Dating late Miocene marine incursions across Argentina and Uruguay with Sr-isotope stratigraphy

Claudia J. del Río [1], Sergio A. Martínez [2], John M. McArthur [3], Matthew F. Thirlwall [3], Leandro M. Pérez [4]

[1] Museo Argentino de Ciencias Naturales B. Rivadavia. A. Gallardo 470 (C1405DJR) Buenos Aires, Argentina (Phone=54 11 4982 6670)

[2] Facultad de Ciencias. Departamento de Evolución de Cuencas. Universidad de la República. Iguá 4225. (11400) Montevideo, Uruguay (Phone= 598 25252646)

[3] Earth Sciences, University College London, Gower Street, London WC1E 6BT, United Kingdom

[4] Museo de La Plata, 1900 La Plata, Argentina.

Corresponding author: Claudia J. del Río

Address: Museo Argentino de Ciencias Naturales B. Rivadavia. A. Gallardo 470 (C1405DJR) Buenos Aires, Argentina (Phone=54 11 4982 6670). claudiajdelrio@gmail.com

Abstract

A Miocene Sr-isotope chronostratigraphy of the sedimentites deposited by the "Paranense" Sea along a NE-SW transect stretching for 1200 km along the southwestern Atlantic coast is performed herein. Determined numerical ages are presented and discussed for shells of *Aequipecten paranensis* from the Argentinean Puerto Madryn Formation, Facies Balneario La Lobería, "Entrerriense Beds" of the Salado Basin, and Paraná Formation, and from the Camacho Formation (Uruguay). The $^{87}Sr/^{86}Sr$ ages fall into five age-groups that embrace the "Paranense" flooding in the latest Serravalian-Messinian interval. For the Puerto Madryn Formation, the ages span the latest Serravalian to the Tortonian and are stratigraphically coherent with the Transgressive Phase (11.90-10.37 Ma) and the Regressive Phase~~s~~ (10.22-9.82 Ma and 9.40-9.05 Ma) of that unit. Ages of 8.85-7.95 Ma for the "Entrerriense Beds" show them to be Tortonian and the Facies Balneario La Lobería, and the Paraná and Camacho formations span the age-range 7.50-6.0 Ma, comprising the Tortonian-Messinian interval. These ages allow correlation of the base of the Barranca Formation with the Regressive Phase of the Puerto Madryn Formation and its middle horizons with the Facies Balneario La Lobería. The "Entrerriense Beds" are correlated with the "Beds of Cabo Buentiempo". Dating the "Paranense" marine incursion permits a reappraisal of its paleogeography and to differentiate their deposits from those of the "Patagoniense" Sea. The flooding ~~surface~~ was more reduced than previously thought being its northwesternmost limit in the surroundings of the Santa Fe Province and its southernmost boundary in southern Santa Cruz Province. Moreover, our results proved that the Paranaian Molluscan Bioprovince was coeval with the Valdesian Molluscan Bioprovince for 2.35 Ma and that the species that constituted the *Aequipecten paranensis* Zone lived for at least 5.9 Ma .

Keywords: Sr-isotope; "Paranense" Sea; late Miocene; Paleogeography; Argentina; Uruguay

1-Introduction

Neogene marine rocks exist along the Southwestern Atlantic coast, where are recorded in narrow areas along the coast that stretch from Southern Argentina to Southeastern Brazil. In Argentina, at least two major transgressions are recorded (Figure 1A-B). The oldest, termed the "Patagoniense" Sea, occurred from the late Oligocene to the earliest middle Miocene times and deposited in Eastern Patagonia the sedimentites included today into the Monte León, Carmen Silva, Chenque and Gaiman Formations. A later transgression, termed the "Paranense" or "Entrerriense" Sea, mostly developed in the late Miocene, and its deposits are identified, from north to south, as Camacho Formation (Department of Colonia, Uruguay), and in Argentina as Paraná Formation (Entre Ríos Province), "Entrerriense" Beds (Salado Basin, subsurface of the Buenos Aires Province), Facies Balneario La Lobería (Río Negro Province) and Puerto Madryn Formation (Chubut, Province). The deposits of this transgression also include the "Beds of Cabo Buentiempo" (Santa Cruz Province), recently dated as late Miocene (del Río *et al.*, 2013) (Figure 2). Each of these "Paranense" units contains a well-documented molluscan assemblage (del Río, 1992, 1994; del Río and Martínez, 1998) that, since the middle of the 19th century, has been diagnostic of "Paranense" rocks and assigned to the *Aequipecten para*nensis Zone by del Río (1988).

Although those Neogene horizons have largely called the attention of naturalists, through a dearth of accurate dates independent of biostratigraphy, many authors regarded some sedimentites of the "Patagoniense" Sea (i.e. (Monte León, Carmen Silva, Chenque and Gaiman Formations) as having been deposited by the "Paranense" transgression (Windhaussen,1931; Yrigoyen, 1975; Uliana and Biddle 1988; Ramos and Alonso, 1995; Aceñolaza and Aceñolaza, 1999; Sprechmann and Aceñolaza 1999; Malumián, 1999; Alonso, 2000; Marengo, 2000; Aceñolaza and Sprechmann, 2002; Hernandez *et al*.. 2005; Malumián and Nañez, 2011).

The numerical ages of 9.41 Ma and 10.1 Ma obtained by Zinsmeister *et al.* (1981) and Scasso *et al.* (2001) respectively, placed the Puerto Madryn Formation in the late Miocene, but this dating was overlooked by some authors who suggested ages ranging from 15 to 5 Ma (Hernandez *et al.*, 2005) or from 15 to 9 Ma (Marengo, 2015) for the “Paranense” transgression.

Controversy also surrounds the area covered by this sea. Some geologists extended it to Northwestern and Western Argentina, but age of those sediments and whether they are even marine, are still matter of discussion. Correlation of those supposedly “Paranense” sediments with the middle Miocene Yecua Formation (southern Bolivia) (Marshall, 1993; Webb, 1995; Räsänen *et al.*, 1995; Hernandez *et al.*, *op.cit.*; Hovikosky *et al.*, 2007; Uba *et al.*, 2009; Hulka *et al.*, 2006) has been used to support the idea of Ihering (1927) and Boltovskoy (1991) who suggested that a major seaway (*e.g.*“-Paranense” Sea) crossed South America in the Miocene, connecting Southwestern Atlantic Ocean with the Caribbean Sea. However, a marine origin of the Yecua Formation, and so the reality of the intra-continental seaway is not universally accepted (*e.g*. Nuttall, 1990; Nicolaides and Coimbra, 2008; Tineo *et al.*, 2015). See Gross *et al.* (2015) for a review of the matter. In reference with the southern limit of the “Paranense” Sea, some authors placed it a few kilometers south of the ~~Valdés Peninsule~~ (Camacho, 1967; Scasso and del Río, 1987; del Río, 2000; Bellosi, 1995; Cione *et al*. 2011; Cuitiño *et al.*, 2017), whilst others, because of considering ~~sedimentites~~ of the “Patagoniense”Sea as deposited by the “Paranense” Sea, extended its boundary to the southernmost tip of Argentina.

As doubts persist still today concerning age and paleogeography of the “Paranense”, we have undertaken further dating of putative “Paranense” deposits along the Southwestern

Atlantic region in order to help resolve the uncertainty. We also review the correlation of the coastal "Paranense" units with sediments of Western and Northwestern Argentina previously thought to have been deposited or related with the "Paranense" Sea.

2.Previous ~~works~~

Since the discovery of the "Paranense" sedimentites and the description of their molluscs by d'Orbigny (1842) and Darwin (1846), age of those rocks deserved most of the attention of geologists and paleontologists. Timing of the transgression as well as the correlation among the "Paranense" deposits have been the focus of controversies for a long time.~~:~~ Below, it will be summarized previous ideas dealing with ages of the "Paranense" lithostratigraphic units.

2.1- Puerto Madryn Formation.- Sedimentites of this unit crop out around the city of Puerto Madryn and Península Valdés, northwards to Puerto Lobos (Cueva Los Leones~~'s~~ area) (Chubut Province) (Figure 1D). Initially described by Ameghino (1890), Frenguelli (1926) and Feruglio (1949) in Península Valdés, these rocks and their molluscan faunas have been the center of detailed systematic and stratigraphic analyses, as well as paleoenvironmental and taphonomic interpretations (Scasso and del Río, 1987; del Río, 1991, 1992, 1994: del Río *et al.*, 2001). On account of its fossiliferous content, the Puerto Madryn Formation has been placed in the Miocene *s. l.*, middle Miocene or late Miocene. Del Río (1988) firstly assigned the formation a middle Miocene age based on the dominance of the typical Caribbean taxa of the Gatun Formation. This proposal was adopted by Malumián (1999), Malumián and Nañez (2011), Aceñolaza and Aceñolaza (1999), Aceñolaza (2000), and by Aceñolaza and Sprechmann (2002). Subsequently, those Caribbean faunas were placed in the late Miocene according to the associated foraminiferal assemblages (see discussion in Martínez, 1994) and since then a late Miocene age was accepted by del Río (2000) and Martínez and del Río (2002).

On vertebrate evidence, Cione and Tonni (1981) assigned it to the late Miocene, while Cozzuol *et al.* (1993), Cozzuol (1996), and Riva Rossi (1997) placed it in the middle Miocene. Subsequent refinements allowed age discrimination within the unit. Cione *et al*. (1996) and Azpelicueta *et al.* (2015) suggested a middle Miocene age for the Highstand Phase exposed at Puerto Pirámides and Cione *et al.* (2005a) recognized the Huayquerian Stage in the uppermost beds that crop out at the surroundings of Punta Delgada (Regressive Phase), estimating that those horizons should be considered younger than 9 Ma. A late Miocene age for the same beds was also supported by Dozo *et al*. (2010) (and bibliography therein). In later work, a probable middle Miocene age for the lower and middle horizons of the Puerto Madryn Formation was suggested by Cione *et al.* (2011).

Palynomorphs and foraminifera place this unit in the late Miocene (Palazzesi and Barreda, 2004; Marengo, 2015) while dinoflagellate cysts recovered from the Highstand Phase at Puerto Pirámides would indicate a Serravalian-Tortonian age (Fuentes *et al*., 2016).

These assignments of age were superseded by numerical dating. Zinsmeister *et al.* (1981) reported ^{40}K/^{40}Ar ages 9.11$\pm$0,1 Ma; 9.56 $\pm$ 0,3 Ma; 9.55 $\pm$ 0,3 Ma (mean 9.41 Ma) for three glass concentrates from tuffs at the top of the Bahía Cracker section (Regressive Phase). Later, Scasso *et al.* (2001) obtained an ^{87}Sr/ ^{86}Sr age of 10 ± 0.3 Ma for shells of the scallops "*Chlamys" actinodes* and *Chesapecten crassus,* placing the Transgressive and the lower part of the Regressive phases in the middle Tortonian.

2.2- Facies Balneario La Lobería.- The marine horizons at the base of the cliffs situated between Bahía Rosas and Punta del Faro (northern littoral of San Matías Gulf, Río Negro Province; Figure 1 C) were described by De Ferraris (1966) and Angulo and Casamiquela (1982). The latter provided detailed lithological descriptions and placed them in the Facies

Balneario La Lobería Angulo and Casamiquela (*op.cit.*), ~~considering~~ it as a marine intercalation in the continental Río Negro Formation. It has been considered of late Miocene, late Miocene-early Pliocene or Pliocene age, depending on the mammal age assignment of the Río Negro Formation (Farinati *et al.*, 1981; Angulo and Casamiquela, 1982; Echevarría, 1988; Pascual *et al.*, 1996; see discussion in del Río *et al.*, 2013). In these marine sedimentites, del Río (1988) recognized the *Aequipecten paranensis* Zone and suggested they are of late Miocene age (del Río, 2000).

2.3-"Entrerriense" Beds.- This name was given by Tapia (1937) to sediments deposited by the "Paranense" transgression in the Salado Basin (subsurface of the Ciudad Autónoma de Buenos Aires). They were considered of late Miocene (Yrigoyen, 1970) or middle-late Miocene age (Yrigoyen, 1975). Foraminiferal assemblage suggests a late Miocene-early Pliocene age (Malumián, 1970), but later works restricted it to the middle Miocene (Malumián and Nañez, 1996; Malumián, 1999). According to its calcareous nannoplancton content, Marengo and Concheyro (2001) and Marengo (2015) proposed a middle Miocene (Serravalian) age.

2.4- Paraná Formation.- This formation is exposed around the cities of Paraná and Diamante (Entre Ríos Province). On account of its microfaunistic content it was placed in the late Miocene (Rossi de García, 1966; Zabert and Herbst, 1977; Zabert, 1978; Herbst and Zabert, 1987), and according to its molluscan assemblage was firstly situated in the middle Miocene (del Río, 1991), which was followed by Aceñolaza and Aceñolaza (1999) and Aceñolaza (2000), and it was later given a late Miocene age (Martínez, 1994; del Río, 2000; Martínez and del Río, 2005). On vertebrate evidence it is ?middle Miocene-late Miocene (Cione *et al.*, 2008) and later refined to be late Miocene (Cione *et al.*, 2000, 2005 b, 2011, 2012, 2013). The only known absolute ~~datation~~ (^{87}Sr/ ^{86}Sr) for the unit places it in the late Miocene (9.47 Ma) (Pérez, 2013).

2.5- Camacho Formation.- This unit is exposed on the southern littoral of the Colonia Department (Uruguay). Molluscs, selachians and mammals indicate that it should be placed in the late Miocene (Figueiras and Broggi, 1971, 1973; Martínez, 1994; 1998a; Martínez and del Río, 2002; Perea and Ubilla, 1989, 1990; Perea, 2005; Perea *et al.*, 1994; 2013). An age of 17 Ma - 18 Ma was obtained by Sprechmann *et al.* (2010) using Sr-isotope stratigraphy, on two species of oysters, placing the formation in the early Miocene.

3. Geological Setting

Studied deposits of the "Paranense" Sea include: surroundings of the city of Puerto Madryn, Península Valdés and Cueva Los Leones (Puerto Madryn Formation, Chubut Province), Balneario La Lobería (Facies Balneario La Lobería) (Viedma, Río Negro Province), the drill-hole Riachuelo IV ("Entrerriense" Beds, Salado Basin, Ciudad Autónoma de Buenos Aires), and sedimentites exposed near the cities of Paraná and Diamante (Paraná Formation, Entre Ríos Province). Sedimentary deposits of the "Paranense" Sea are also recognized in Uruguay at Cantera Geymonat (Colonia Department). Figure 3 illustrates lithological sections exposed at the mentioned localities.

3.1. Península Valdes.- Samples dated here come the Puerto Madryn Formation exposed at Punta Logaritmo (42° 25´ 17´´S; 64° 29´29´´W), Bahía Cracker (42° 57´23´´S; 64° 25´25´´W), and Salina Grande (42° 39´39´´S; 63° 57´ 07´´W). At Punta Logaritmo crops out the Transgressive Phase of the unit overlaying whitish tuffaceous sandstones of the Gaiman Formation (middle Miocene). Samples for dating were collected from the only fossiliferous horizon represented by up to 3 m thick, medium and fine, ochreous sandstones, that grades upwards to a multi-event shell-supported bed, where *Aequipecten paranensis* is associated to *Crassostrea patagonica*, *Cubitostrea alvarezi*, *"Chlamys" actinodes*, *Pachymagas* *piramidesia* and *Turritella piramidesia*. Fossils are abundant, and bivalves are disarticulated and well preserved (Figure 4-F).

Lithological section at Salina Grande corresponds to the Regressive Phase of the Puerto Madryn Formation and comprises intercalations of muddy heterolitic or massive, bioturbated very fine sandstones, fine bioturbated sandstones and up to a 0,8 m thick, medium to fine multi-event, shell-supported beds with erosive lower and upper planar contacts. *Aequipecten paranensis* is associated to *Amusium paris*, *Crassostrea patagonica* and *Leopecten piramidesensis*. (FIGURE 4 D-E)

At Bahía Craker, the upper part of the Regressive Phase of the Puerto Madryn Formation is exposed as 30 m thick of intercalated of gray heterolitic mudstones and very fine sandstones with fossiliferous, cross-bedded, fine sandstones where fossils are usually broken except for the uppermost tuffaceous sandstones that containes shell-beds where *Aequipecten paranensis* is associated to oysters and *Monophoraster darwini*.

3.2. Cueva Los Leones- Miocene marine fossiliferous sedimentites are recorded 66,5 km north to the city of Puerto Madryn, and 25 km southwest from Puerto Lobos (Chubut Province). Exposures consists of a narrow strip that stretches over 33 kilometers between 42° 17´S and 42° 01´S, along the western side of Highway 3. Cortes (1987) placed the basal beds in the Gaiman Formation and the upper horizons in the Puerto Madryn Formation. The measured section of the Puerto Madryn Formation (42° 14’ 30’’S and 65 ° 20’W) comprises a sequence of up to 22 m thick of cross-bedded or laminated, fairly loose, very fine and fine gray sandstones, and four 1,5 m thick shell-beds constituted by ochreous, fine or very fine sandstones. Those shell-beds contain a rich invertebrate fauna which varies laterally from well-preserved to highly fragmented accumulations. The fossiliferous assemblage contains dense accumulations of *Aequipecten paranensis*, *Cubitostrea alvarezi* and *Crassostrea patagonica*, co-occurring with scarce *Monophoraster darwini*, *Pachymagas piramidesia*, rare

Trophon sp. and isolated vertebrate remains. Capping the sequence there is 0.8 m thick of gray cross-bedded sandstones bioturbated with *Skolitos* and *Ophiomorpha.*

3.3- Balneario La Lobería.- The section is exposed at 41° 09´ 18.80´´S - 63° 07´ 28.84´´ W, some 40 km southwest of the town of Viedma and 225 m to the east of the staircase down to the beach of the Balneario La Lobería. At the base of the section is 1 meter laminated very fine sandstones followed by 2 meters of barren ochreous, cross-stratified medium sandstones, overlain by 7 m thick, yellowish, massive, fine sandstones that contain three loosely packed fossiliferous horizons. The lowermost, of 1,5 metres thick, was sample for Sr-isotope stratigraphy and contains concentrations of exceptionally well-preserved both disarticulated and articulated shells of *Aequipecten paranensis*, *Ostrea* sp and *Pododesmus camachoi*. Laterally, this association is replaced by molds of *Chionopsis* sp., *Ameghinomya* sp, and *Anadara* sp. This bed is capped by a 10 cm thick horizon, composed mostly of well-preserved *Monophoraster darwini* in life position and bunches of articulated oysters lying on the left valve. The second and third shell-beds comprise disarticulated and chaotically dispersed valves of *Ostrea* sp. The Río Negro Formation, which overlies the Facies Balneario La Lobería, is represented by 53.5 m of bluish gray, medium and fine cross-stratified sandstones, capped by a highly bioturbated, massive and compact white siltstones of 0,5 m thick (Figure 4 A-B).

3.4. Drill-hole Riachuelo IV.- Drilled by the Dirección Argentina de Minas y Geología, this core recovered 280 m of the "Entrerriense Beds" at Puente Pueyrredón (34° 39´ 23´´S, 58° 22´ 13´´W). The section is mainly composed of ochreous-reddish or greenish mudstones, with fine and medium sandstones intercalated at its base. Two fossiliferous beds are located between 44.8 – 54.40 mbgs and 68.10 – 72.70 mbgs. Shells of *A. paranensis* come from the lower and are associated to *Chionopsis muensteri, Crassatella suburbana, Anadara lirata,* *Amusium darwinianum* and abundant bryozoans. Capping this section there are the Quaternary "Puelchense" beds.

3.5- Paraná and Punta Gorda.- Specimens of *Aequipecten paranensis* that we have dated were collected by B. Bicego in 1892 and A. Bravard between 1854 and 1856 from isolated exposures of the Paraná Formation along the left bank of the Paraná River, in the city of Paraná, and by C. del Río and L. Pérez in Punta Gorda Sur (Diamante, 32°04´15´´S, 60°39´11´´W). In Punta Gorda there is a small outcrop, 2,5 m thick that comprises from base to top, an intercalation of gray laminated, very fine sandstones and mudstones, followed by a massive poorly fossiliferous medium sandstone. The section is capped by an amalgamated ochreous, compact, shell-bed that reaches up to 30 cm thick that contains *Anadara bonplandeana*, *Glycymeris minuta*, *Crassostrea* cf. *rhizophorae*, *Crassostrea patagonica*, *Cubitostrea alvarezii*, *Aequipecten paranensis*, *Leopecten oblongus*, *Miltha iheringiana*?, *Venericardia crassicosta*, *Dinocardium platense*, *Mactra bonariensis*?, *Chionopsis munsterii*, and abundant bryozoans (Perez, 2013) (Figure 4 I-J).

3.6. Cantera Geymonat (Uruguay).- Dated shells come from the Camacho Formation exposed at Cantera Geymonat (34° 25´ 57´´S; 57° 49´ 0.6´´W), near the city of Colonia del Sacramento. The exposures have a reduced areal extension, and consist of a thin basal conglomeradic sandstones with abundant oysters. This is overlain by 3 m ~~thick~~ of tuffaceous sandstones that grade upwards to highly fossiliferous, loose, fine sandstones containing a concentration of oysters associated with few terebratulids, balanids, *Pododesmus* sp., *Trophon* sp and *Aequipecten paranensis.* Capping the section there are barren fine sandstones (Figure 4 H).

4.Material and Methods

Twenty samples of *Aequipecten paranensis* have been dated by Sr- isotope stratigraphy (Table 1). Specimens were cleaned of adhering matrix by physical abrasion coupled with brief immersion in dilute nitric acid. Cleaned specimens were fragmented to mm-sized pieces in an agate pe~~w~~stle-and-mortar, cleaned again by immersion for a few seconds in dilute nitric acid, washed with 18 MΩ water, and dried in a clean environment. The best preserved fragments were picked under the microscope to select 10 mg of thin, sheet-like, fragments that were the best preserved. The diagnostic features of good preservation are fragmentation along the original layering, clear calcite as fragments, and an absence of Fe or Mn stain. The picked samples were dissolved in nitric acid, evaporated to dryness, and Sr was separated using Eichrom Sr-spec resin.

Measurements of ^{87}Sr/^{86}Sr were made on a Phoenix Isotopx magnetic-sector thermal-ionization mass-spectrometer using Re filaments. Values of ^{87}Sr/^{86}Sr were normalized to an ^{87}Sr/^{86}Sr value of 0.1194 using exponential correction for fractionation. The long-term value of NIST987 measured before, during, and after the analysis of our samples was 0.710 236 ± 0.000 007 (2s.d.) All values of ^{87}Sr/^{86}Sr reported in Table 1 have been normalised to a value for NIST987 of 0.710 248, which is equivalent to a value for EN-1 (modern seawater) of 0.709 174.

Numerical ages were derived from ^{87}Sr/^{86}Sr ratios using the LOWESS calibration curve of McArthur *et al.* (2012). The uncertainties on the numerical ages are derived by compounding the uncertainty of measurement with the uncertainty on the LOWESS calibration line, and are shown in Table 1 as standard errors of the mean values.

5. Results and Discussion

5.1- Age of the "Paranense" Sea.- Numerical ages presented here rounded to three significant figures, clustered into five age-group (Figure 5 A): 11.90–10.37 Ma (latest Serravalian- Tortonian); 10.22 – 9.82 Ma (Tortonian); 9.40– 9.05 Ma (Tortonian); 8.85–7.95 Ma (Tortoninan); 7.50–6.0 Ma (latest Tortonian- Messinian).

The ~~three~~ older age~~-groups~~ are recorded in the Puerto Madryn Formation and represent both the Transgressive, and the entire Regressive phases of this unit. The oldest ages occur in the basal beds exposed at Cueva Los Leones, which is correlative with the Transgressive Phase at Punta Logaritmo. Ages 10.22–9.82 Ma correspond~~s~~ to the middle portion of Regressive Phase at Salina Grande, and the youngest of the three (9.40 to 9.05 Ma) to the upper Regressive Phase at Bahía Cracker. This age range was obtained on shells from the top of the unit at Bahía Cracker and are similar to the 9.40 Ma using $^{40}K/^{40}Ar$ determined by Zinsmeister *et al.* (1981), for samples coming from the same beds sampled in this paper.

Previous numerical dating of the Puerto Madryn Formation by Scasso *et al.* (2001) was insufficiently precise to discriminate ages of the basal, middle and upper parts of the unit which represent a complete transgressive-regressive cycle. The mean age given by those authors was 10.0 $\pm$ 0.3 Ma and comes from 1)- lowest beds belonging to the Transgressive Phase, exposed at Eje Tentativo and El Doradillo; 2)- horizons from the Maximum Flooding surface that crop out in the Puerto Piramide-Lobería´area, and in the upper section at Eje Tentativo; 3)- lowermost part of the Regressive Phase in Lobería Punta Pirámide (Figure 5 B). Our more precise determinations of $^{87}Sr/^{86}Sr$, made possibly by improved mass-spectrometry (VG 354 v Phoenix Isotopx), has reduced 2 s.d of external precision from $\pm$0.000015 to 0.000006. Moreover, the ~~samples~~ analyzed herein are preserved better than ~~were those~~ of Scasso *et al.* (2001).

The results obtained herein suggest that the basal beds of the Transgressive Phase of the Puerto Madryn Formation must be placed in the latest Serravalian, and the overlying sedimentites in the Tortonian, which disagree with Cione *et al*. (2011), who estimated a middle Miocene age for the basal and middle part of the unit (i.e. Transgressive and Highstand Phases). It also precludes the Highstand Phase being Serravalian as suggested on dinoflagellates evidence (Fuentes *et al*., 2016). Besides, these results also permits correlation of the upper portion of the Puerto Madryn Formation (Regressive Phase) with the base of the Barranca Final Formation at its type locality, which has been dated in 9.61Ma (Palazzesi *et al*., 2014).

The fourth age-group (8.85 to 7.95 Ma, Tortonian) comprises the first numerical ages for the "Paranense" Sea in the Salado Basin and is stratigraphically concordant with the other sections that yield the *Aequipecten paranensis* Zone such as the Paraná and Camacho formations and Facies Balnerario La Lobería, and younger than the Serravalian age proposed by Marengo and Concheyro (2001) and Marengo (2015) on the basis of the calcareous nannoplancton NN5 Zone in the Riachuelo V drill-hole. This core is situated a few meters from Riachuelo IV and beds containing the NN5 Zone could be correlated with Riachuelo IV core. (Marengo, *oral com*.), but these drill holes are old and the discrepancy in age may be attributable to curation errors, since foraminifers and the *Aequipecten paranensis* Zone indicate a late Miocene age as our numerical dating do. "Beds of Cabo Buentiempo" recently dated by means of Sr-isotope stratigraphy as 8.95 $\pm$ 0.82 Ma and correlated with the upper part of the Puerto Madryn Formation (del Río *et al*., 2013), are now also correlated with the base of the "Entrerriense Beds" in the Salado Basin.

The youngest deposits (7.5–6.0 Ma) of the "Paranense" transgression comprise the Facies Balneario La Lobería, and the Paraná and Camacho formations.

These are the first numerical ages determined for the Facies Balneario La Lobería (7.08–6.55 Ma, early Messinian) and make it correlative with the middle part of the Barranca Final Formation at its type locality, 117 km west from Balneario La Lobería, which has been recently dated in 6.48 Ma (Palazzesi *et al.*, 2014) and not coeval with the ~~section the~~ Highstand of the Puerto Madryn Formation, as proposed by those authors. The finding of a typical open marine molluscan assemblage (including *Aequipecten paranensis*, *Glycymerita magna*, *Ameghinomya argentina*, *"Chlamys" actinodes* and *Turritella pyramidesia)* in the lower and upper fossiliferous beds of the Barranca Final Formation, firstly reported herein, corroborates the presence of the "Paranense" Sea along the entire northern littoral of the San Matías Gulf extending northwards to reach the Salinas del Gualicho's area.

The ages obtained herein for the Paraná Formation (7.55–6.67 Ma, latest Tortonian-Messinian) based on five samples, is much younger than 9.47 Ma provided by Pérez (2013) through Sr-isotope stratigraphy from a single valve of *Leopecten oblongus.* The age discrepance may result from differences in preservational state; we have repeatedly found that altered samples have lower $^{87}Sr/^{86}Sr$ (and so older ages) than do well-preserved ones.

The age range of 7.20-6.0 Ma (Messinian) for the Camacho Formation is concordant with a late Miocene age for the unit suggested by Martínez (1994) and Martínez and del Río (2002) on the basis of molluscan assemblages. A date of 17 - 18 Ma obtained by Sr-isotope stratigraphy is given in an abstract by Sprechmann *et al.* (2010), but preservational assessment was lacking and we again suspect that the old age may be a feature of alteration.

Our interpretation of the age of the "Paranense" Sea, which embraces the 11.9-6.0 Ma interval, disagrees from that of Hernández *et al.* (2005), who stated that the "Paranense" transgression spanned 15–5 Ma, and comprised two different events, *i.e.* at 15–13 Ma (middle Miocene) and 10–5 Ma (late Miocene). According to those authors the older event would have deposited the sediments of the Puerto Madryn, Camacho and Paraná Formations. This event and the youngest one would have also reached West and Northwestern Argentina (see below).

5.2- Paleogeography of the "Paranense" Sea. As explained in the Introduction, some authors considered the Chenque, Monte León, Gaiman and Carmen Silva formations (FIGURE 1B; FIGURE 2) as deposited by the "Paranense" transgression and extended the area covered by that sea from the southernmost tip of Patagonia to Northwestern Argentina. Our new dating along with those obtained for the sedimentites of the "Patagonian" Sea (Parras *et al*. 2012, Cuitiño *et al*., 2015) and the biostratigraphic information based on palynomorphs and molluscs (Barreda and Palamarczuk, 2000; del Río, 2004) allow to differentiate both the deposits of the ~~Late~~ Miocene "Paranense" and the early-earliest middle Miocene "Patagoniense" seas. This permit a reappraisal of the paleogeography of the "Paranense" Sea, as it will be discussed below.

5.2.1- Southern extension.- The lower section of the Chenque Formation, at its type section, records the early Miocene JR Molluscan and the C-T/L Palynological Assemblages. The middle and upper sections of that unit contains the middle Miocene NVG Molluscan and T-B/H Palynological Assemblages (Figure 2). Cuitiño *et al*. (2015) obtained numerical ages of 17.03–17.35 Ma (Burdigalian) for the base and of 15.37–15.85 Ma (Langhian) for the middle part of the Chenque Formation. These values coincide with the relative age proposed for the JR Assemblage, and restrict the NVG Assemblage to the earliest Langhian. In reference to the Monte León Formation, molluscs (RSP and PA Assemblages) and palynomorphs (C-T/L and G/C Assemblages), place it in the early Miocene (Barreda and Palamarczuk, *op. cit*.; del Río, *op. cit*), an age also supported by numerical dating that constrains it to the 22 Ma -18 Ma interval (Parras *et al*., 2012). There is no numerical dating or formal molluscan assemblages defined for the Carmen Silva Formation and Malumián and

Olivero (2006) considered it of middle Miocene and correlated it with the "Entrerriense" (= "Paranense") Sea.

On one hand, the new ages obtained in this paper show that the oldest marine rocks of the "Paranense" Sea were deposited during the latest Serravalian, whilst most of the transgression occurred during the Tortonian-Messinian interval, being in this way, younger than the "Patagoniense" Sea. On the other hand, while the sedimentites of the "Paranense" Sea are clearly characterized by the *Aequipecten paranensis* Zone, the Gaiman, Chenque, Monte León and Carmen Silva formations are identified by remarkable different molluscan associations. For reasons given above, it is unlikely that sedimentites underlying the Puerto Madryn Formation were deposited by the "Paranense" transgression. Until now, no latest middle or late Miocene marine horizons have been recognized south of the city of Trelew, except for the geographically isolated Tortonian incursion of the sea detected in the latitude of Río Gallegos where the "Beds of Cabo Buentiempo" are exposed in a very reduced area.

5.2.2- Northern extension.- Whether the "Paranense" Sea extended into Northwest and West Argentina is still a controversial issue. Roth (1908) was the first author to propose the presence of open marine facies correlated with that sea in Santiago del Estero Province whilst Stappenbeck (1926) did so for Catamarca Province, where it would have been represented by brackish facies. Windhaussen (1931) carried out the first paleogeographic reconstruction of the sea, showing it extending from the southernmost tip of South America northwards to Paraguay. Since then, few changes have been made to its areal extent except for the addition of some minor incursions of the sea into Mendoza and San Juan provinces (Groeber, 1949; Yrigoyen, 1993; Pérez and Ramos, 1996). Units exposed in Northwest and West Argentina are the continental Anta, Del Buey, Chinches and San José formations, and the carbonatic beds intercalated in them were thought to have had a marine origin related to the presence of the "Paranense" Sea, or to an hipersaline lagoon permanently or sporadically connected with that sea (Russo and Serraioto, 1978; Cione *et al.*, 1995; Quatrocchio *et al.*, 2003; Davila and Astini, 2002; Ottone *et al.*, 1998; Hernandez *et al*., 2005). The age of those units are undoubtly middle Miocene (Reynolds *et al.*, 2000; Davila, 2005; Jordan *et al.*, 1996; Gavriloff and Bossi, 1992) and the analysis of Ruskin *et al.* (2011), bring to an end the idea of the presence of any marine influence in West and Northwest Argentina. Among other aspects, and due to the ratio of ~~stable isotopes of carbon and oxygen~~, those authors demonstrated that the carbonatic strata are of lacustrine origin, concluding that the "Paranense" marine incursion would have never reached those regions of Argentina, rejecting any marine connection between the Caribbean Sea and the South Atlantic Ocean.

The San José Formation, exposed in the Santa María Valley (Tucumán and Catamarca provinces) was not included by Ruskin *et al* (*op.cit*.) in their analysis. The diagenetic aspects of the ostracod *Cyprideis herbsti*, and the foraminifers *Streblus parkinsoniana* and *Streblus compactus* found at the base of the San José Formation, led to Bertels and Zabert (1980) to infer the presence of a lagoon with high salinities directly connected with the "Paranense" Sea, an idea later followed by Bossi and Palma (1982). Gavriloff and Bossi (1992) also claimed for an obvious relationship between this microfauna and the "Paranense" transgression, but they concluded that the San José Formation "would not represent a typical marine sequence or if so, it would have been soon stopped being one" (p.28). Later, Gavriloff (1999) and Bossi *et al.* (1999) proposed for this unit a paralic environment related to the "Paranense" Sea.

Chaia (in Vergani *et al.*, 1991), Leiva and Morton (2001) and Espíndola (2004) increased the number of foraminifer and ostracod species of the San José Formation. According to the nomenclature used in those papers, the foraminifers are: *Ammomia beccari parkinsoniana* (= *Streblus parkinsoniana*), *Rotalia beccari*, *Bucella frigida*, *Nonion demens*, *Protelphidium tuberculatum*, *Trochammina* sp., *Streblus compactus*, and the ostracods are: *Cyprideis* *herbsti*, *Cyprideis* cf. *torosa*, *Cyprideis salebrosa*, *Darwinula* sp., *Perissocytheridea* sp., *Limnocythere* sp., *Cyprinotus cingalensis*, and *Cyamocytheridea ovalis*. Chaia (*op.cit.*) considered the microfauna as a Late Miocene assemblage of Atlantic origin, and distinguished three transgressive episodes in the base of the formation.

Except for those provided by Bertels and Zabert (1980), there are no illustrations of the microfossils mentioned above, making difficult any evaluation. Some taxa are extinct, others are not useful as paleoenvironmental indicators, *e.g. P. tuberculatum* is tolerant to brackish waters (Malumián, 1978) or to open marine environments, as it is demonstrated by their presence in the Puerto Madryn Formation (Marengo, 2015) where is associated to a molluscan assemblage of normal salinity (del Río, 1992; 1994). The species *Nonion demens* can be restricted to brackish environments (Boltovskoy, 1991). Among extant species, *Buccella frigida* is tolerant to low salinities (Boltovskoy and Wright, 1976), and *A. beccari parkinsoniana* can either inhabits in fresh environments with intermittent influence of brackish waters, as happens in ~~La Plata River~~, in lagoons with influx of fresh waters (Boltovskoy and Boltovskoy, 1968; Boltovskoy and Lena, 1971; Boltovskoy and Wright, *op.cit.*) or present in the Puerto Madryn Formation (Marengo, *op.cit.*) In reference to the ostracods, *Cyprideis herbsti* is an endemic taxa, *C. salebrosa* is a limnic to oligohaline species (up to 5 psu; Keyser, 1977), and *C. cingalensis* is a freshwater inhabitant (Eagar 2000; Karanovic, 2008). In some cases, the microfauna ~~are~~ associated with freshwaters gastropods, carophytes and bones remains (Herbst *et al.*, 2000). Moreover, there is a strong abundance and diversity decrease of the microfaunas towards northwestern region, being dominated by only two species typical of ~~stress~~ environments (*P. tuberculatum* and *A. parkinsoniana*) (Marengo, 2000). Regarding molluscs, there is no evidence of open marine species in the San José Formation as those recorded in easternmost exposures (*i.e*. Paraná and Puerto Madryn formations, and "Entrerriense Beds" of the Salado Basin), but instead, microfaunas are associated with fresh water molluscs (Herbst *et al.*, 2000; Morton and Herbst, 2003).

In consequence, the idea of any marine incursion in the Tucumán and Catamarca provinces cannot be supported. Even if the base of the San José Formation would have been deposited in brackish environments, it should be expected the presence of a sea close to the area (*i.e*. Santiago del Estero Province) where, until now, it was not found any other unequivocally evidence of open marine conditions, but it was recorded a low diversified and scarce microfauna (Zabert, 1978; Herbst and Zabert, 1987; Marengo, 2015). Last, but not least, even in the improbable case that will be proved in the future the development of an unequivocally marine microfauna in the middle Miocene San José Formation, the inference of a ~~close sea~~ to the area should not be related any more to a late Miocene sea, but with an older transgression of middle Miocene age. In this way, the westernmost limit of the "Paranense" Sea would have reached the Santa Fé Province such it is demonstrated by the still moderate high diversity of foraminifers in this region.

5.3.- Late Miocene Bioprovinces and long-term living species- Martínez and del Río (2002) defined the late Miocene Molluscan Valdesian and the Paranaian bioprovinces. According to the numerical Sr-ages presented herein, the Valdesian province existed between about 11.9–6.5Ma while the Paranaian one between 8.85 and 6 Ma, having little overlap in time (2.35Ma). Compared with the duration of other late Paleogene-Neogene Tertiary bioprovinces such as those defined by Petuch (1988; 2014) for the Western Atlantic and Eastern Pacific, the Valdesian and Paranaian provinces have lasted for a considerable shorter time.

The present analysis also contributes to assess the duration of species that were restricted to the *Aequipecten paranensis* Zone as *A. paranensis* itself, *Anomalocardia entrerriana, Anadara bomplandeana, Epitonium borcherti, Calliostoma bravardi* and *Trophon leanzai.*

These taxa are widely distributed in each one of the studied region, and demonstrate to have lived at least during 5.9 Ma which is in accordance to the mean values for duration of molluscs proposed by Crampton *et al*. (2010). The time-life elapsed for those late Miocene species is even shorter when compared with the long-living taxa associated, such as *Ameghinomya argentina, A. meridionalis, Dosinia meridionalis, Crassatella kokeni, Macoma perplana*, *Tellina jeguaensis* and *Panopea regularis*, which are present in the region since the early Miocene. The time range of the late Miocene species is also shorter in comparison with those taxa that survived from the late Miocene into modern times in the region: *Leionucula puelcha, Felaniella vilardeboana Caryocorbula pulchella* and *Cyrtopleura lanceolata*. Moreover, the flooding interval of the "Paranense" Sea, was time enough for the evolution to occur of closely related species such as *Chionopsis australis, Amusium paris, Leopecten piramidesensis* and *Dosinia cuspidata* (that lived at the beginning of the transgression) and the later taxa *Chionopsis muensteri, Amussium darwinianum, Leopecten oblongus* and *Dosinia entrerriana*.

6. Conclusions

1- Numerical dating by Sr-isotope stratigraphy shows that flooding time of the "Paranense" Sea elapsed from 11.9 to 6 Ma (latest Serravalian-Messinian), with sediments showing a general trend to be younger northwards. These dates are the first to be performed for the "Entrerriense" Beds" located in the Salado Basin, for the Facies Balneario La Lobería and the Puerto Madryn Formation exposed at Cuevas Los Leones.

2- Numerical ages fall into five intervals: 1) 11.9–10.37 Ma; 2) 10.22–9.82 Ma; 3) 9.40–9.05 Ma; 4) 8.85 –7.95 Ma; and 5) 7.50– 6.0 Ma.

3- The first three ~~intervals,~~ stratigraphically coherent, allow to discriminate the time of deposition of the entire Puerto Madryn Formation at its type locality (Península Valdés and surroundings of the city of Puerto Madryn). The lowest beds of the Transgressive Phase ~~belong to~~ the latest Serravalian and are correlated with the basal horizons of the unit exposed at Cueva de Los Leones. The second and third intervals constrain the entire Highstand and the Regressive phases to the Tortonian. The third interval coincides with values obtained by Zinsmeister *et al.* (1981) through ^{40}K/^{40}Ar who dated the same beds than us, exposed at Bahía Cracker, which are herein correlated with the basal deposits of the Barranca Final Formation.

4- The interval 8.8–7.95 Ma corresponds to the "Entrerriense" Beds deposited in the Salado Basin, resulting younger than the previously proposed biostratigraphic age by means of the nannoplancton content, and allow their correlation with the "Beds of Cabo Buentiempo", slightly younger than the uppermost strata of the Puerto Madryn Formation.

5- The youngest units clustered in the interval 7.50–6 Ma, correspond to the Facies Balneario La Lobería, and the Paraná and Camacho formations. The numerical dating for the Facies Balneario la Lobería (6.6–7.08 Ma), lead us to state the definitive relationship between those sedimentites and the "Paranense" Sea, which is also corroborated by the presence of the *Aequipecten paranensis* Zone. It also correlates with the middle strata of the Barranca Final Formation at its type locality, where this zone has been recognized in this paper

6- The Paraná Formation is 6.67–7.50 Ma (Messinian), being much younger than previously thought.

7- Values obtained for the Camacho Formation are younger than those estimated by Sprechmann *et al.* (2010), and their similarity with those obtained for the Paraná Formation supports the proposal of Martínez (1989) that, in the frame of a global similitude, the Paraná and Camacho Formations are more related between them than to the Puerto Madryn Formation.

8- Neither the early Miocene -earliest middle Miocene marine sedimentites recorded in the Chenque Formation, nor the middle Miocene carbonate beds intercalated in the continental units of Western and Northwestern Argentina should be related with the latest Serravalian-Messinian “Paranense” Sea.

9- The maximum westwards extension of the “Paranense” Sea would have reached the Santa Fe Province and so precludes any connection during the late Miocene with the Caribbean Sea.

10- In reference to the southern extension of the sea, the studied sedimentites show a continuous extension of late Miocene deposits from northern littoral of the San Matías Gulf southwards to around the city of Trelew as proposed by Scasso and del Río (1987), and are recognized again in the “Beds of Cabo Buentiempo”, which represent the southernmost incursion of the “Paranense” Sea in Patagonia.

11- The *Aequipecten paranensis* Zone had a duration of 5.9 Ma and the Paranaian Molluscan Bioprovince was coeval with the Valdesian one for the younger 2.35 Ma of that interval.

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LEGENDS

Figure 1 A – Paleogeography of the late Miocene "Paranense" Sea (dotted line), exposures of the studied sedimentites (in orange) and location of measured lithological sections: 1- Cueva Los Leones; 2- Punta Logaritmo; 3- Salina Grande; 4- Bahía Cracker; 5- Balneario La Lobería; 6- Riachuelo IV; 7- Paraná; 8- Punta Gorda; 9- Cantera Geymonat. **B-** Paleogeography of the "Patagoniense" Sea and eastern exposures of lithological units mentioned in the text. **C-** Enlargment of Northern coast of the San Matías Gulf. **D-** Geographic location of the study sites in Península Valdes.

Figure 2 – Chronostratigraphic chart of deposits of the "Patagoniense" and "Paranense" seas on Eastern Patagonia based on isotopic data calculated by: 1-Parras *et al*., (2012), 2- Cuitiño *et al*. (2015); 3- del Río *et al*. (2013); 4- this paper; 5- Palazzesi *et al*. (2014)) no isotopic data available for these units. Abbreviations: PP=*Panopea sierrana-Parinomya patagonensis* Assemblage; RSP=*Reticulochlamys zinsmeisteri-Struthiolarella patagoniensis- Pleuromeris cruzensis* Assemblage; JR= *Jorgechlamys centralis-Reticulochlamys borjasensis* Assemblage; NVG= *Nodipecten* sp.-*Venericor abasolensis-Glycymerita camaronesia* Assemblage; M-M/R= *Multisiappolis viteauensis-Margocolporites tenuireticulatus - Reticulatosphaera? actinocoronata* Assemblage; C-T/L= *Cypereaceaepollis neogenicus–Tricolpites triloblatus /Lingulodinium hemicystum* Assemblage; G/C= *Glencopollis ornatus/ Cannosphaeropsis utinensis* Assemblage

Figure 3- Lithological sections of the studied "Paranense" deposits. Mean ages in red.

Figure 4- Exposures of the "Paranense" deposits. **A-C**- Facies Balneario La Lobería at Balneario la Lobería (Viedma, Río Negro); **D-E**- Regressive Phase of the Puerto Madryn Formation at Salina Grande and detail of the uppermost fossiliferous bed (Península Valdés,

Chubut); **F-** Panoramic view of Gaiman and Puerto Madryn formations at Punta Logaritmo (Peninsula Valdés, Chubut); **G-H-** Panoramic view of Camacho Formation at Cantera Geymonat and detail of fossiliferous accumulation (Colonia, Uruguay); **I-J** –Exposure of the Paraná Formation and detail of shell-bed (Punta Gorda, Entre Ríos). White arrow indicates the procedence of the material dated herein.

Figure 5-A- $^{87}Sr/^{86}Sr$ numerical ages clustered into five groups. Groups 1, 2 and 3 are stratigraphically coherent with the Transgressive (1) and Regressive Phases (2 and 3) of the Puerto Madryn Formation exposed at Cueva Los Leones and Peninsula Valdés; **B-** Numerical ages obtained by Scasso *et al.* (2001)

Table 1- Values of $^{87}Sr/^{86}Sr$ in 20 samples of *Aequipecten paranensis* from the “Paranense” sedimentary deposits.