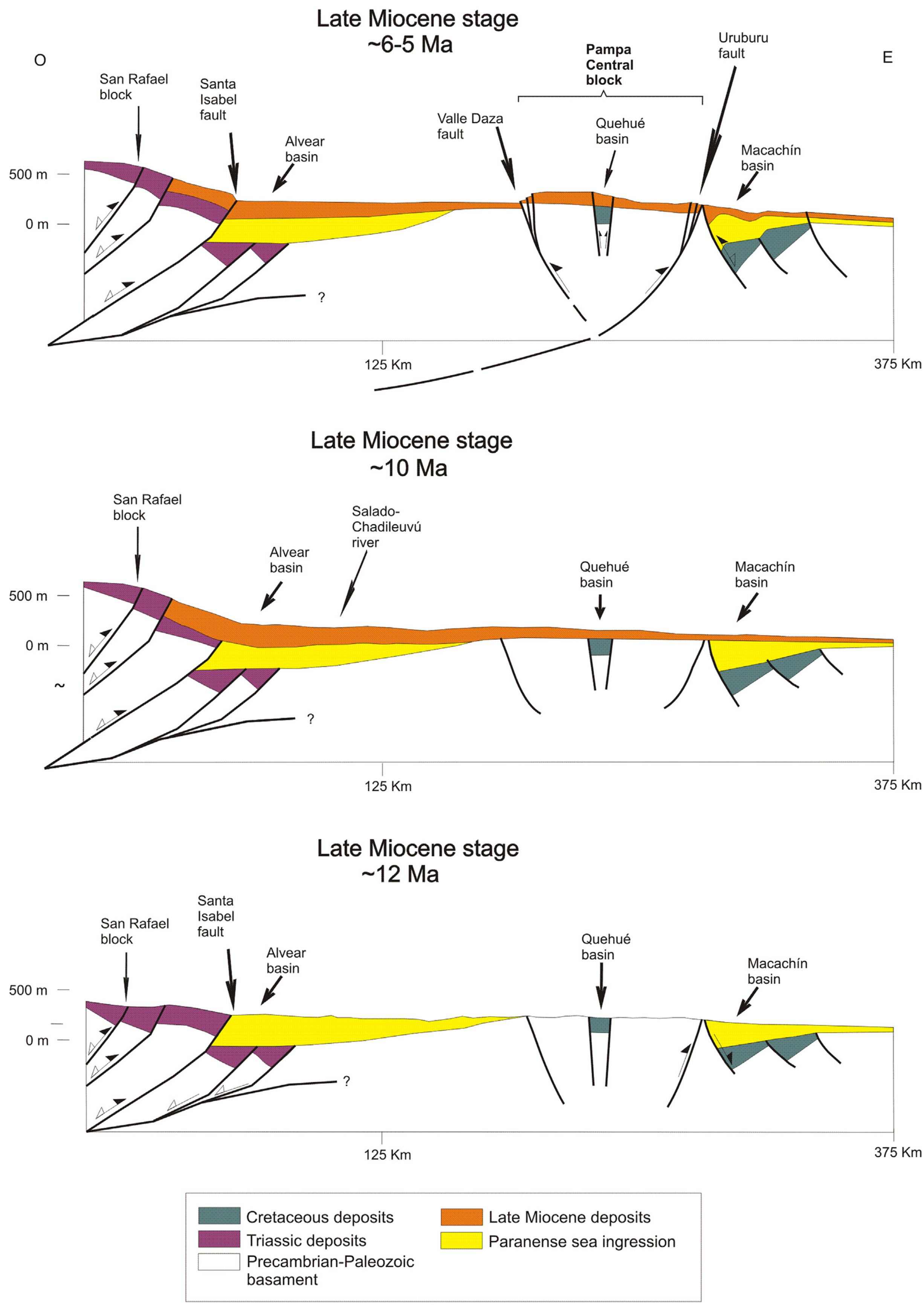

Fig. 8. Southern Pampa basin evolutionary scheme, with development and further cannibalization of the synorogenic basin.

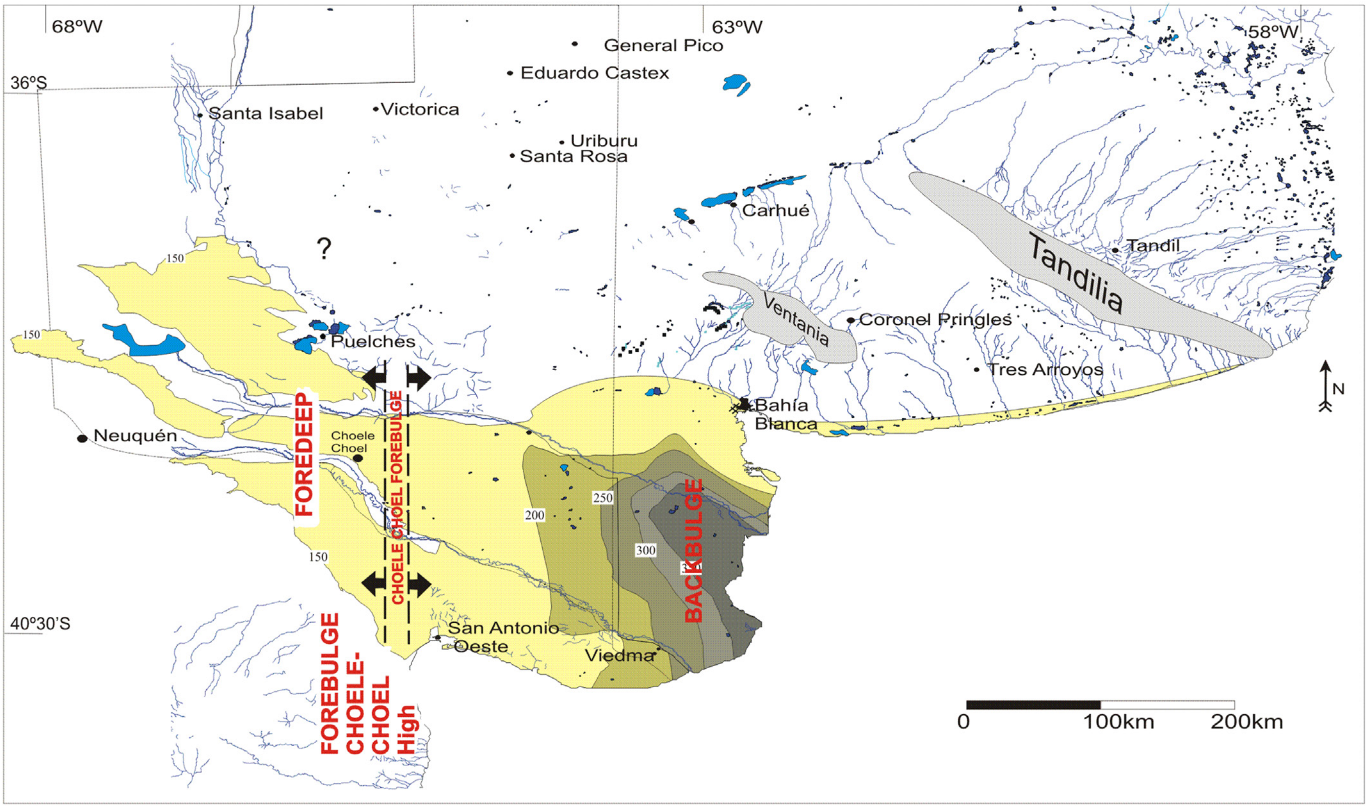

Fig. 9. Isopach map of Pliocene deposits.

distal foreland proposed by Folguera et al. (2005a,b) and Ramos and Folguera (2005).

6.2. Northern Patagonia basin

The sedimentation pattern in this basin is very different from that of the Southern Pampas basin, suggesting the occurrence of different controlling mechanisms. Catuneanu (2004) proposed that the relation between the rates of dynamic loading and flexural loading is the controlling factor of the base level and the stratigraphic architecture in foreland basins. It is here proposed that the accommodation space in the Northern Patagonia Basin was generated by flexural tectonics related to orogenic loading and dynamic subsidence acting at different scales.

The need to explain the erosive and depositional cycles above described for the northern Patagonian basin leads to the proposal of a model of alternating periods of dynamic subsidence with others of no active dynamic subsidence.

In the foredeep, subsidence is probably more related to tectonic loading than dynamic subsidence, because of its proximity to the orogenic front. The activity of this sector started at ~14 My. The sedimentation is related to the filling of the Andean synorogenic basin and the by-pass towards the foreland. This process generated the accumulation of the older alloformations (I and II). A tectonic pulse may have reactivated the basement structures producing the foredeep uplift; in turn, this may have triggered the erosion of the deposits. Calcretization took place in uplifted and exposed surfaces during intervals of tectonic quiescence and low sedimentation.

The backbulge sedimentation is considered to occur in active orogenic periods which generate dynamic subsidence, alternating with periods of tectonic quiescence when isostatic rebound is produced that results in uplift. Consequently, dissection takes place, and gives way to the occurrence of a regional unconformity. As a result, backbulge sedimentation was not continuous, but rather episodic, and related to Andean tectonic pulses that reactivated regional dynamic subsidence, generating accommodation space in very distal areas from the orogenic front. This dynamics acting repeatedly would be responsible for the genesis of alloformations III, IV and V, and the unconformities between them (Fig. 11).

An alternative plausible explanation is the relationship of the deposition and erosion events with relative sea level changes since variations in the stratigraphic architecture of a foreland basin may be generated by eustatic variations. Nevertheless, the predominantly upward-coarsening sequences under analysis are deposited in areas of high rates of subsidence and sediment supply with minor eustatic influence in relation to tectonic activity.

Climate is another factor that must have been involved in the process of sediment accumulation in the basin. In this respect, Uba et al. (2005, 2007). Interpreted that a shift to more humid conditions in Neogene subandean settings of Bolivia generated an increased in sediment supply by the end of the Miocene–Pliocene. The late Miocene climate of the Northern Patagonia basin was under the influence of the rain shadow effect caused by the Andes uplift; hence sedimentation took place under general semiarid-arid conditions. In addition, the occurrence of conglomerates, interpreted as distal glacifluvial deposit in the area of Lago Aluminé (Neuquen) indicate Andean glaciation in the latest Miocene (Schlieder, 1989 in Rutter et al., 2012): This is the oldest glacial record so far reported at these latitudes which may have modulated the sediment supply by the time: No earlier late Miocene glacial records have been mentioned during the accumulation of Alloformation I and II. The evidences available so far allow us to hypothesize that the changes in accommodation space was controlled

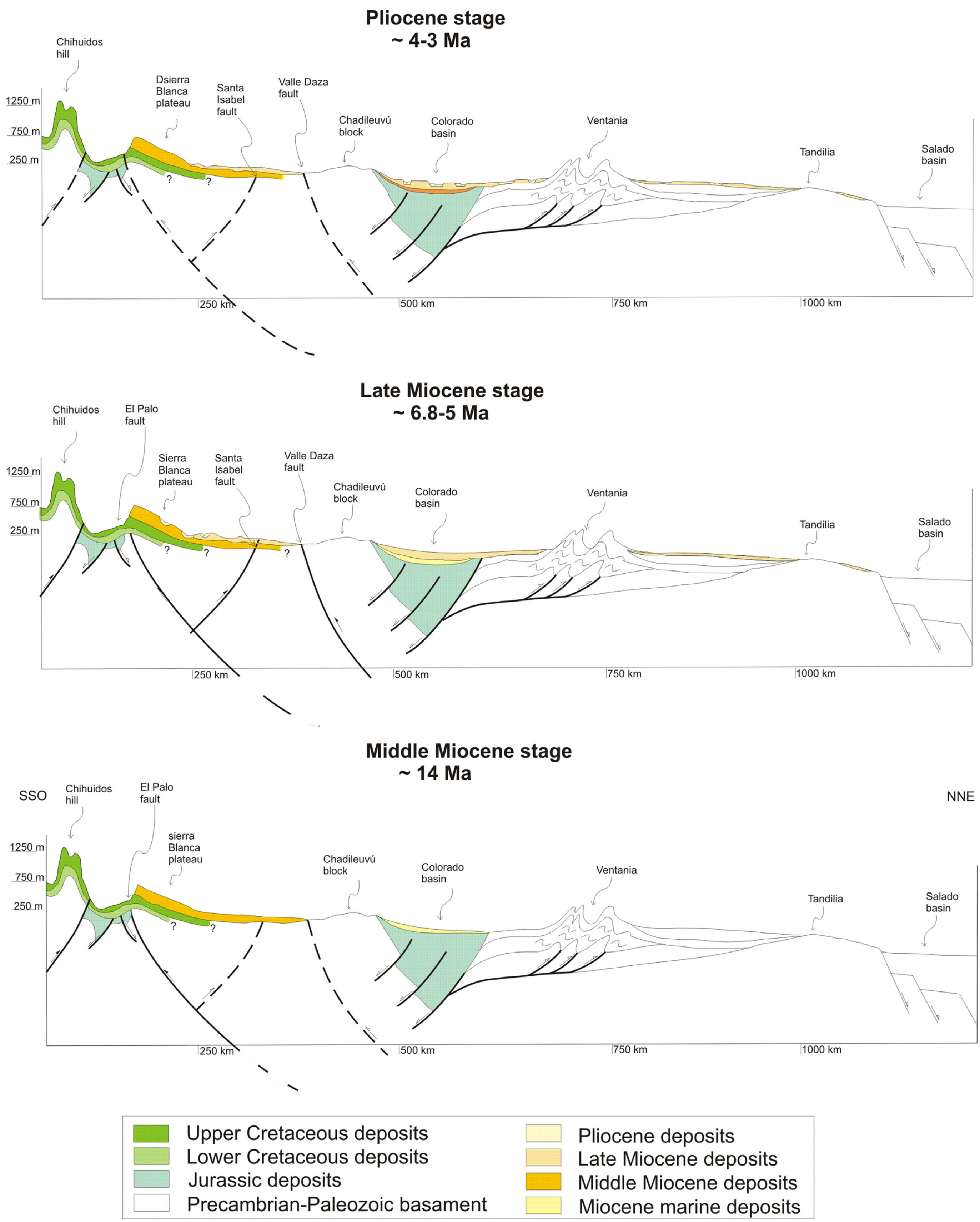

Fig. 10. Evolutionary scheme of the Northern Patagonian basin.

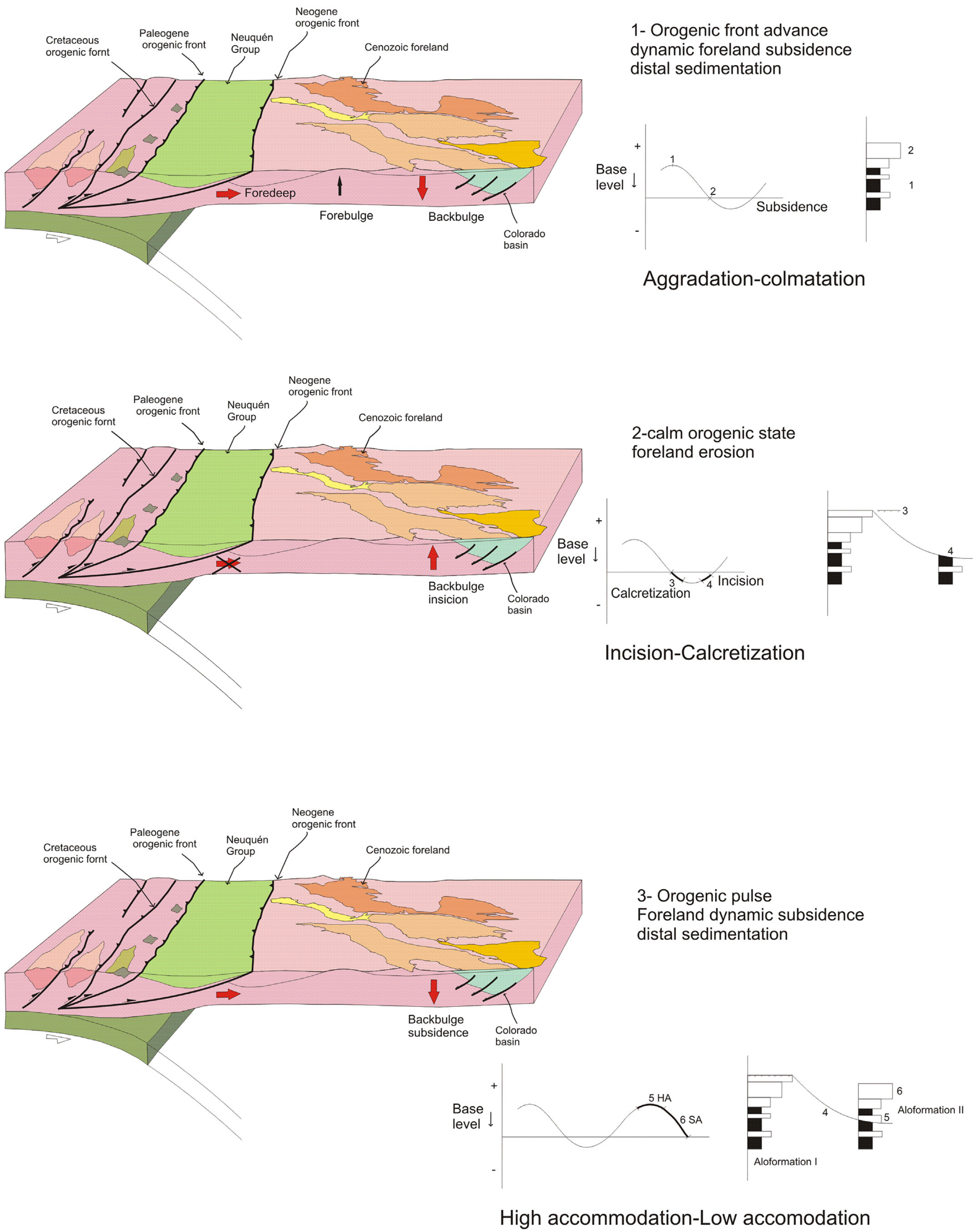

Fig. 11. Proposal model for the Northern Patagonian basin.

by tectonic dynamic, while the volume of sediment supply delivered to the basin was related to increased denudation during episodes of Late Miocene uplift at likely regulated by climatic conditions during the latest Miocene–Pliocene. Regarding the southern Pampa basin, the late Miocene and Pliocene pattern of alternation of loess-loess-like deposits and paleosols suggest a ciclicity that has been hypothetically related to changing climatic conditions (glaciation) with tectonism generating the conditions for glaciation to develop (Rutter et al., 2012).

7. Final remarks

The comparison between the Southern Pampa basin and the Northern Patagonia basin evidences different evolutionary histories during the Neogene as it is inferred from the arrangement, grain size, and age of their sedimentary fillings and the resulting geometries. The differences are thought to be associated with the dissimilar dynamic of the Andean segments along the western limit of the foreland.

The significant volume of synorogenic sediments accumulated in the basins, much larger than previously thought (Zapata and Folguera, 2004), were disregarded because of their location far away from the orogenic front. The Late Miocene record shows a dominance of fine grained sediments in the southern Pampa basin (loess and loess-like) and coarser sediments mainly of fluvial origin in the Northern Patagonian basin. The Pliocene record occurs in the Northern Patagonian basin including the sequences outcropping in the south of the Bonaerian High. Because of a result of the Pampa Central uplift that promoted the eastward by-pass of the sediments (likely the Salado tectonic basin of Buenos Aires), the Pliocene depocenter would have been situated in the back-bulge: Tandilia and Salado basin.

The basin geometry and facies distribution across the Southern Pampas in the Neogene is considered to be related to dynamic forces that might have contributed to the generation of the accommodation space and the preservation of the forebulge successions. In the Northern Patagonian basin the accommodation space is thought to be the result of discontinuous dynamic subsidence active during orogenic periods.

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