

# SR AGES FOR THE CHENQUE FORMATION IN THE COMODORO RIVADAVIA REGION (GOLFO SAN JORGE BASIN, ARGENTINA): STRATIGRAPHIC IMPLICATIONS

José I. Cuitiño <sup>1\*</sup>; Roberto A. Scasso <sup>2,3</sup>; Roberto Ventura Santos <sup>4</sup>; Luis H. Mancini <sup>4</sup>

<sup>1</sup> Centro Nacional Patagónico (CENPAT), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). Boulevard A. Brown 2915, Puerto Madryn 9120, Chubut, Argentina. jcuitino@cenpat-conicet.gob.ar

<sup>2</sup> Universidad de Buenos Aires, Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales.

<sup>3</sup> Instituto de Geociencias Básicas y Ambientales de Buenos Aires (IGeBA), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). Intendente Güiraldes 2160 (C1428EHA), Ciudad Autónoma de Buenos Aires, Argentina. rscasso@gl.fcen.uba.ar

<sup>4</sup> Universidade de Brasília, Instituto de Geociências. Campus Universitário Darcy Ribeiro (CEP 70910-900), Brasília, Brazil. rventura@unb.br; geochronos.lais@gmail.com

## ARTICLE INFO

### Article history

Received March 21, 2015

Accepted August 2, 2015

Available online August 19, 2015

### Handling Editor

Ernesto Schwarz

### Keywords

Chenque Formation

Miocene

Sr isotopes

Patagoniense transgression

Golfo San Jorge Basin

## ABSTRACT

The age and stratigraphic subdivisions for the late Oligocene-Miocene, marine deposits of Patagonia (Patagoniense succession) have been largely debated. Most studies for the Comodoro Rivadavia region were focused on its biostratigraphy and stratigraphic relations with the underlying and overlying mammal-bearing terrestrial strata. We report here thirteen new <sup>86</sup>Sr/<sup>87</sup>Sr ages obtained from well-preserved oyster valves of the Chenque Formation in the classical Patagoniense outcrops around the city of Comodoro Rivadavia (Golfo San Jorge Basin, Argentina). According to these ages, the deposition of the unit in the region occurred between 19.69 and 15.37 Ma (Burdigalian-early Langhian). A lower interval of normal sedimentation rate (Sequences 1 and 2) and an upper interval of high sedimentation rate (Sequence 3) are defined according to these new ages of the Chenque Formation. Subsequently, the depositional age of the Chenque Formation is compared with other well-dated marine successions of southern Patagonia located within the Austral Basin. This analysis suggests that the Austral and Golfo San Jorge basins were flooded by the Atlantic sea at about the same time (~21-20 Ma), inundating what was before a vast continental region of southern Patagonia. A renewed phase of continentalization occurred at about 18 Ma in the Austral Basin and at about 15 Ma in the study region of the Golfo San Jorge Basin. This 3 my difference combined with the elevated sedimentation rate estimated for the upper part of the study interval, suggest that the Golfo San Jorge Basin may have locally experienced relatively high subsidence rates during the early Miocene, allowing prolonged marine sedimentation in the Comodoro Rivadavia area. Consequently, the accumulation of the terrestrial deposits assigned to the Santa Cruz Formation started at about 15 Ma in the study region, later than in other localities of southern Patagonia. This results clearly indicate a remarkable interdigitation between the Santa Cruz and Chenque formations in a west-east transect across central Patagonia.

## INTRODUCTION

The shallow-marine Patagoniense deposits comprise a sedimentary succession mostly of late Oligocene-Miocene age that crops out extensively in Patagonia (Fig. 1). This succession accumulated in several basins, particularly in the extra-Andean region, as a result of a major Atlantic transgression. The depositional age, stratigraphic subdivisions, and correlations in such a large area have been a matter of debate since the first studies by Darwin, D'Orbigny, Florentino and Carlos Ameghino, Hatcher, and Ortmann (for a detailed list of contributions see Ameghino 1906; Feruglio, 1949-1950; Bertels, 1970; Camacho, 1995; del Río, 2004; Parras *et al.*, 2012; Cuitiño *et al.*, 2012). Recently, a number of publications devoted to the geochronology of the Miocene deposits in the Austral Basin provided a high-resolution chronostratigraphic framework for the Patagoniense succession in that region (Cuitiño *et al.*, 2012; Parras *et al.*, 2012; Perkins *et al.*, 2012; Cuitiño *et al.*, 2015). However, the precise age of the Patagoniense and related terrestrial Miocene deposits in the Golfo San Jorge Basin remained uncertain.

The objective of this paper is to report new  $^{87}\text{Sr}/^{86}\text{Sr}$  ages from oyster shells that allow constraining the depositional age of the marine deposits belonging to the Chenque Formation in the Comodoro Rivadavia region, a classic Patagoniense locality of the Golfo San Jorge Basin. The new data, checked by means of stable isotopes and stratigraphic coherence, is consistent with age determinations for the Austral Basin, providing a solid across-basin chronostratigraphic framework for the Patagoniense succession and overlying terrestrial units (i.e., the Santa Cruz Formation). In light of the new results, a second objective is to discuss the implications of these new ages for the stratigraphy of marine and terrestrial strata of the Golfo San Jorge Basin during the early Miocene.

## STRATIGRAPHIC BACKGROUND

### Stratigraphy of the Patagoniense succession

Ameghino (1906), based on mollusk biostratigraphy and stratigraphic relations with terrestrial mammal-bearing strata, subdivided his marine Formación Patagónica into an older Juliense and a younger Leonense stages. This author also

recognized a younger marine stage within his overlying Formación Santacruceña, called the Superpatagoniense stage. This stratigraphic scheme was proposed for most of the Cenozoic coastal outcrops of Chubut and Santa Cruz provinces, including the study area of this contribution. It is not the objective of this work to focus on the long-lived discussion about these stages. An exhaustive analysis on the evolution of the stratigraphic proposals for this unit can be found in Feruglio (1949-1950), Camacho (1979) and Griffin and Parras (2012). Camacho (1979, 1995) analyzed the historical meaning and use of terms such as Formación Patagónica, Patagoniano and Patagoniense, whereas Legarreta and Uliana (1994) discussed the biostratigraphic criteria used to date these units. In this contribution we refer as "Patagoniense" to all the late Oligocene-early Miocene marine successions of Patagonia related to the Atlantic transgression.

In the Austral Basin (Fig. 1), the Patagoniense succession comprises several lithostratigraphic units (Fig. 2). In the southeast region of Santa Cruz it is represented by strata of the San Julián and Monte León formations (Bertels, 1970)), whereas in the southwest of Santa Cruz and Sierra Baguales in Chile, it is represented by the Estancia 25 de Mayo Formation (Cuitiño and Scasso, 2010; Bostelmann *et al.*, 2013). In the northwest of Santa Cruz and the region of Aisén in Chile, it comprises the El Chacay/Guadal formations (Chiesa and Camacho, 1995; De la Cruz and Suárez, 2006). Finally, in the Golfo San Jorge Basin (Fig. 2), strata of the Patagoniense comprise the Chenque Formation (Bellosi, 1990). The older San Julián Formation recognized in southeastern Santa Cruz was traditionally assigned to the Late Eocene-Oligocene, but recent studies suggest its age is limited to the Oligocene (Chattian; Parras *et al.*, 2012; Fig. 2). This unit is excluded from our analysis because time-equivalent deposits are not present in the Comodoro Rivadavia area.

Age estimations for the Patagoniense succession have been approached from different disciplines, which include physical correlation and sequence stratigraphy (Legarreta and Uliana 1994; Bellosi, 1995), palynology (Bellosi and Barreda, 1993), invertebrate biostratigraphy (Ameghino, 1906; Camacho and Fernández, 1956; Bertels 1970; del Río 2004), and isotopic dating (Parras *et al.* 2008, 2012; Cuitiño *et al.*, 2012; Cuitiño *et al.*, 2015).

The Patagoniense deposits were considered as old

as Eocene (Camacho and Fernández, 1956) because it bears the bivalve *Venericardia planicosta*. Based on foraminifera studies Bertels (1970) assigned the Monte León Formation to the late Oligocene (Chattian), Bertels and Ganduglia (1977) gave a similar age to the Patagoniense deposits at Astra (near the city of Comodoro Rivadavia), and Malumián *et al.* (1999) suggested an age ranging between 26 and 20 Ma for the “Transgresión Patagoniana”, mostly equivalent to the Monte León Formation. Later on, Malumián (2002) extended the age of the transgression in the Golfo San Jorge Basin up to the middle Miocene (Neogene climax). More recently, del Río (2004) defined several molluscan assemblages within the Patagoniense succession. Two of them, the JR (*Jorgechlamys centralis*–*Reticulochlamys borjasensis* of late Oligocene–early Miocene age) and the NVG (*Nodipecten* sp.–*Venericor abasolensis*–*Glycymerita camaronesia* of latest early Miocene to earliest middle Miocene), were found in the sections close to Comodoro Rivadavia and Astra (Fig. 3). There, however, the age of the JR assemblage seems to be not older than early Miocene (see figure 15 of del Río, 2004), in agreement with the palynological associations of Barreda and Palamarczuk (2000).

Palynological studies and sequence-stratigraphic correlation with the Global Cycle Chart (Haq *et al.*, 1987, 1988) led Belloso and Barreda (1993) to assign ages from 25.5 to about 16 Ma for the Patagoniense in the Golfo San Jorge Basin. Mammal biostratigraphy and sequence-stratigraphic correlation with the same global chart allowed Legarreta and Uliana (1994) to propose an age between 30 and 21 Ma for the lower part of the Patagoniense in the area of Comodoro Rivadavia, and an age between 21 and 10.5 Ma for the upper part of the unit. For the same strata, Belloso (1995) proposed two separated transgressions, an older one (Leonense) with ages between 26 to 21 Ma, and a younger one (Superpatagoniense), with ages between 19 to 16 Ma. Later on, Barreda (1996) assigned the Chenque Formation to the late Oligocene? - early to middle? Miocene in the area of Comodoro Rivadavia-Cañadón Bauman, based on four spore and pollen assemblages and their comparison with New Zealand, Australia and Antarctica assemblages. Palamarczuk and Barreda (1998) arrived to similar conclusions studying dinoflagellate cysts, but suggested a slightly younger age (early Miocene) for the lower part of the Patagoniense in the Cerro Chenque area. Barreda

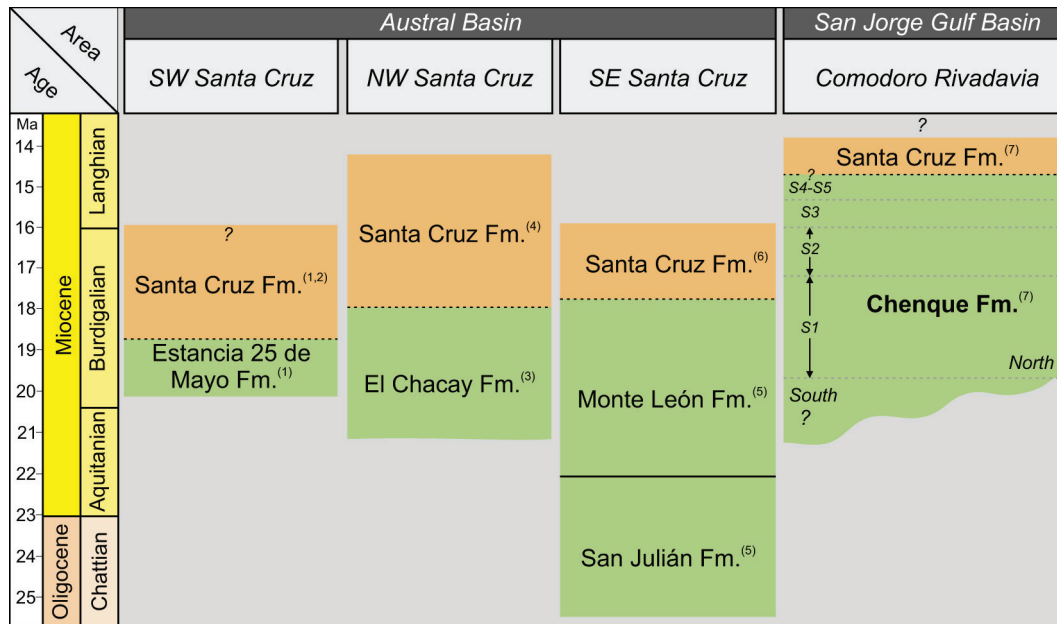


**Figure 1.** Regional location of the studied sites. The shadowed area represents the distribution of Patagoniense deposits after Malumián *et al.* (1999). The approximate boundaries of the Golfo San Jorge (GSJ) and Austral basins are indicated with brown, dashed lines.

and Palamarczuk (2000) proposed four informal Angiosperm pollen and dinocyst associations that span from the late Oligocene to the late early/middle Miocene. The three younger associations (early Miocene-middle Miocene) are present in the area of Comodoro Rivadavia.

### Isotopic ages for the Patagoniense succession

Recent advances in geochronology methods allow several authors to date the Miocene successions of the Austral Basin more precisely. This provided a more accurate chronostratigraphic framework for some key regional geologic events, such as the deposition of the Patagoniense succession, which allows for comparison to other areas of Patagonia.  $^{87}\text{Sr}/^{86}\text{Sr}$  studies for the Patagoniense succession of several regions of Santa Cruz Province (Parras *et al.*, 2008) yielded ages between 23.8 and 25.9 Ma (Chattian, late Oligocene) for the San Julián



**Figure 2.** Chronostratigraphic chart of the studied succession and correlative units in southern Patagonia (Austral Basin) based on isotopic age determinations. Modified after Cuitiño *et al.* (2012). Superscript numbers indicate source of information: 1) Cuitiño *et al.* (2012); 2) Bostelmann *et al.* (2013); 3) Cuitiño *et al.* (2015); 4) Blisniuk *et al.* (2005); 5) Parras *et al.* (2012); 6) Perkins *et al.* (2012); and 7) This work. S1 to S5 indicate the approximate age of depositional sequences defined by Bellosi (1987, 1990). Green color represents units composed largely of marine deposits; orange color represents units comprising mostly continental sediments.

Formation at its type locality; between 21.2 and 22.8 Ma (Aquitania, early Miocene) for the lower part of the Estancia 25 de Mayo Formation in Lago Argentino; and between 25 and 26.3 Ma (Chattian) for the equivalent Patagoniense El Chacay Formation deposits in the NW of the province. Additionally, Parras *et al.* (2008) provided a  $^{40}\text{Ar}/^{39}\text{Ar}$  age of 20.48 Ma (early Miocene) in a tuff interbedded in the lower part of the Patagoniense section in SW Santa Cruz. Later on, Parras *et al.* (2012) reinforced the Chattian age of the San Julián Formation with additional  $^{87}\text{Sr}/^{86}\text{Sr}$  ages and provided new Sr ages for the Monte León Formation between 22.1 and 17.9 Ma (Aquitania-Burdigalian) in SE Santa Cruz province (Fig. 2). U-Pb ages in zircons from tuffs at two separated levels combined with  $^{87}\text{Sr}/^{86}\text{Sr}$  ages in oysters support a Burdigalian age-range between 20 and 18.8 Ma for the entire Patagoniense column at the Lago Argentino region (Estancia 25 de Mayo Formation), in southwest Santa Cruz (Cuitiño *et al.*, 2012) (Fig. 2). The equivalent marine Patagoniense succession in NW Santa Cruz (El Chacay Formation) was dated by  $^{87}\text{Sr}/^{86}\text{Sr}$  from 20.1 Ma near the base to ~18 Ma at the top (Cuitiño *et al.*, 2015). The Burdigalian ages of the Patagoniense from SW to

NW of Santa Cruz suggest that previous Chattian  $^{87}\text{Sr}/^{86}\text{Sr}$  ages provided by Parras *et al.* (2008) in the same regions are anomalously older in comparison with the present chronostratigraphic scenario (Fig. 2).

Radiometric ages of the Santa Cruz Formation overlying all the marine Patagoniense successions in the Austral Basin are in concordance with the ages of the marine deposits (Fig. 2). In southeastern Santa Cruz the unit is dated by numerous  $^{40}\text{Ar}/^{39}\text{Ar}$  data from tuff layers between 17.7 and 16 Ma (Perkins *et al.*, 2012). Blisniuk *et al.* (2005) obtained six  $^{40}\text{Ar}/^{39}\text{Ar}$  ages varying from 22.36 to 14.24 Ma for the Santa Cruz Formation in the NW part of the Santa Cruz province, although Perkins *et al.* (2012) and Cuitiño *et al.* (2015) suggested that accumulation of the continental Santa Cruz Formation started at about 18 Ma. Using detrital zircon U-Pb dating, Bostelmann *et al.* (2013) estimated the beginning of deposition of the Santa Cruz Formation in southwestern Santa Cruz at about 18.8 Ma, in concordance with the age of the underlying Patagoniense deposits in that region (Cuitiño *et al.*, 2012) (Fig. 2).

In contrast to the Austral basin, previous isotopic ages for the Patagoniense succession of the Golfo San Jorge Basin are rare. Low-precision K-Ar radiometric



ages between  $25 \pm 5$  and  $30 \pm 3$  Ma (Linares, 1979; Riggi, 1979) were obtained for the Astra section, while Bellosi (1990) mentioned a radiometric age of  $26 \pm 2$  Ma for the base of the Chenque Formation at Pico Salamanca.

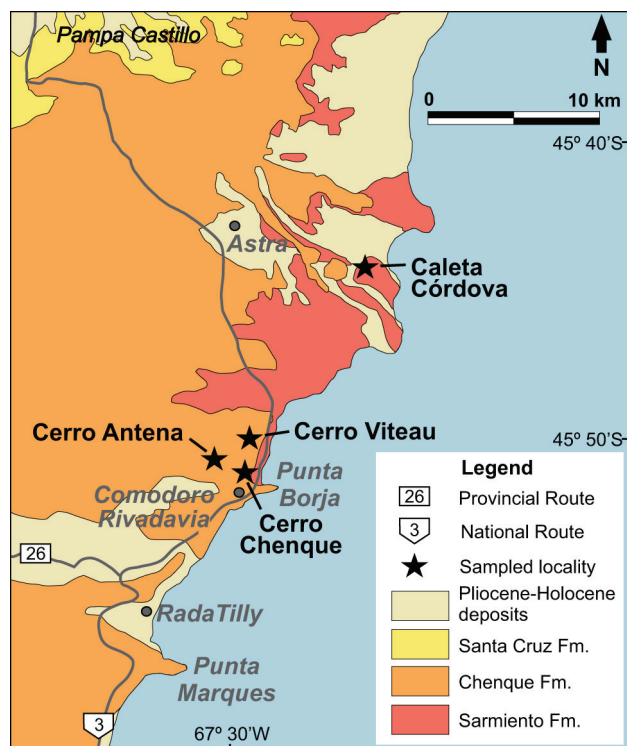
### STUDY AREA

The study area is located in the northern flank of the Golfo San Jorge Basin, in the coastal zone around the city of Comodoro Rivadavia, Chubut Province, where the Sarmiento, Chenque and Santa Cruz formations crop out (Sciutto 2000, 2008; Figs. 2 and 3). The Sarmiento Formation is composed mainly of whitish tuffs, deposited in a terrestrial environment (Bellosi, 1995, 2010; Sciutto 2000, 2008). This unit is exposed in the badlands just north of Comodoro Rivadavia, around Astra and Caleta Córdova (Fig. 3), where it is overlain by the Chenque Formation. Abundant tuff beds allowed the Sarmiento Formation to be precisely dated at Gran Barranca, to the west of the study area. U-Pb ages constrained the age of this unit from 40 to 19 Ma (late Eocene to early Miocene; Dunn *et al.*, 2013). In the study area the Sarmiento Formation is solely represented by the Gran Barranca Member (Bellosi, 1995), which is dated at about 40 Ma (Dunn *et al.*, 2013).

The contact between the Sarmiento and Chenque formations dips gently to the south and “sinks” below the sea-level at Punta Borja (Fig. 3), where it can be traced in the subsurface (Bellosi, 1987; Sciutto, 2000). The Chenque Formation makes up most of the hills around Comodoro Rivadavia like the Cerro Chenque, Cerro Viteau and Cerro Antena. Five stratigraphic sequences were defined for the Chenque Formation at a regional scale (Bellosi, 1987; Paredes and Colombo, 2001; Paredes, 2003). The lower three of them, and the lower part of the fourth, are nicely exposed in the study area (Fig. 4). The Santa Cruz Formation, composed of sandstone and mudstone beds of fluvial origin (Sciutto 2000; 2008), transitionally overlies the Chenque Formation. It crops out in the northwestern sector of the study area, along the elevated cliffs of the Pampa del Castillo tableland (Fig. 3).

### METHODOLOGY

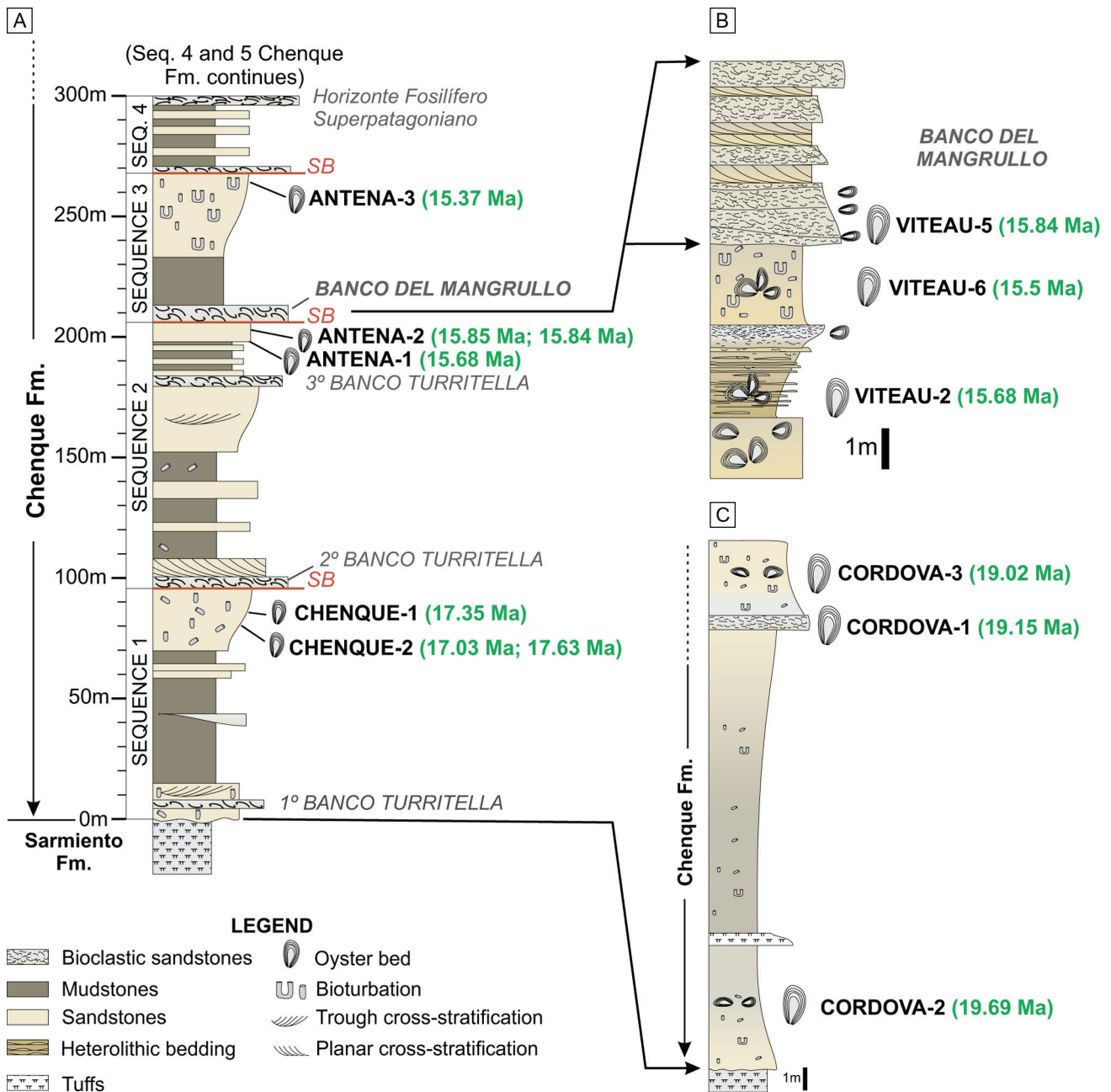
We sampled unbroken, well-preserved entire oyster valves for Sr-dating in the Chenque Formation.



**Figure 3.** Simplified geologic map of the study area after Sciutto (2000, 2008). Sample localities are highlighted with black stars.

Most of the samples come from Cerro Chenque, Cerro Viteau and Cerro Antena, but the base of the unit was sampled at Caleta Córdova (Figs. 3 and 4). Each valve was cut and polished for microstructure observation and microsampling, following the criteria established by Cuitiño *et al.* (2012, 2013). About 30 mg of calcite powder was obtained from each valve using a microdrill and avoiding chalky layers. From each microsample, a small aliquot of carbonate powder was used to perform  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotopic analyses, in order to check for diagenetic alterations or freshwater input into the marine environment where the oysters lived. The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotopic composition of the carbonates were determined by a Thermo Fisher DELTA V Plus Isotope Ratio Mass Spectrometer attached to Gas Bench II analyzer. The associated errors are 0.1‰ for  $\delta^{18}\text{O}$  and 0.05‰ for  $\delta^{13}\text{C}$ . Stable isotope results are expressed in the Pee Dee Belemnite (PDB) notation (Table 1).

Aliquots used for Sr ratio determination were initially attacked with an acid solution following by Sr separation using Teflon columns filled with 0.5 ml of Eichrom Sr Resin/50-100  $\mu\text{m}$ . The  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic ratio determinations of the samples were



**Figure 4.** Stratigraphic position of oyster samples that were used to calculate the  $^{87}\text{Sr}/^{86}\text{Sr}$  ages. a) Schematic composite section for the Chenque Formation integrating different outcrops from the Comodoro Rivadavia region (after Bellosi 1987, 1990; Paredes, 2003, and our observations). Sequences are numbered following Bellosi (1987) and Paredes (2003). SB: sequence boundary. b) Detailed section of the sampled interval at Cerro Viteau. c) Detailed section of the sampled interval at Caleta Córdova. Marker horizons after Feruglio (1949-1950). Green numbers are the  $^{87}\text{Sr}/^{86}\text{Sr}$  ages (see Table 1).

obtained by a Neptune ICP Mass Spectrometer and the analytical accuracy was estimated by the analysis of the NBS standard 987, which produced a mean value of  $0.710243 \pm 0.0000102$  ( $N = 21$ ).

Age calculations from  $^{87}\text{Sr}/^{86}\text{Sr}$  are based on the Look-Up Table Version 4B: 08/04 of McArthur *et al.* (2001) with an uncertainty of 0.07 my derived from

the mean curve. All  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  analyses were carried out at the Geochronos Laboratory of the University of Brasilia, Brazil.

## RESULTS

Thirteen  $^{87}\text{Sr}/^{86}\text{Sr}$  ages were obtained from

Locality	Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	Age (Ma)	$\pm$ (Ma)	$\delta\text{C13}$ (PDB)	$\delta\text{O18}$ (PDB)	Mean age*
Caleta Córdova	Cordova 3	0.70851	<b>19.02</b>	0.2	1.04	-0.01	
Caleta Córdova	Cordova 2	0.70846	<b>19.69</b>	0.2	1.49	0.27	<b>19.29</b>
Caleta Córdova	Cordova 1	0.70850	<b>19.15</b>	0.2	-2.89	0.00	
Cerro Chenque	Chenque 2b	0.70866	<b>17.03</b>	0.2	0.84	-0.18	
Cerro Chenque	Chenque 1	0.70864	<b>17.35</b>	0.2	0.77	-1.41	<b>17.34</b>
Cerro Chenque	Chenque 2a	0.70862	<b>17.63</b>	0.2	0.74	-1.00	
Cerro Antena	Antena 3	0.70876	<b>15.37</b>	0.2	-0.52	-3.91	<b>15.37</b>
Cerro Antena	Antena 2a	0.70873	<b>15.85</b>	0.2	-0.88	-1.00	
Cerro Antena	Antena 1	0.70874	<b>15.68</b>	0.2	1.39	-2.54	<b>15.79</b>
Cerro Antena	Antena 2b	0.70873	<b>15.84</b>	0.2	0.85	-2.81	
Cerro Viteau	Viteau 5	0.70873	<b>15.84</b>	0.2	1.96	-2.21	
Cerro Viteau	Viteau 2	0.70874	<b>15.68</b>	0.2	1.10	-2.41	<b>15.68</b>
Cerro Viteau	Viteau 6	0.70875	<b>15.52</b>	0.2	1.53	-1.36	

**Table 1.** Sr, C, and O isotope data. Ages are derived from the Look Up table of McArthur *et al.* (2001). \* Average ages for samples of the same stratigraphic horizon, used for sedimentation rate calculations.

the oysters shells (Table 1). Carbon and oxygen isotopic studies were carried out in order to discard diagenetic recrystallization of the carbonate in the shells. The older  $^{87}\text{Sr}/^{86}\text{Sr}$  ages were obtained in the Caleta Córdova region, where the contact between the Sarmiento and Chenque formations is well exposed. There, the lowermost 25 m of the Chenque Formation, composed of highly bioturbated, fine-grained tuffaceous deposits with a few shell beds, overlies the continental white tuffs of the Sarmiento Formation (Fig. 4c). Three beds showing well-preserved, large oysters in life position yielded ages between 19.69 and 19.02 Ma (Fig. 4c). At Cerro Chenque in Comodoro Rivadavia city, at about 80 to 90 m from the bottom of the unit, and within the upper half of a coarsening-upward succession (Sequence 1 of Bellosi, 1987; lower sequence of Paredes, 2003), autochthonous oysters yielded  $^{87}\text{Sr}/^{86}\text{Sr}$  ages varying between 17.63 and 17.03 Ma (Fig. 4a). Upward in the section, at about 100 m stratigraphically above the samples of Cerro Chenque, three samples from Cerro Antena and other three from Cerro Viteau yielded consistent results between 15.85 to 15.5 Ma (Fig. 4a,b). Five of the sampled beds occur just below

the “Banco del Mangrullo” and one just above the base of this bed (Fig. 4a,b). This prominent bed is a 4- m thick, coarse-grained complex shell bed with highly reworked shells (Fig. 4b), which can be used as a stratigraphic marker in all the sections around Comodoro Rivadavia, and, according to Bellosi (1987), represents the base of his Sequence 3 (Fig. 4a). Therefore the ages of the underlying beds would represent a minimum age (15.85 to 15.5 Ma) for the top of the underlying Sequence 2 of Bellosi (1987). The youngest sample analyzed in this contribution comes from a fossiliferous bed located 70 m stratigraphically above the Banco del Mangrullo at Cerro Antena (Fig. 4a). This sample, corresponding to the top of the Sequence 3 of Bellosi (1987) yielded an age of 15.37 Ma.

## DISCUSSION AND FINAL REMARKS

The Chenque Formation is dated for the first time by means of  $^{87}\text{Sr}/^{86}\text{Sr}$ . Age results are stratigraphically coherent (i.e., stratigraphically lower samples are older while the stratigraphically upper samples are younger) and carbon/oxygen isotopes indicate

Interval	Thickness (m)	Time span (my)	Sedimentation rates (m/my)	Stratigraphic Sequence (S)
1	80	1.9	41	Most of S1
2	110	1.55 – 1.66	71 - 66	Most of S2 (an uppermost interval of S1)
3	60	0.42 – 0.31	143 - 194	Most of S3 (an uppermost interval of S2)

**Table 2.** Summary of sedimentation rates estimations derived from the  $^{87}\text{Sr}/^{86}\text{Sr}$  ages. Because the sample position in the column does not coincide with sequence boundaries, calculations are made for intervals 1, 2 and 3 which are roughly equivalent to depositional Sequences 1, 2 and 3 (after Bellosi, 1987), respectively.

neither diagenetic alteration nor large freshwater input into the sea during deposition. The dated interval (Fig. 4a) comprises the lower three sequences of the unit as defined by Bellosi (1987) and Paredes (2003). The uppermost beds of the Chenque Formation (sequences 4 and 5 of Bellosi, 1987) are not present in the study area. The temporal interval involved in the deposition of the study interval at the Comodoro Rivadavia region is established from 19.69 to 15.37 Ma, younger than previously reported by other authors such as Camacho and Fernández (1956), Bertels and Ganduglia (1977), Bellosi (1995), Barreda (1996) and Malumián *et al.* (1999).

The position of the oyster beds from Caleta Córdova into the sequence stratigraphic scheme of Bellosi (1987; 1995) and Paredes (2003) is somehow uncertain. These beds lie 2 to 20 m above the contact with the Sarmiento Formation (Fig. 4c) and provided the oldest ages (mean 19.29 Ma) for the Chenque Formation in the study area (Table 1). The Cerro Chenque-Punta Borja section is located 15 km south of the Caleta Córdova section (Fig. 3). There, the lower 100 m of the Chenque Formation were assigned to its Sequence 1 by Bellosi (1987, 1995) or to the lower sequence (Paredes, 2003). As it is the oldest sequence defined for the Chenque Formation in Comodoro Rivadavia, we assume that the beds from Caleta Córdova belong to this sequence. Because the basin depocenter is located to the south of the Comodoro Rivadavia area (Fitzgerald *et al.*, 1990; Sylwan, 2001), it is possible that even older Patagoniense deposits might be preserved in the subsurface of that area (Fig. 2).

Assuming that the age of the lowermost beds at Caleta Córdova is synchronous with the lowermost beds at Cerro Chenque-Punta Borja (Fig. 4), and using the average ages for the overlying samples of Cerro Chenque (mean age 17.34 Ma, Table 1) the lower 80

m of the Chenque Formation in the Cerro Chenque-Punta Borja region (interval 1, Table 2) accumulated during an interval of about 1.9 my. This part of the unit belongs mostly to the Sequence 1 of Bellosi (1987) and the estimated duration points to sedimentation rates of about 41 m/my, on the average of terrigenous shelves (Ricken, 1991). Samples of Cerro Chenque are separated by a stratigraphic interval of about 110 m (interval 2, Table 2) from samples of Cerro Antena and Cerro Viteau, which occur at the top of Sequence 2 of Bellosi (1987). The estimated duration for this interval (1.55 my for Cerro Antena and 1.66 my for Cerro Viteau, Table 2) would imply that sedimentation rates during the accumulation of this sequence ranged from about 71 to 66 m/my, somewhat higher than for Sequence 1. The following interval up to the sample Antena-3 (Fig. 4a) comprise a stratigraphic interval of about 60 m (interval 3, Table 2), which corresponds mostly to Sequence 3 of Bellosi (1987). Using the average ages (Table 1), the temporal interval ranges from 0.42 my (Cerro Antena) to 0.31 my (Cerro Viteau), thus providing an estimated sedimentation rate varying from 143 to 194 m/my (Table 2). These values fall at the highest end for terrigenous shelves (Ricken, 1991), probably suggesting a relatively increase of sediment supply during the upper part of the study interval.

The ages reported in this paper are in agreement with other ages obtained for the Patagoniense succession elsewhere in southern Patagonia (Fig. 2). At Lago Posadas the Patagoniense (El Chacay Formation) is dated from 20.3 to 18 Ma (Cuitiño *et al.*, 2015), whereas the equivalent Estancia 25 de Mayo Formation at Lago Argentino is dated between 20 to 18.8 Ma (Cuitiño *et al.*, 2012; Bostelmann *et al.*, 2013). In the southeastern sector of Santa Cruz, the Monte León Formation is dated from 22.12 to 17.9 Ma (Parras *et al.*, 2012) (Fig. 2). All these partially



equivalent marine units, together with the Chenque Formation, represent the Miocene Patagoniense deposits in southern Patagonia (Austral and Golfo San Jorge basins). Considering all the available isotopic ages, we argue that the sea flooded large areas of continental Patagonia at about 21-20 Ma. After the maximum depths were achieved, regressive marine deposits accumulated, displaying different thickness and facies style, in different temporal intervals.

All across the Austral Basin a renewed phase of continentalization was established at about 18 Ma (Perkins *et al.*, 2012; Parras *et al.*, 2012; Cuitiño *et al.*, 2012; Cuitiño *et al.*, 2015), whereas in the Golfo San Jorge Basin the terrestrial systems were established later than 15 Ma (Fig. 2). The difference of at least 3 my in the timing of continentalization suggests that the Golfo San Jorge Basin might have experienced a relatively high subsidence rate in its eastern depocenter, close to Comodoro Rivadavia. In this area, even the highest sedimentation rates reported for the uppermost part of the successions (Table 2) were not capable of filling all the marine accommodation space being created.

The new isotopic ages for the lower three sequences of the Chenque Formation imply that the overlying Santa Cruz Formation in this region has to be younger than 15.37 Ma, therefore younger than the classic fossiliferous sections at the southeast of Santa Cruz province (Fig. 2), dated between 18 to 16 Ma (Perkins *et al.*, 2012), and only partially coeval with the strata of Santa Cruz Formation near Lago Posadas, dated between 18 and 14 Ma (Blisniuk *et al.*, 2005; Cuitiño *et al.*, 2015). Moreover, the older strata of the Santa Cruz Formation in the Andean region are mostly coeval with the Patagoniense succession of Comodoro Rivadavia and suggest interdigitation of both units in a west-east transect across Patagonia.

## Acknowledgements

We thank the comments and suggestions provided by Eduardo Bellosi and Silvio Casadío. The manuscript was also improved through the revision of the editor Ernesto Schwarz. We thank the staff of the Geochronos laboratory of the University of Brasilia (Brazil) for their help in Sr isotope analyses, and Roberto Pujana (MACN-CONICET) for his help in oyster preparation. This work was funded through grants of the Consejo Nacional de Investigaciones Científicas y Técnicas and the University of Buenos Aires.

## REFERENCES

- Ameghino, F., 1906. Les formations sédimentaires du Crétacé Supérieur et du Tertiaire de Patagonie avec un parallèle entre leurs faunes mammalogiques et celles de l'ancien continent. *Anales Museo Nacional de Buenos Aires* 15:1-568.
- Barreda, V.D., 1996. Bioestratigrafía de polen y esporas de la Formación Chenque, Oligoceno Tardío? - Mioceno de las Provincias de Chubut y Santa Cruz, Patagonia, Argentina. *Ameghiniana* 33:35-56.
- Barreda, V.D. and S. Palamarczuk, 2000. Estudio palinoestratigráfico del Oligoceno tardío-Mioceno en secciones de la costa patagónica y plataforma continental argentina. In F.G. Aceñolaza and R. Herbst (Eds.), *El Neógeno de Argentina*. Serie Correlación Geológica 14:103-138.
- Bellosi, E.S., 1987. *Litoestratigrafía y sedimentación del "Patagoniano" en la cuenca San Jorge, Terciario de Chubut y Santa Cruz, Argentina*. PhD Thesis, Buenos Aires University, 252 pp (unpublished).
- Bellosi, E.S., 1990. Formación Chenque: Registro de la transgresión patagoniana (Terciario medio) de la cuenca de San Jorge, Argentina. *XI Congreso Geológico Argentino Actas* 2:57-60, San Juan.
- Bellosi, E.S., 1995. Paleogeografía y cambios ambientales de la Patagonia central durante el Terciario medio. *Boletín de Informaciones Petroleras* 44:50-83.
- Bellosi, E.S., 2010. Loessic and fluvial sedimentation in Sarmiento Formation pyroclastics, middle Cenozoic of central Patagonia. In Madden, R.H., A.A. Carlini, M.G. Vucetich and R.F. Kay (Eds.), *The Paleontology of Gran Barranca: Evolution and Environmental Change through the Middle Cenozoic of central Patagonia*. Cambridge University Press, Cambridge:278-292.
- Bellosi, E.S. and V.D. Barreda, 1993. Secuencias y palinología del Terciario medio en la cuenca San Jorge, registro de oscilaciones eustáticas en Patagonia. *XII Congreso Geológico Argentino y II Congreso Exploración de Hidrocarburos Actas* 1:76-87, Mendoza.
- Bertels, A., 1970. Sobre el "Piso Patagoniano" y la representación de la época del Oligoceno en Patagonia Austral, República Argentina. *Revista de la Asociación Geológica Argentina* 25:496-501.
- Bertels, A. and P. Ganduglia, 1977. Sobre la presencia de foraminíferos del Piso Leoniano en Astra (provincia del Chubut). *Ameghiniana* 14:308.
- Bestelmann, J.E., J.P. Le Roux, A. Vázquez, N.M. Gutiérrez, J.L. Oyarzún, C. Carreño, T. Torres, R. Otero, A. Llanos, C.M. Fanning and F. Hervé, 2013. Burdigalian deposits of the Santa Cruz Formation in the Sierra Baguales, Austral (Magallanes) Basin: Age, depositional environment and vertebrate fossils. *Andean Geology* 40:458-489.
- Blisniuk, P.M., L.A. Stern, C.P. Chamberlain, B. Idleman, and P.K. Zeitler, 2005. Climatic and ecologic changes during Miocene surface uplift in the Southern Patagonian Andes. *Earth and Planetary Science Letters* 230:125-142.
- Camacho, H.H., 1979. Significados y usos de "Patagoniano", "Patagoniense", "Formación Patagónica", "Formación Patagonia" y otros términos de la estratigrafía del Terciario marino argentino. *Revista de la Asociación Geológica Argentina* 34:235-242.
- Camacho, H.H., 1995. La Formación Patagónica (F. Ameghino, 1894): Su actual significación estratigráfica y paleontológica. *Anales de la Academia Chilena de Ciencias* 5:117-151.

- Camacho, H.H.** and **J.A. Fernández**, 1956. La Transgresión Patagónica en la costa Atlántica entre Comodoro Rivadavia y el curso inferior del río Chubut. *Revista de la Asociación Geológica Argentina* 11:23-45.
- Chiesa, J.O.** and **H.H. Camacho**, 1995. Litoestratigrafía del Paleógeno marino en el noroeste de la provincia de Santa Cruz, Argentina. *Monografías de la Academia Nacional de Ciencias Exactas, Físicas y Naturales de Buenos Aires* 11:9-15.
- Cuitiño, J.I.** and **R.A. Scasso**, 2010. Sedimentología y paleoambientes del Patagoniano y su transición a la Formación Santa Cruz al sur del Lago Argentino, Patagonia Austral. *Revista de la Asociación Geológica Argentina* 66:406-417.
- Cuitiño, J.I., M.M. Pimentel, R. Ventura Santos and R.A. Scasso**, 2012. High resolution isotopic ages for the "Patagoniense" transgression in southwest Patagonia: stratigraphic implications. *Journal of South American Earth Sciences* 38:110-122.
- Cuitiño, J.I., R. Ventura Santos and R.A. Scasso**, 2013. Insights into the distribution of shallow marine/estuarine early Miocene oysters from Southwestern Patagonia: sedimentologic and stable isotope constraints. *Palaos* 28:583-598.
- Cuitiño, J.I., R. Ventura Santos, P.J. Alonso Muruaga and R.A. Scasso**, 2015. Sr-stratigraphy and sedimentary evolution of early Miocene marine foreland deposits in the northern Austral (Magallanes) Basin, Argentina. *Andean Geology* 42:364-385.
- De la Cruz, R.** and **M. Suárez**, 2006. Geología del Área Puerto Guadal-Puerto Sánchez, Región de Aisén del General Carlos Ibáñez del Campo. *Servicio Nacional de Geología y Minería*, Carta Geológica de Chile, Serie Geología Básica 95:58 p.
- del Río, C.**, 2004. Tertiary marine molluscan assemblages of eastern Patagonia (Argentina): a biostratigraphic analysis. *Journal of Paleontology* 78:1097-1122.
- Dunn, R.E., R.H. Madden, M.J. Kohn, M.D. Schmitz, C.A.E. Strömberg, A.A. Carlini, G.H. Ré and J. Crowley**, 2013. A new chronology for middle Eocene-early Miocene South American Land Mammal Ages. *GSA Bulletin* 125:539-555.
- Feruglio, E.**, 1949-1950. *Descripción Geológica de la Patagonia*, Vol. I-II. Ministerio de Industria y Comercio de La Nación, Dirección General de Yacimientos Petrolíferos Fiscales, Buenos Aires, 349 pp.
- Fitzgerald, M.G., R.M. Mitchum Jr., M.A. Uliana and K.T. Biddle**, 1990. Evolution of the San Jorge Basin, Argentina. *AAPG Bulletin* 74:879-920.
- Frassinetti, D.** and **V. Covacevich**, 1999. Invertebrados fósiles marinos de la Formación Guadal (Oligoceno superior - Mioceno inferior) en Pampa Castillo, Región de Aisén, Chile. *Servicio Nacional de Geología y Minería*, Boletín 51:1-96.
- Griffin, M.** and **A. Parras**, 2012. Oysters from the base of Santa Cruz formation (late Early Miocene) of Patagonia. In Vizcaíno, S.F., R.F. Kay and M.S. Bargo (Eds.), *Early Miocene Paleobiology in Patagonia: High-latitude Paleocommunities of the Santa Cruz Formation*. Cambridge University Press, Cambridge:83-90.
- Haq, B.U., J. Hardenbol, and P.R. Vail**, 1987. The chronology of fluctuating sea level since the Triassic. *Science* 235:1156-1167.
- Haq, B.U., J. Hardenbol, and P.R. Vail**, 1988. Mesozoic and Cenozoic chronostratigraphy and eustatic cycles. In Wilgus, C.K., B.S. Hastings, C.G. St. C. Kendall, H.P. Posamentier, C.A. Ross and J.C. Van Wagoner (Eds.), *Sea level changes: an integrated approach*. SEPM Special Publication 42:71-108.
- Legarreta, L.** and **M.A. Uliana**, 1994. Asociaciones de fósiles y hiatos en el supracretácico-neógeno de Patagonia: una perspectiva estratigráfico-secuencial. *Ameghiniana* 31:257-281.
- Linares, E.**, 1979. Catálogo de edades radimétricas determinadas para la República Argentina y Catálogo de edades radimétricas realizadas por INGEIS y sin publicar. *Revista de la Asociación Geológica Argentina*, Special Publication Serie B n°6, 32 pp.
- Malumián, N.**, 2002. El terciario marino. Sus relaciones con el eustatismo. In M.J. Haller (Ed.), *Geología y recursos naturales de Santa Cruz*. Relatorio del XV Congreso Geológico Argentino:237-244.
- Malumián, N., A.A. Ardolino, M. Franchi, M. Remesal and F. Salani**, 1999. La sedimentación y el volcanismo terciarios en la Patagonia Extra-andina. In R. Caminos (Ed.), *Geología Argentina*. Instituto de Geología y Recursos Minerales, Anales 29:557-612.
- McArthur, J.M., R.J. Howarth and T.R. Bailey**, 2001. Strontium isotope stratigraphy: LOWESS Version 3: best fit to the marine Sr-isotope curve for 0-509 Ma and accompanying look-up table for deriving numerical age. *The Journal of Geology* 109:155-170.
- Palamarczuk, S.** and **V.D. Barreda**, 1998. Bioestratigrafía de dinoflagelados de la Formación Chenque (Mioceno), provincia del Chubut. *Ameghiniana* 35:415-426.
- Paredes, J.M.**, 2003. A sequence stratigraphy scheme in a tide-dominated estuary: the Chenque Formation, Miocene of the San Jorge Basin, Argentina. *III Latin American Congress of Sedimentology* Actas:135-137, Belém.
- Paredes, J.** and **F. Colombo**, 2001. Sedimentología de la Formación Chenque (Oligoceno-Mioceno) en Comodoro Rivadavia. Argentina. *Geogaceta* 30:103-106.
- Parras, A., M. Griffin, R. Feldmann, S. Casadio, C. Schweitzer and S. Marensi**, 2008. Correlation of marine beds based on Sr- and Ar-date determinations and faunal affinities across the Paleogene/Neogene boundary in southern Patagonia, Argentina. *Journal of South American Earth Sciences* 26:204-216.
- Parras, A., G.R. Dix and M. Griffin**, 2012. Sr-isotope chronostratigraphy of Paleogene/Neogene marine deposits: Austral Basin, southern Patagonia (Argentina). *Journal of South American Earth Sciences* 37:122-135.
- Perkins, M.E., J.G. Fleagle, M.T. Heizler, B. Nash, T.M. Bown, A.A. Tauber and M.T. Dozo**, 2012. Tephrochronology of the Miocene Santa Cruz and Pinturas Formations, Argentina. In Vizcaíno, S.F., R.F. Kay and M.S. Bargo (Eds.), *Early Miocene Paleobiology in Patagonia: High-Latitude Paleocommunities of the Santa Cruz Formation*. Cambridge University Press, Cambridge:23-40.
- Ricken, W.**, 1991. Time span assessment - an overview. In G. Einsele, W. Ricken, A. Seilacher (Eds.), *Cycles and events in stratigraphy*. Springer Verlag, Berlin, Heidelberg:773-794.
- Riggi, J.C.**, 1979. Nomenclatura, categoría litoestratigráfica y correlación de la Formación Patagonia en la costa atlántica. *Revista de la Asociación Geológica Argentina* 34:243-248.
- Sciutto, J.C.**, 2000. Hoja Geológica 4566-III Comodoro Rivadavia. *Programa Nacional de Cartas Geológicas de la República Argentina*. Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino, Boletín 244.
- Sciutto, J.C.**, 2008. Hoja Geológica 4569-IV Escalante. *Programa Nacional de Cartas Geológicas de la República Argentina*. Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino, Boletín 351.
- Sylwan, C.A.**, 2001. Geology of the Golfo San Jorge Basin, Argentina. *Journal of Iberian Geology* 27:123-157.