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High resolution isotopic ages for the early Miocene "Patagoniense" transgression in Southwest Patagonia: Stratigraphic implications

José I. Cuitiño [a,b,*], Marcio M. Pimentel [c], Roberto Ventura Santos [d], Roberto A. Scasso [a,b]

[a] Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Intendente Guiraldes 2160 (C1428EHA), Ciudad Autónoma de Buenos Aires, Argentina
[b] CONICET, Argentina
[c] Instituto de Geociências, Universidade Federal do Rio Grande do Sul, CP 15001, 91501-970 Porto Alegre, Brazil
[d] Instituto de Geociências, Universidade de Brasília, Campus Universitário Darcy Ribeiro, CEP 70910-900 Brasília, DF, Brazil

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ABSTRACT

The classical marine Patagoniense succession at Lago Argentino, southwestern Patagonia (Argentina), known as Estancia 25 de Mayo Formation, was dated by radiometric U–Pb on zircon grains from pyroclastic rocks and $^{87}Sr/^{86}Sr$ ratio on calcitic oyster shells. U–Pb data yielded an age of 19.14 Ma for the lower portion of the Patagoniense succession and 18.85 Ma for the lowermost part of the overlying Santa Cruz Formation. $^{87}Sr/^{86}Sr$ data yielded ages ranging from 20.05 Ma at the lower part and 19.1 Ma for the upper portion of the Estancia 25 de Mayo Formation, in good agreement with respect to the U–Pb results. Our results constrain the age of these beds entirely into the early Miocene Burdigalian stage, and locally into the Superpatagoniense stage. Correlation with other Patagoniense units in Santa Cruz, especially in the westernmost parts of the Austral Basin, reveals the existence of a shallow and extended sea, and lack of correlation with global sea-level highstands suggests a local Andean tectonic overprint as the cause of the sea level rise.

1. Introduction

The Patagoniense transgression represents one of the largest events of Cenozoic Atlantic marine invasion over Patagonia. The resulting sedimentary deposits cover a huge area of the Argentine continental Patagonia, from the Río Negro province, in the north, to the Santa Cruz province, in the south, as well as in Tierra del Fuego and southern Chile (Fig. 1A). In Santa Cruz province outcrops are present along the entire present-day cliffy Atlantic coast, the surrounding areas of the Deseado Massif and in its southernmost part, where our study area is located. Apart from Patagonia, lower Miocene marine deposits are recorded elsewhere in South America, such as the Laguna Paiva Formation in the Chaco Paranaense Basin (Marengo, 2006) in northern Argentina and the Pirabas/Barreiras Formations (Rossetti, 2001) in northern Brazil, pointing to an event of continental magnitude. The lack of reliable age control in many of these localities precludes precise correlations useful to determine the main driving controls over these deposits.

The term "Patagoniense" used in this work is informal and represents a geologic event (a marine transgression) rather than a rock unit. Much confusion exists around this nomenclature since the proposal of Ameghino (1906) as the "*Patagonian Formation*". The Ameghino's concept of *Formation* has chronostratigraphic significance, whereas many workers used this nomenclature with a lithostratigraphic meaning during the 20th century. This misinterpretation of the Ameghino's concept and the large area covered by these deposits resulted in a complex and confusing variety of names in the literature. A review of the history and meaning of nomenclatures of the Patagoniense deposits can be seen in Camacho (1979) and Legarreta and Uliana (1994). We use the suffix "ense" to denote chronostratigraphic units following the criteria established by Feruglio (1949–1950), whereas lithostratigraphic units with modern significance are described as Formations or Members. In this sense, the Patagoniense transgression was the geologic event responsible for the deposition of a number of rock units of different nature and geographic distribution. The usage of the term "Patagonia Formation" (Russo and Flores, 1972; Riggi, 1979) referring to all these deposits with a modern lithostratigraphic sense should be disregarded.

* Corresponding author. Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, Pabellón II, primer piso, Intendente Guiraldes 2160 (C1428EHA), Ciudad Autónoma de Buenos Aires, Argentina. Tel.: +54 11 1562854266.
E-mail addresses: jicuiti@yahoo.com.ar, joseignacio@gl.fcen.uba.ar (J.I. Cuitiño), marcio.pimentel@ufrg.br (M.M. Pimentel), rventura@unb.br (R. Ventura Santos), rscasso@gl.fcen.uba.ar (R.A. Scasso).

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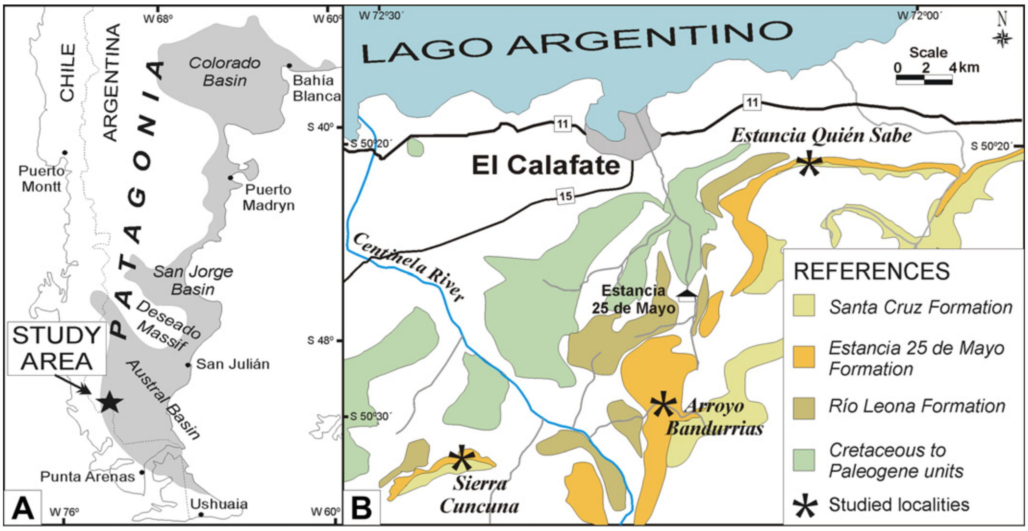


Fig. 1. (A) Location of the study area. The gray part is the estimated area covered by the Patagoniense transgression (after Malumián et al., 1999). (B) Schematic geologic map of the study area to the south of Lago Argentino. The three localities mentioned in the text are figured.

The age and stratigraphic subdivision of the Patagoniense deposits has been a matter of debate since the pioneer studies of d'Orbigny (1842) and Darwin (1846), who broadly estimated a Tertiary age for them. Later, Hatcher (1900) proposes an Eocene to Miocene age while Ameghino (1906) proposes an Eocene age. These pioneer investigations also arose the question about the subdivision of the Patagoniense deposits into stages of different ages. Hatcher (1900) proposed an indivisible succession, whereas Ameghino (1906) proposed a three-fold subdivision for these deposits: the lower *Juliense* stage, the *Leonense* stage and the upper *Superpatagoniense* stage, the latter considered being the lower part of the younger *Santacrucense* stage. This subdivision in stages was based on biostratigraphic correlation and the observation of changes in fossil marine molluscan assemblages for marine deposits and fossil mammal assemblages for terrestrial beds. Modern work of basin-scale in the San Jorge Basin defined bounding discontinuities for the deposits assigned to these stages (Bellosi and Barreda, 1993; Legarreta and Uliana, 1994) and redefined each of the marine stages as a marine transgression.

Up to date much work has been done in trying to correlate and date these marine beds in spite of the low temporal resolution given by fossil marine molluscan assemblages (Legarreta and Uliana, 1994; Del Río, 2004; Parras et al., 2008). The abundance of pyroclastic material interbedded and mixed within these deposits, which are also rich in oysters, represents a good opportunity for radiometric age determinations. Available geochronological data are restricted to the overlying pyroclastic-rich terrestrial beds of the Santa Cruz Formation, which is of major interest in South America Land Mammal Ages (SALMA) (e.g. Marshall et al., 1986).

Many lithostratigraphic units cropping out in the Santa Cruz province have been interpreted to be the result of the Patagoniense transgression, including the Monte León Formation (Bertels, 1970) to the southeast near the mouth of the Santa Cruz River, the Chenque Formation in the San Jorge Basin to the northeast (Bellosi, 1987, 1990), the Chacay Formation (Chiesa and Camacho, 1995) in the region of Lago Posadas to the northwest of the province, and the Estancia 25 de Mayo Formation (Cuitiño and Scasso, 2010) in the southwestern end of the Santa Cruz province, around Lago Argentino region. An equivalent unit is known as the Guadal Formation (Niemeyer, 1975; Niemeyer et al., 1984; Frassineti and Covacevich, 1999) in the region of Lago General Carrera in Aysen, Chile. Farther north in Patagonia, there are other units related to this transgression, such as the Chenque Formation that outcrops in a large area of the San Jorge Basin (Bellosi, 1987, 1995) and the Gaiman Formation (Mendía and Bayarsky, 1981; Scasso and Castro, 1999) that occurs in the Valdés peninsula area. All these units are considered to span a Late Oligocene–Early Miocene age in this work, whereas other workers disregarded some of these correlations based in different age determinations (e.g. Camacho et al., 1998).

When the age of the marine deposits is not known, we use in this work the term "Patagoniense" *sensu lato* (*s.l.*); on the contrary, the name of the corresponding stage is used. We analyze a Patagoniense section in the area of Lago Argentino, in the southwestern end of Patagonia. We present two new U–Pb zircon datings of interlayered pyroclastic rocks, as well as the strontium isotopic composition of oysters that are found across the section. These new data allowed determining coherent and precise ages and hence the time of deposition of the unit in a short event of marine inundation over the studied area.

2. Study area and geologic framework

The units under study are part of the Cenozoic infill of the Austral or Magallanes Basin. Its northwestern part acted as a foreland basin since late Cretaceous, when the Andean thrusts began to move eastward (Biddle et al., 1986), up to the late Miocene, when the basin was completely filled with sediments and uplifted. The stratigraphic record of the study area in the region located between the Lago Argentino, to the north, and the Sierra Baguales, to the south (Fig. 1B), is composed by the Maastrichtian shallow marine Calafate Formation (Marenssi et al., 2004), the Eocene marine Man Aike Formation (Casadío et al., 2009) and a succession of late Paleogene to Neogene, relatively conformable units of the Río Leona, Estancia 25 de Mayo and Santa Cruz formations. Finally, a complex succession of upper Miocene to Quaternary glacial deposits and basaltic lava flows culminate the stratigraphic record of the region. Here, the Patagoniense deposits were formally named as Estancia 25 de Mayo Formation (Cuitiño and Scasso, 2010) in place of the inappropriate name of Centinela Formation (Furque and Camacho, 1972), which was previously used for another unit in northern Argentina.

The Estancia 25 de Mayo Formation is a 180 m thick succession deposited in a marine to estuarine environment that was subdivided into two members based on lithologic and sedimentologic features: the lower Quién Sabe and the upper Bandurrias members (Cuitiño and Scasso, 2010; Cuitiño, 2011). The Quien Sabe Member is composed mainly of fine to medium-grained, massive fossiliferous sandstones and the Bandurrias Member consists of medium- to coarse-grained sandstones with crossbedding and intercalations of muddy to heterolithic beds. Both members are bounded by a discontinuity. The underlying unit is the Río Leona Formation, composed of fluvial conglomerates, sandstones and carbonaceous shales (Marenssi et al., 2005), with abundant leaves and trunk remains of late Oligocene age (Barreda et al., 2009). A poorly known thick pile of fluvial deposits assigned to the Santa Cruz Formation (early–middle? Miocene) overlies the Estancia 25 de Mayo Formation. The Santa Cruz Formation is well-known for its rich mammal fossil content of Santacrucian South American Land Mammal Age (Marshall et al., 1977, 1986; Flynn and Swisher, 1995). The contact between the Estancia 25 de Mayo and Santa Cruz formations is transitional, with neither significant discontinuity nor abrupt change in sedimentary facies. The estuarine intertidal deposits of the lower unit grade upward into the low energy fluvial deposits of the upper unit.

The Estancia 25 de Mayo Formation crops out in a northeast to southwest belt of nearly 50 km, being part of a large homoclinal gently plunging to the east and southeast, which represents the deformation front of the present day Andean Belt (Ghiglione et al., 2009). Detailed sedimentological logs as well as bed by bed sampling for isotopic analysis were carried out at Estancia Quién Sabe, Arroyo Bandurrias and Sierra Cuncuna localities (Figs. 1B and 9).

3. Previous age determinations in the Lago Argentino region

Previous age estimations for the marine Patagoniense s.l. deposits range from Eocene to Miocene (Fig. 2). Most of these estimates are based on the fossil content, mainly marine invertebrates and palynological assemblages, and correlations with other, better-known, equivalent units of Patagonia, such as the Monte León and the Chenque formations. The stratigraphic subdivision of Ameghino (1906) into three stages named, from older to younger, *Juliense*, *Leonense* and *Superpatagoniense*, was based on differences in marine invertebrate assemblages observed in numerous localities around Patagonia. From this pioneer work arose the conception of a major transgression (i.e. the Patagoniense transgression) that occurs in three episodes (*Juliense*, *Leonense* and *Superpatagoniense*), which is still in mind of many researchers, and many later studies on these deposits attempted to place them into one or more of these stages.

Feruglio (1949–1950) first approached the age of the marine Patagoniense beds in Lago Argentino and compared their molluscan faunas with the Monte León faunas at the Atlanctic coast. He estimated an Oligocene to lower Miocene age, disregarding the Eocene age previously suggested by Hatcher (1900) for similar beds at Lago Posadas. Feruglio (1949–1950) recognized the absence of the "*Superpatagoniense*" stage, suggesting a more restricted age for the Lago Argentino beds. Furque and Camacho (1972) and Furque (1973) named the Patagoniense beds of Lago Argentino as the Centinela Formation, not aware this name was already used for another sedimentary unit in Argentina (see Cuitiño and Scasso (2010) for further discussion) and estimated a lower Miocene age for the unit, based on the study of the molluscan fauna. Malumián and Náñez (1998) also determined a Lower Miocene age based on the presence of the foraminifer *Transversigerina* sp. Later Camacho et al. (1998) assigned the succession to the Eocene on the basis of the bivalve *Venericardia* (*venericor*) sp., thus giving a much older age to the transgression.

The first radiometric age for the Patagoniense beds in the Lago Argentino region was a whole rock $^{40}Ar/^{39}Ar$ age of 46 Ma for a tuff bed (Casadío et al., 2000a) apparently validating the Eocene age proposed by Camacho et al. (1998). Shortly afterward, however, the same authors rejected the reported Eocene age based on paleontological and stratigraphic evidences (Casadío et al., 2000b; Guerstein et al., 2004) as well as new $^{87}Sr/^{86}Sr$ ages on oyster shells (Casadío et al., 2001), considering the age of these deposits to be near the Oligocene–Miocene boundary (Fig. 2).

Recently, Parras et al. (2008) correlate the Patagoniense units of Santa Cruz province in terms of faunistic comparisons, $^{87}Sr/^{86}Sr$ age determinations and a $^{40}Ar/^{39}Ar$ age of a pyroclastic intercalation, giving a reliable chronostratigraphic framework. They provided a Lower Miocene (Aquitanian) age for the lower part of the succession on the basis of two $^{87}Sr/^{86}Sr$ ages of 22.86 and 21.24 Ma in the Lago Argentino region, and correlated it with the Monte León Formation in southeast of Santa Cruz. Barreda et al. (2009) analyzed the palynological content of the underlying Río Leona Formation and the base of the Estancia 25 de Mayo Formation, concluding that they respectively have late Oligocene and early Miocene ages, and suggesting a brief hiatus between them (Fig. 2).

There are no radiometric age determinations for the terrestrial Santa Cruz Formation in the study area. However, the early–middle Miocene age of this unit is well constrained according to a number of studies made on different localities in the Santa Cruz province (Marshall et al., 1977, 1986; Flynn and Swisher, 1995; Fleagle et al., 1995; Blisniuk et al., 2005).

4. Materials and methods

4.1. U–Pb method

The studied rocks for this geochronologic method are two conspicuous beds of pure pyroclastic material, which were used to obtain zircon grains for U–Pb dating. The levels are named the Lower Pyroclastic Level (LPL) and the Upper Pyroclastic Level (UPL). The LPL (Fig. 3) is composed of vitric pyroclastic particles (shards

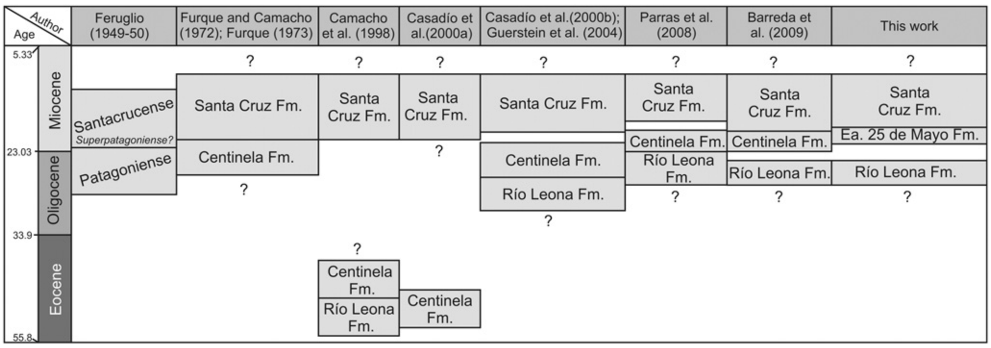


Fig. 2. Previous age determinations for the Patagoniense beds in the Lago Argentino region.

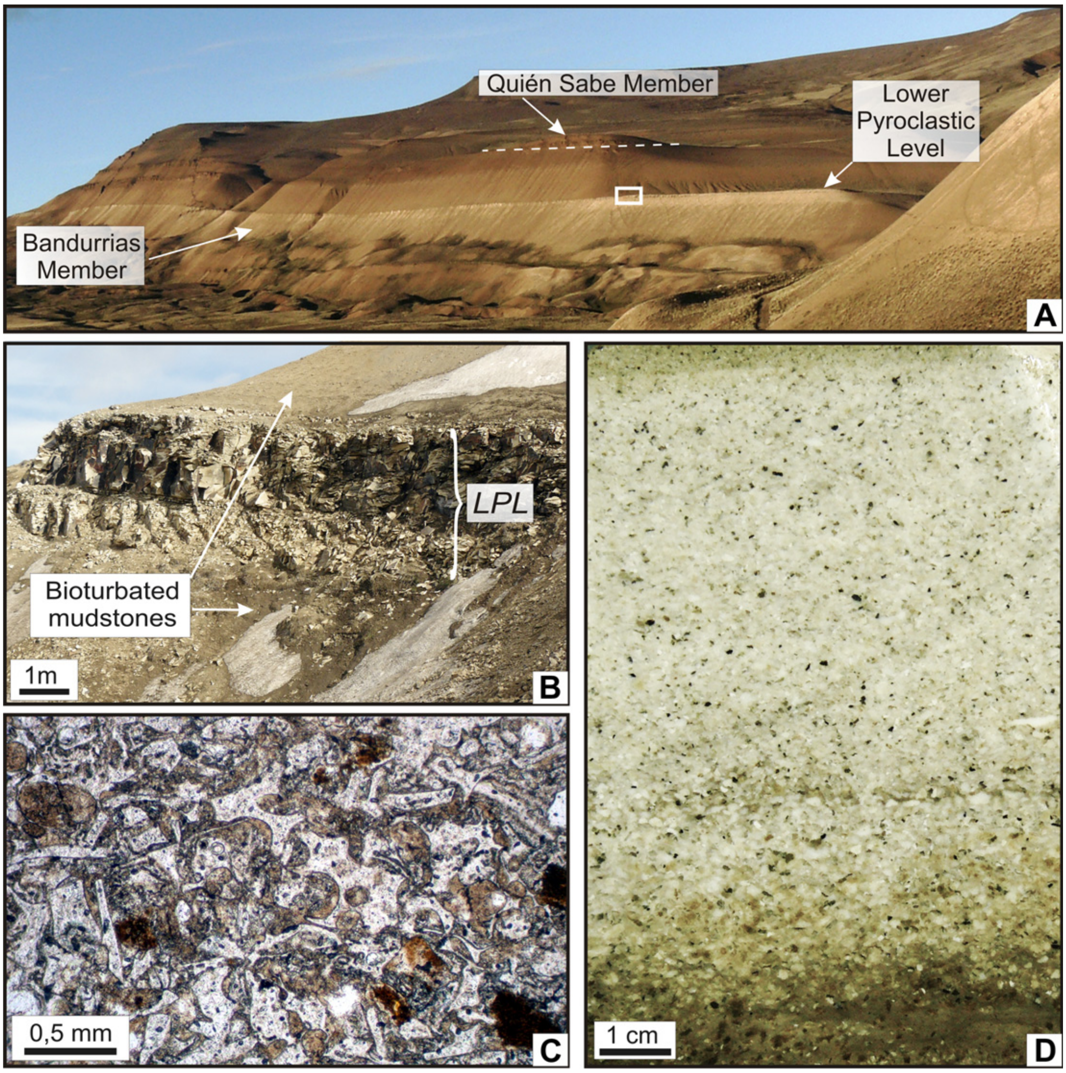


Fig. 3. Lower pyroclastic level. (A) General view of the LPL at Arroyo Bandurrias. Note the lateral extent of the level which is 3 m thick in this locality. The white frame corresponds to location of B. (B) Close-up view of the LPL interbedded within marine mudstones of the Bandurrias Member. (C) Thin section image under plain polarized light showing dominance of glass shards. Brownish interstitial materials are authigenic clays. (D) Polished surface of a sample from the base of the LPL at Sierra Cuncuna locality. This represents the coarsest deposits of the level. The lower dark band is the underlying mudstones.

and minor pumice) of sand to silt grain-size and occurs near the base of the Estancia 25 de Mayo Formation, interbedded between the marine siltstones and mudstones of the Quién Sabe Member. Coarser facies (lapilli) appears near the base of the body (Fig. 3D) in the Sierra Cuncuna locality (Fig. 1B), where samples for U–Pb dating were taken. The UPL (Fig. 4) is interbedded in the transition between the Estancia 25 de Mayo Formation and the overlying Santa Cruz Formation. It is composed of a number of lenticular bodies, which all together make a discontinuous level. It appears mainly to the northeast of the study area. Samples from Estancia Quién Sabe locality (Fig. 1B) were taken for U–Pb dating.

Approximately 2 kg samples were taken from each pyroclastic level in sectors showing no mixing with epiclastic material and coarse grain-size. Samples were named *Cuncuna 1*, from the LPL, and *Toba V* from the UPL. Each sample was crushed and sieved at different grain sizes and then passed through a hydraulic separator in order to concentrate a heavy mineral aliquot. This heavy mineral concentrate was passed through a 2.8 g/cm^3 heavy liquid and through a Frantz magnetic separator, thus obtaining a small amount of heavy, non-magnetic minerals, including zircon.

For U–Pb geochronologic analyses of pyroclastic deposits a large amount of zircon grains is needed because epiclastic contamination could happen, either through the incorporation of exotic material during the eruption or during the transport to the final deposit. So, the larger amount of grains dated the more confident results. Taking this into consideration, up to 50 zircon grains were separated from each sample by hand picking under a binocular lens and mounted on a double tape, then covered with a plastic cylinder and filled with an epoxy resin. After drying and hardening of the resin, the mount was polished and cleaned.

U and Pb isotopic analyses were carried out using the Laser Ablation methodology (Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry – LA–ICP–MS, Bühn et al., 2009) at the Laboratory of Geochronology of the Brasilia University, Brazil. Each zircon grain was investigated with a UP-213 nm laser microprobe connected to a Neptune ICP–MS. The standard used was the GJ-1 zircon (Jackson et al., 2004). The succession of analyses was organized in the following order: a blank or background measuring the vacuum, a standard GJ, and four zircons from the sample, so that the isotopic composition of each zircon was corrected with the previous and subsequent blanks and standards.

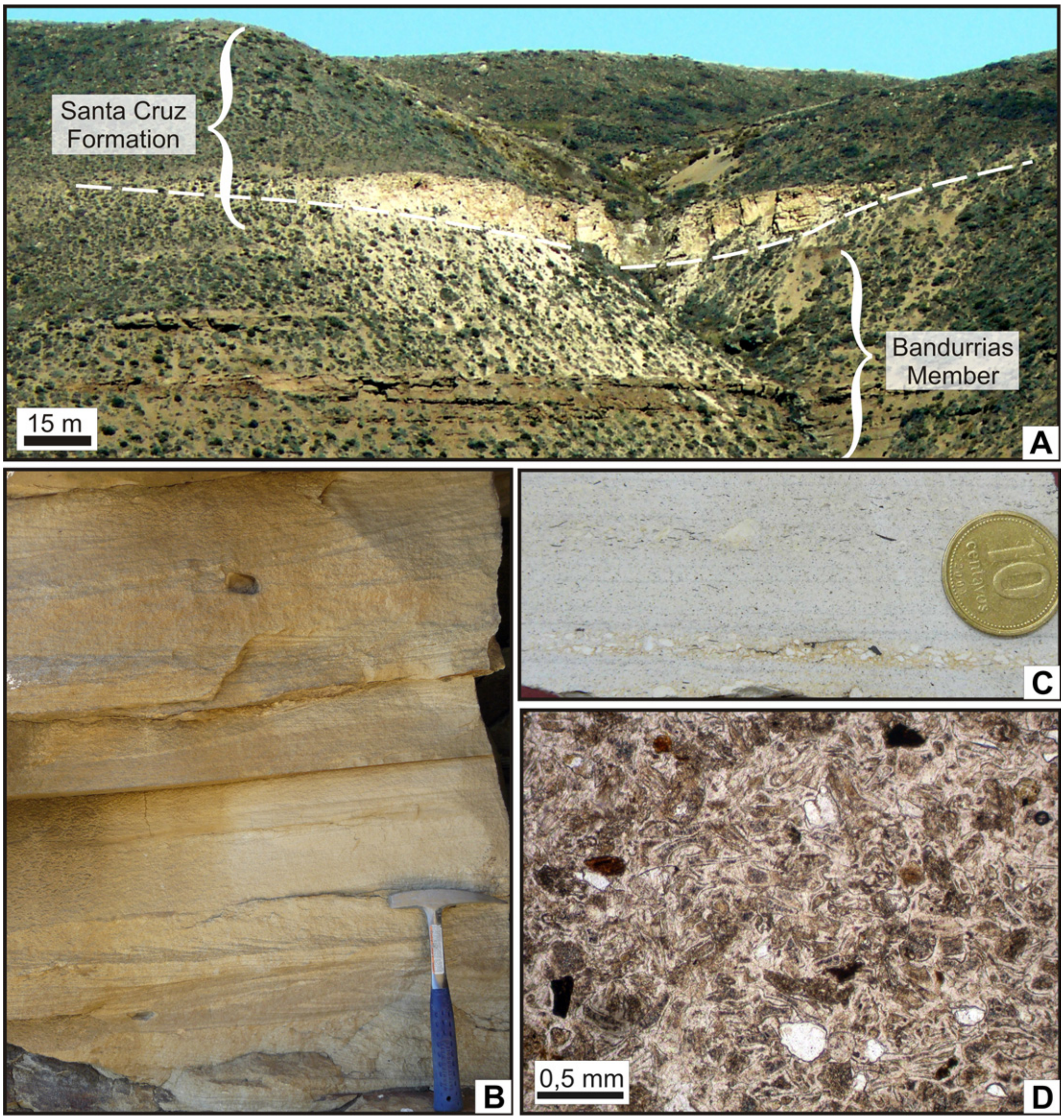


Fig. 4. Upper pyroclastic level. (A) General view of the upper portion of the outcrop at Quién Sabe Locality. The UPL shows a clear lenticular shape. (B) Close-up view of facies composing the lens figured in A. Note crossbedding and sand-sized pyroclastic material. (C) Polished surface of a sample at the base of the UPL composed of silt-size ash and levels rich in pumice and plant detritus. (D) Thin section image under plain polarized light showing the dominance of shards and pumice with few quartz, plagioclase and magnetite crystals.

The analyzed isotopic ratios for each zircon are $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$. Both ratios are related in the Concordia Curve. Due to the low contents of radiogenic Pb in young zircons, the laser diameter was raised to 55 μm in order to obtain a larger amount of material for the measurement in the mass spectrometer. For this reason, only zircon grains larger than 55 μm across were used, and 42 grains for each sample were subsequently analyzed. The age calculations were carried out with the Isoplot software. The isotopic ratio used for age calculations was the $^{206}Pb/^{238}U$ because it yields more reliable ages for young zircons (Jackson et al., 2004). From the overall age results, few values were discarded because of excessively high errors or incoherent age values (e.g., negative or very old ages caused by the anomalous $^{207}Pb/^{235}U$ ratios). The age values from all zircon grains were plotted in probability diagrams that allowed identifying the most representative peak of ages for each sample (Fig. 5A,B). Based on the values composing each peak it is possible to apply different methodologies in order to obtain more accurate values. These are the Concordia Curve (Fig. 5C,D) and the Mean Age (Fig. 5E,F), calculated with the Isoplot software. Additionally, the ages were calculated using the Tera-Waseburg (T-W) diagram, which is useful for handling data from young zircons (Jackson et al., 2004). The ages obtained are identical to those obtained using the Concordia diagrams.

4.2. $^{87}Sr/^{86}Sr$ method

The $^{87}Sr/^{86}Sr$ ratio of the ocean water is homogeneous worldwide and shows somewhat known variations during the geologic time (Veizer et al., 1999; McArthur et al., 2001). These time dependent variations allow age estimates based on comparison with carbonate $^{87}Sr/^{86}Sr$ global reference curves for some age periods (McArthur et al., 2001). For the Cenozoic, and especially after ca. 40 Ma before present, this curve shows a steep and fairly constant slope. Calculation of ages in this period provides less uncertainty than in other geologic times.

For Sr isotopic analysis thick oyster shells were sampled throughout the entire marine section of the Estancia 25 de Mayo Formation. These shells are composed mainly of calcite (Stenzel, 1971; Carter, 1990), thus giving good chances of preservation of the original chemical composition. Two species of oysters were

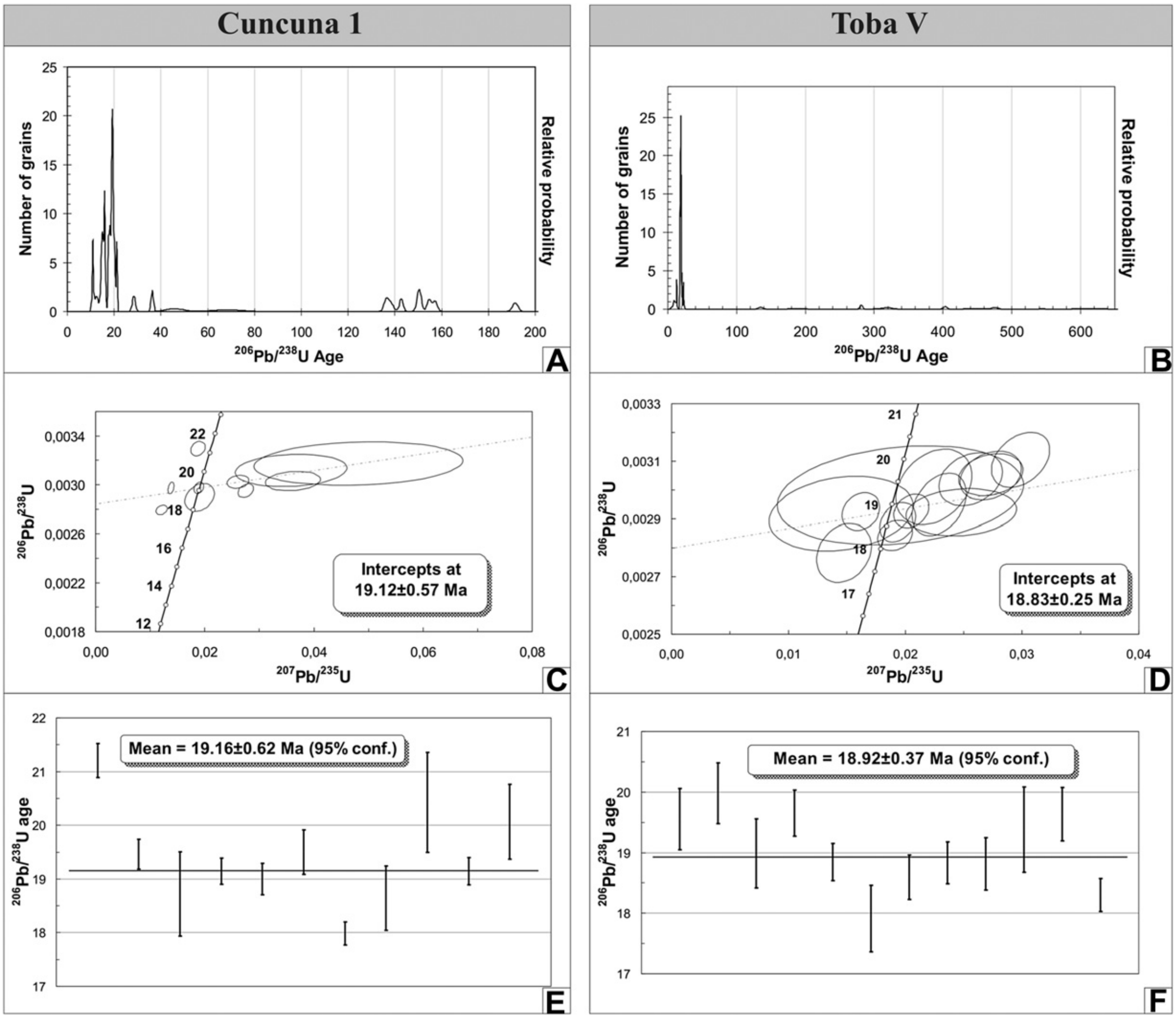


Fig. 5. U–Pb data. (A–B) probability diagrams for both the *Cuncuna 1* and *Toba V* samples, respectively. In (A) the main peak is near 20 Ma although other minor peaks are present. In (B) a unique main peak is at around 19 Ma. (C–D) Concordia curves for both samples. Zircon used in this curve is those composing the main peaks in (A) and (B). (E–F) Mean age diagrams for both samples. The age derived from these diagrams coincides well with those in (C) and (D).

recognized: *Crassostrea? hatcheri* (Fig. 6A,B), which is the most conspicuous fossil in the section and dominate in the lower and middle part; and *Crassostrea orbignyi* (Fig. 6C,D), which appears in the upper part of the marine section within estuarine deposits. Samples were taken from autochthonous or parautochthonuos shell accumulations with no evidence of prolonged transport or reworking in order to get significant ages. Many of these oyster-beds are monospecific and show specimens in life position. Other levels (not sampled) consist of residual concentrations (Cuitiño and Scasso, 2010; Cuitiño, 2011). Thick-shelled oysters were preferred, as internal microstructures were easily observed and sampled separately.

Each oyster shell was cut in a dorsal–ventral plane and its surface was polished to observe the internal layer arrangement (i.e. Fig. 8). Thin sections for petrographic observation were made with the same orientation, and Scanning Electron Microscope (SEM) images were obtained from small broken surfaces of shells. Two main types of layers were recognized: those composed mainly of translucent material and those composed of opaque material. The former normally show prismatic and foliated microstructures (Fig. 7A–C), whereas the latter are composed of fine-grained carbonate with a poor developed structure known as "Chalky Layers" (Fig. 7D) that is a common feature in oysters (Stenzel, 1971; Carter, 1990).

Microsampling of discrete layers with different microstructures was carried out in order to obtain 20 mg of rock needed for isotopic analysis in the mass spectrometer. This aliquot was obtained with a microdrill that allowed sampling within individual and homogenous layers. Only thick and homogeneous layers were sampled to avoid mixing of microstructures. Thus, each microsample contains a powder of carbonate from exclusively one microstructure (e.g., foliated, prismatic, or chalky material). The ^{87}Sr/^{86}Sr ratio was successfully measured in 25 microsamples (Table 1) with a Neptune ICP Mass Spectrometer at Brasilia University, Brazil. Age calculations were based upon the Lookup Table proposed by McArthur et al. (2001) with an uncertainty of 0.07 Ma derived from the mean curve.

5. Age results

5.1. U–Pb ages

Age results obtained with the ^{206}Pb/^{238}U ratio were plotted in probability diagrams in which it is possible to observe the age

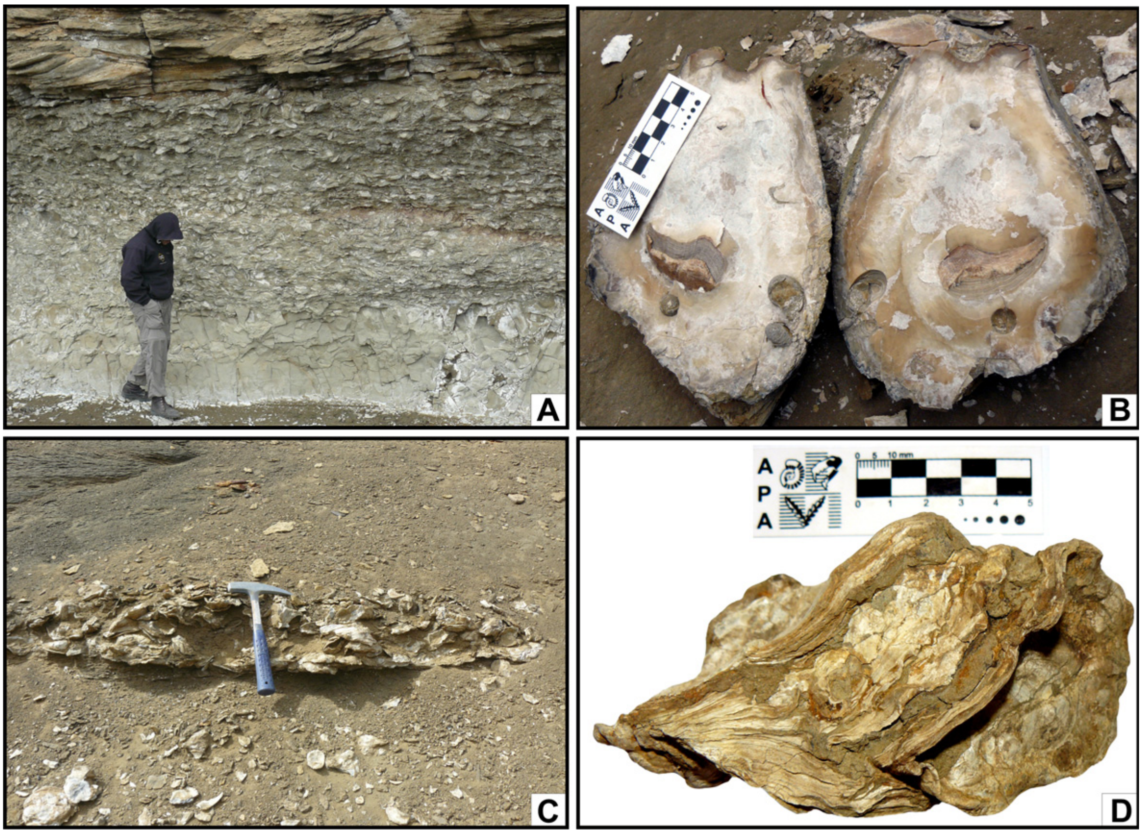


Fig. 6. (A) Thick oyster bed dominated by *Crassostrea? hatcheri*. Specimens are articulated or disarticulated showing a small degree of reworking. (B) Large specimen of *C. hatcheri* showing the interior of both articulated valves. (C) Oyster bed composed exclusively by *Crassostrea orbignyi*. Note the convex-up shape of the build-up. (D) Valves of *C. orbignyi* cemented one to each other. Specimens are articulated and were found in life position.

pattern distribution for each sample (Fig. 5A–B). In both cases a marked peak is observed which may be interpreted to be the age of the pyroclastic deposit.

For the *Cuncuna 1* sample (Fig. 5A) 140–160 Ma old zircon grains are present and may be interpreted as contamination by acidic volcanic rocks belonging to the El Quemado Complex of middle to late Jurassic age (Pankhurst et al., 1998). Few zircon grains with ages between 30 and 40 Ma have no statistic significance. On the other hand, peaks younger than the main peak reach ages of approximately 10 Ma which have no geological meaning because it is known

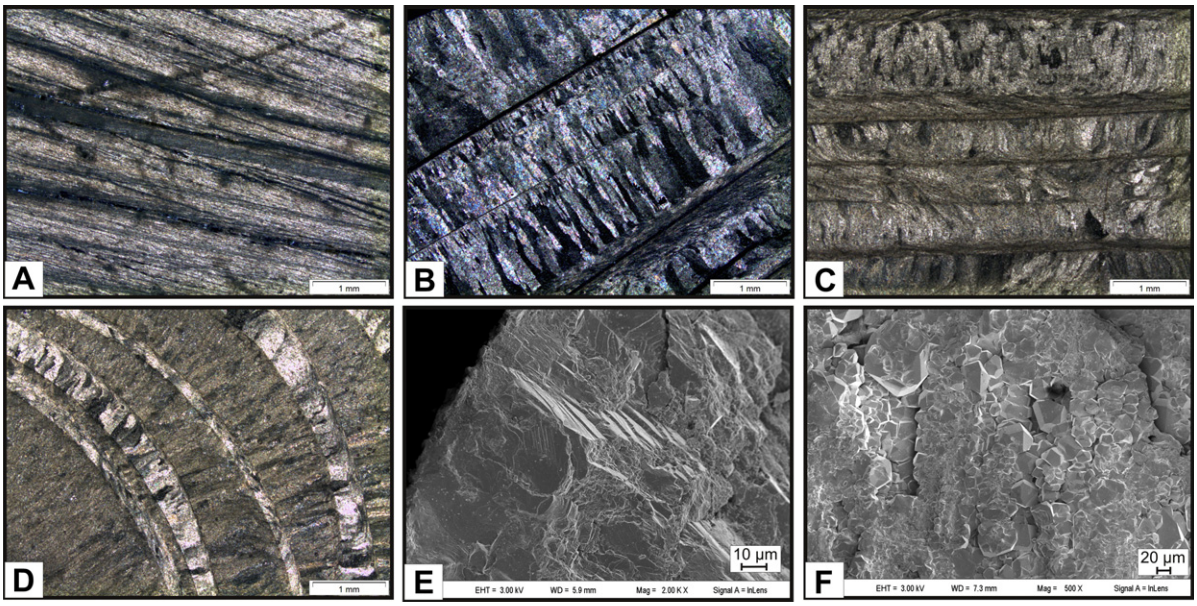


Fig. 7. Shell microstructures. (A–D) Microphotographies under cross polarized light of thin sections of oyster valves. (A) Foliated layers, (B) Prismatic layers, (C) Interbedding of foliated and prismatic layers, (D) Interbedding of prismatic (thinner and lighter) and chalky (thicker and darker) layers. (E–F) Scanning electron microscope images. (E) Foliated layer. (F) Chalky layer. Note euhedral calcite crystal of secondary origin and large poral space.

Table 1
List of samples, microstructures, $^{87}Sr/^{86}Sr$ data, and the resultant ages from the lookup table of McArthur et al. (2001). Samples named "QS" are from the Estancia Quién Sabe locality, and those named "AB" are from Bandurrias Creek locality. Note the larger dispersal of data coming from chalky microsamples in comparison to that of translucent microsamples.

Sample	Microsample	$^{87}Sr/^{86}Sr$	Sd dev	Microstructure	Age
SBS 987	Standard	0.710213	0.000026	–	–
AB-IX	79	0.708489	0.000028	Translucent	19.29
AB-X	35	0.708537	0.000027	Chalky	18.67
AB-X	36	0.708449	0.000034	Chalky	19.84
AB-XV	39	0.708483	0.000030	Translucent	19.38
AB-XVI	47	0.708488	0.000069	Chalky	19.31
AB-XVI	48	0.708512	0.000070	Translucent	18.99
AB-XVII	51	0.708501	0.000036	Translucent	19.13
AB-XVII	52	0.708457	0.000072	Chalky	19.73
QS-I	2	0.708435	0.000077	Translucent	20.05
QS-I	69	0.708305	0.000071	Chalky	22.17
QS-III	70	0.708514	0.000036	Translucent	18.96
QS-III	71	0.708396	0.000030	Chalky	20.79
QS-VII	72	0.708464	0.000016	Translucent	19.63
QS-VIII	73	0.708464	0.000029	Translucent	19.63
QS-X	74	0.708485	0.000024	Translucent	19.35
QS-XIII	75	0.708350	0.000038	Chalky	21.53
QS-XV	76	0.708496	0.000027	Translucent	19.20
QS-XVII	78	0.708494	0.000036	Translucent	19.23
QS-XIX (2)	63	0.708508	0.000054	Translucent	19.04
QS-XIX (2)	64	0.708543	0.000055	Chalky	18.59
QS-XIX (2)	65	0.708485	0.000035	Translucent	19.34
QS-XIX (2)	66	0.708411	0.000045	Chalky	20.48
QS-XIX (2)	67	0.708500	0.000022	Translucent	19.15
QS-XXIII (5)	30	0.708533	0.000075	Chalky	18.72
QS-XXIII (5)	31	0.708500	0.000031	Translucent	19.15

that the overlying Santa Cruz Formation is not younger than 14–15 Ma (Marshall et al., 1977; Marshall and Salinas, 1990; Blisniuk et al., 2005). Thus, the most representative peak of the diagram is at ca. 19–20 Ma and is considered to be the age of the LPL.

For the *Toba V* sample most of the age results are coincident within one single peak. The resulting age is about 18–19 Ma (Fig. 5B) which is consistent with the stratigraphic position of this layer in relation to the LPL. Few younger and older ages are observed, but they are not statistically significant.

Ages of 19.12 ± 0.57 Ma for *Cuncuna 1* and 18.83 ± 0.25 Ma for *Toba V* samples were obtained using the data of the main peaks in a Concordia Curve (Fig. 5C–D). On the other hand, the mean $^{206}Pb/^{238}U$ ages yielded 19.16 ± 0.62 Ma for *Cuncuna 1* and 18.92 ± 0.37 Ma for *Toba V* (Fig. 5E–F).

The Concordia Curve, Mean Age, and Tera-Wasseburg diagram, gave consistent values with older ages at the base of the stratigraphic column (LPL) and younger ages at the top (UPL). These data indicates that the deposition of the Estancia 25 de Mayo Formation occurred between 19.14 ± 0.5 and 18.85 ± 0.3 Ma, the last age being the beginning of the deposition of the fluvial deposits of the Santa Cruz Formation. These two ages lie into the early Miocene Burdigalian stage.

5.2. $^{87}Sr/^{86}Sr$ ages

The samples analyzed record a small variation of $^{87}Sr/^{86}Sr$ ratio, in a spectrum from 0.70830 to 0.70854 (Table 1). Values obtained from layers with different microstructures show subtle variations. Translucent layers show values ranging from 0.70843 to 0.70853, while chalky layers show more spread values ranging from 0.70830 to 0.70854, twice the range of translucent layers.

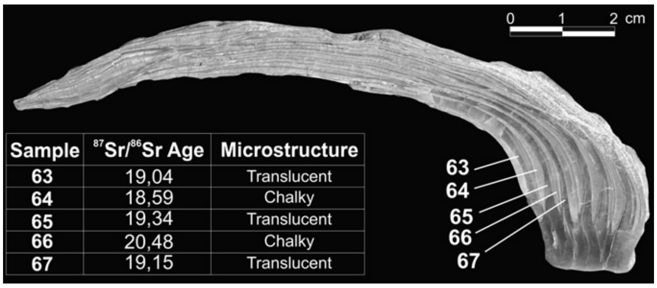
The ages obtained for translucent layers fit very well with the ages obtained trough U–Pb analysis and span a range of 1 Ma (from 20 to 19 Ma, Fig. 9), whereas the ages calculated from chalky layers span a range of 3.5 Ma. Although ages derived from chalky layers might be still consistent with the probable age of the oysters, the microstructure-related changes in isotopic ratios are significant for high resolution age calculations. Sr isotope ratios in the chalky layers are more variable (Fig. 8) and a similar pattern was also noted in the O and C stable isotope ratios (Cuitiño et al., 2010; Cuitiño, 2011), with chalky layers showing a lighter and highly variable isotopic composition in comparison to the uniform and heavier composition of translucent layers. In addition, variation of Sr isotope ratios within successive layers of a single shell are evident (Fig. 8) and SEM images of chalky layers showed they are composed, at least in part, of euhedral rhomboidal calcite crystals (Fig. 7F). Therefore, we interpret that the original Sr isotope ratio was slightly modified in the chalky layers as a result of post-depositional alteration of the original pristine microstructure, and consequently we disregard the ages calculated for the chalky layers and accept the more reliable ages obtained from translucent layers. Furthermore, the calculated ages for all the translucent layers are consistent with the stratigraphic position of each sample (Fig. 9). The same is not true for the chalky layers.

5.3. Age integration

The U–Pb ages are 19.14 ± 0.5 Ma for the LPL, near the base of the Estancia 25 de Mayo Formation (Quién Sabe Member), and 18.85 ± 0.3 Ma for the UPL in the uppermost part of the unit (transitions between the Bandurrias Member and Santa Cruz Formation, Fig. 9). The range of $^{87}Sr/^{86}Sr$ ages for the Quién Sabe Member varies from 20.05 to19.40 Ma, whereas for the Bandurrias Member the range is from 19.45 to 18.95 Ma.

The U–Pb age of the LPL is slightly younger (about 0.5 Ma) in comparison to the $^{87}Sr/^{86}Sr$ ages obtained for the same stratigraphic position (Fig. 9). This discrepancy is probably related to the elevated errors obtained in U–Pb analysis of the *Cuncuna 1* sample (Fig. 5A, C, E). However, few $^{87}Sr/^{86}Sr$ ages are available for the same stratigraphic level and we are not totally sure of what of both methods is giving the most precise age.

The UPL is interbedded in the transitional deposits of the uppermost part of the Estancia 25 de Mayo Formation and the lower part of the Santa Cruz Formation. The boundary between both units is arbitrarily placed in the top of the uppermost bed containing marine fossil invertebrates. The UPL lies just above or occasionally at the same level of the last oyster bed. Following the criteria discussed above, it must be regarded as part of the Santa Cruz Formation (Fig. 4A). Thus, the 18.85 ± 0.3 Ma of the UPL represents the age of the beginning of the Santa Cruz Formation sedimentation and the end of the Patagoniense transgression in the region. The $^{87}Sr/^{86}Sr$ date stratigraphically closer to the UPL is 19.15 Ma, coming from the uppermost oyster bed situated just 2 m below the UPL. Both ages show a reasonable agreement taking into account they were obtained from different methods (Fig. 9).



Sample	$^{87}Sr/^{86}Sr$ Age	Microstructure
63	19,04	Translucent
64	18,59	Chalky
65	19,34	Translucent
66	20,48	Chalky
67	19,15	Translucent

Fig. 8. Polished cross section of an oyster valve with selected microsample analysis. The shell is composed of alternating chalky and translucent layers. Age results are comparable among translucent layers whereas chalky layers show higher discrepancy.

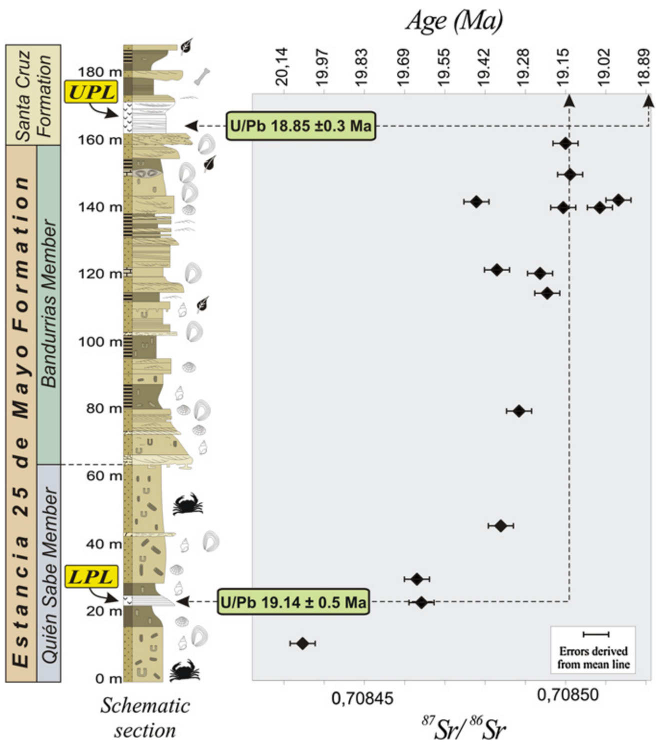


Fig. 9. Integration of U–Pb and $^{87}Sr/^{86}Sr$ ages related to the position of each sample in the sedimentary column. The left column represents the formal stratigraphic nomenclature. The ages above are calculated from the Lookup table of McArthur and Howarth (2004). Positions of both pyroclastic levels (LPL and UPL) are figured in the sedimentary column with their corresponding U–Pb age. Note the tendency of younger $^{87}Sr/^{86}Sr$ ages to the top.

The data integration restricts the age of the Patagoniense transgression in Lago Argentino region (the Estancia 25 de Mayo Formation) to an interval between 20 and 18.8 Ma (Fig. 9), i.e. it is restricted to the early Burdigalian stage. The difference between U–Pb ages for both pyroclastic levels is about 0.3 Ma, whereas the maximum age difference for $^{87}Sr/^{86}Sr$ ages is 1 Ma. Taking into account the errors obtained for the U–Pb method, especially that of the LPL, the age span between levels may probably increase up to 1 Ma considering the maximum errors. These age differences indicate that the 170 m of sediments belonging to the Estancia 25 de Mayo Formation were deposited in a period lasting as much as 1 Ma, which represents an accumulation rate of 170 m/Ma. This rate of deposition agrees well with expected sedimentation rates for coastal depositional environments (Einsele, 2000). Considering the $^{87}Sr/^{86}Sr$ ages individually for each member of the Estancia 25 de Mayo Formation, some differences in the sedimentation rate arise (Fig. 9). A sedimentation rate of 60 m/Ma is calculated for the Quién Sabe Member, whereas a sedimentation rate of 200 m/Ma is obtained for the Bandurrias Member. This difference in sedimentation rate is in concordance with the degree of bioturbation observed within each member (Cuitiño and Scasso, 2010; Cuitiño, 2011), considering that slower sedimentation rates give time enough for marine organisms to fully bioturbate the substratum (i.e. Quién Sabe Member), whereas higher sedimentation rates give better chances for preservation of deposits with a small degree of bioturbation (i.e. Bandurrias Member).

Recently, Parras et al. (2008) obtained two $^{87}Sr/^{86}Sr$ ages of 22.86 and 22.45 Ma from oyster shells from the lower part of the Estancia 25 de Mayo Formation, which are slightly older than the obtained here. The cause of this age difference is not clear. However, since some of the $^{87}Sr/^{86}Sr$ ages calculated based on chalky material isotopic ratios give similar results as that reported by Parras et al. (2008), it is possible that these authors may have used material with some degree of diagenetic alteration. This interpretation is reinforced by the $^{40}Ar/^{39}Ar$ age of 20.48 Ma reported by Parras et al. (2008) for a tuff layer intercalated in the lower part of an equivalent deposit located 200 km to the north in the Lago Cardiel region, and is consistent with our ages for the lower part of the Patagoniense deposits at Lago Argentino.

6. Correlations

The age calibration of the Patagoniense deposits at Lago Argentino gives new insights for their correlation with other Patagoniense beds for neighboring areas of the Santa Cruz Province. Most previous studies generally considered longer time-intervals for the accumulation of the marine sediments. The early Burdigalian ages (20–19 Ma) obtained in this work are one of the best estimations for the age of the Patagoniense beds and may constitute a solid start-point for correlations.

To the southeast of the Santa Cruz province, along the present day Atlantic coast, the Monte León Formation is considered the representative of the Patagoniense s.l. transgression, and is believed to be of lower Miocene age based in palynological assemblages (Barreda and Palamarczuk, 2000). A tuff in the uppermost part of this unit (Monte Observación Member) is dated by the $^{40}Ar/^{39}Ar$ technique at 19.33 ± 18 Ma, while the lower part of the overlying terrestrial Santa Cruz Formation is dated as old as 16.42 ± 23 Ma by the same technique (Fleagle et al., 1995), pointing to the existence of a hiatus between both units. For the same area, Marshall et al. (1977, 1986) reported ages in a range of 17.3–16.0 Ma for the Santa Cruz Formation. On the other hand, there are no radiometric ages for the basal portion (Punta Entrada Member) of the Monte León Formation and its age is estimated within an interval from 24 to 19.33 Ma, according to the ages of the underlying San Julián Formation (Parras et al., 2008) and the overlying Monte Observación Member, respectively. Therefore, it is possible to correlate the Estancia 25 de Mayo Formation and the lowermost beds of Santa Cruz Formation at Lago Argentino with the Monte Observación Member of the Monte León Formation (Fig. 10), whereas the correlation with the Punta Entrada Member is poorly constrained by its doubtful age.

To the north of Lago Argentino numerous and poorly known localities show exposures of the Patagoniense (s.l.) beds. In the Lago Cardiel region Parras et al. (2008) obtained an $^{40}Ar/^{39}Ar$ age of 20.48 ± 0.27 Ma from a tuff interbedded within the marine section. These authors also obtained two $^{87}Sr/^{86}Sr$ ages of 26.38 Ma (Chattian) in underlying marine beds (Fig. 10). This age discrepancy within an apparently continuous succession could be the cause of alterations of the pristine carbonate used for $^{87}Sr/^{86}Sr$ analysis (for example usage of chalky material) or, on the other hand, considering the $^{87}Sr/^{86}Sr$ as correct, the older beds could be related to the presence of the Juliense stage, which might suggest the existence of an important hiatus within the Patagoniense (s.l.) deposits in this region. Further stratigraphic and sedimentologic work is needed in this region in order to construct the stratigraphic framework. Summarizing, the Estancia 25 de Mayo Formation can be correlated with the upper part of the Patagoniense (s.l.) beds to the north of Lago Argentino.

Farther north, in the region located between the Lago Posadas, to the north, and Lago Belgrano, to the south, there are continuous exposures of the Patagoniense (s.l.) deposits. In this place, the marine unit has been named Chacay Formation (Chiesa and Camacho, 1995). Equivalent beds are the Guadal Formation (Niemeyer et al., 1984; Frassineti and Covacevich, 1999; Flynn et al., 2002) located to the northwest of Lago Posadas, in Chile. The Chacay Formation conformably underlies the Santa Cruz

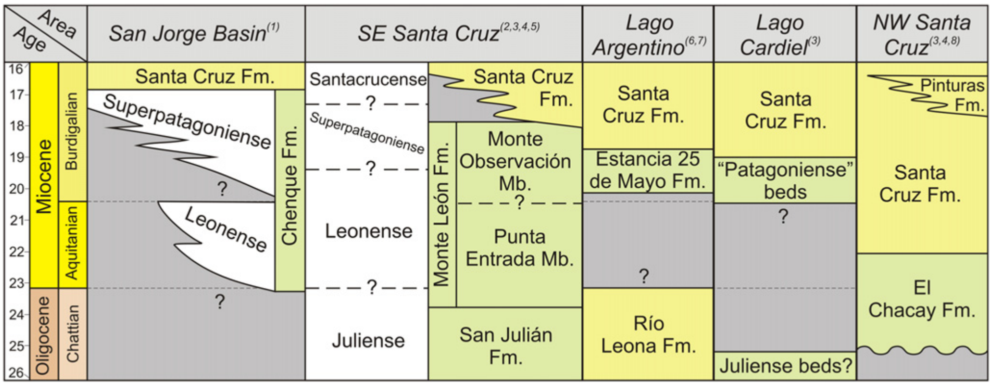


Fig. 10. Stratigraphic chart for the Patagoniense deposits and related units. Green and yellow areas correspond to marine-transitional and terrestrial lithostratigraphic units, respectively. White areas correspond to chronostratigraphic units whereas gray areas are hiatuses. Numbers in brackets associated to each area indicate the source of information as follows: (1) Barreda and Bellosi (2003); (2) Barreda and Palamarczuk (2000); (3) Parras et al. (2008); (4) Fleagle et al. (1995); (5) Marshall et al. (1986); (6) this work; (7) Barreda et al. (2009); (8) Blisniuk et al. (2005). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Formation, which has a well-constrained $^{40}Ar/^{39}Ar$ age in the range of 22–14 Ma (Blisniuk et al., 2005). Additionally, Parras et al. (2008) obtained one $^{87}Sr/^{86}Sr$ age of 25 Ma for the lower part of this marine unit. This might indicate that the Chacay Formation is older than 22 Ma, disregarding the correlation with the Estancia 25 de Mayo Formation, and might represent an older marine invasion, probably the Juliense transgression.

South of Lago Argentino area the Patagoniense (s.l.) deposits are scarce and poorly exposed, with a few outcrops in the Río Turbio region. Farther south equivalent marine deposits appear along the Atlantic coast of the Tierra del Fuego Island although precise age assignment of these deposits is still missing.

7. Stratigraphic implications – discussion

As it was previously mentioned, the Patagoniense transgression was subdivided into three stages by Ameghino (1906) based on observations in many areas of Patagonia: the Juliense, Leonense and Superpatagoniense stages (or transgressions). The age of each of these stages was later estimated by fossil content, mainly palynological assemblages for the San Jorge Basin (Barreda and Bellosi, 2003). The temporal resolution of these estimations is low and precise correlation between adjacent basins is hard to perform. The Juliense stage is considered to be of late Oligocene age, the Leonense of early Miocene (Aquitanian) age and the Superpatagoniense of Burdigalian age (Barreda and Palamarczuk, 2000; Barreda and Bellosi, 2003). Regardless the ages, in the San Jorge Basin in central Patagonia, these stages were recognized bounded by regional discontinuities so they were identified as individual stratigraphic sequences (Bellosi and Barreda, 1993; Legarreta and Uliana, 1994), and a paleogeographic reconstruction of each marine invasion was sketched (Bellosi, 1995; Barreda and Bellosi, 2003). According to these paleogeographic reconstructions, the Juliense transgression covered mainly the southeast of the basin (Mazarredo sub-basin), the Leonense transgression occupied a limited areal extension (to the eastern part of the basin), whereas the Superpatagoniense transgression flooded a wider area reaching the westernmost localities (Bellosi, 1995).

Unfortunately, a discontinuity-based analysis of the Patagoniense transgression in the Austral Basin is not available, so the temporal assignments and stratigraphic correlations of these beds are based upon scarce isotopic ages and fossil mollusk content. In this basin, the Juliense stage is represented essentially by the San Julián Formation. This unit is conformably overlaid by the Monte León Formation (Fig. 10), representing both the Leonense and Superpatagoniense stages in two differentiated members: the Punta Entrada and Monte Observación members, respectively. The association of the stages with lithostratigraphic units (members) suggests a sedimentologic or paleoenvironmental control over the faunistic content of each member and it is not clear whether the faunal differences (mainly molluscan assemblages) are controlled by the age of each member or by the different sedimentary environments they represent. No regional unconformity has been observed between both members of the Monte León Formation (Cuitiño, 2011), so a continuum sedimentary record from base to top of the unit is estimated.

The Patagoniense beds at Lago Argentino coincide in age with the Superpatagoniense stage of the San Jorge Basin (Fig. 10). The mollusk fauna of the Patagoniense beds in Lago Argentino is similar to the fauna of the Monte León Formation (Feruglio, 1949–1950; Parras et al., 2008) and suggests a Leonense age for these beds. Our results give rise to a contradiction between isotopic ages and paleontological affinities. Two possible causes can be regarded as responsible of this contradiction: 1) correlation based on faunal affinities is of limited use due to facies-control over the molluscan faunal content or; 2) the ages and durations of the transgressions as traditionally known (i.e. in San Jorge Basin) are not correctly established, and the Leonense is actually of Burdigalian age, similar to that of the Superpatagoniense transgression. New isotopic ages are needed, especially for type localities, in order to solve this problem and create a solid chronostratigraphic framework for the Patagoniense deposits.

According to our new isotopic ages, the Patagoniense beds of Lago Argentino were deposited during the Superpatagoniense transgression (early Burdigalian) and no Leonense deposits are recorded in this area. It implies that this "Superpatagoniense Sea" reached westernmost positions within the Austral Basin in comparison to the previous "Leonense sea" that is recorded only in the eastern part of the basin. Similar distributions were observed in the San Jorge Basin (Bellosi, 1995; Barreda and Bellosi, 2003). However, according to the existing isotopic ages, the presence of Superpatagoniense beds in the northwest areas of Santa Cruz province is still uncertain (Fig. 10).

The areal extent, age and lithologic differences of the marine Patagoniense deposits in the Austral Basin suggest they must be the result of single transgressive events. Are they the response of single eustatic events? Or are they the result of a broad eustatic sea level rise locally controlled by differential subsidence or rate of sedimentary supply for each of locality? Can the stratigraphic units in San Jorge and Austral Basins be correlated? Considering the huge areal extent of the Patagoniense transgression (Fig. 1A), especially the Leonense and Superpatagoniense stages, and the possible correlation of this high sea level across many basins of South America (Rossetti, 2001; Marengo, 2006), it seems reasonable to suggest a primary eustatic control of these marine invasions over the continental shelf. Additionally, McGowran et al. (2004) reported high eustatic long term sea levels during the early Miocene in South Eastern Australia with remarkably similar stratigraphy than that of Patagonia (Malumián, 2002). The revised eustatic sea level curves for the lower Miocene (Van Sickel et al., 2004; Kominz et al., 2008) show two episodes of sea level fall, one at around 24 Ma and the second at 22 Ma, both followed by rapid eustatic sea level rises. These episodes could be considered to be the cause of the sequence boundary observed between Leonense and Superpatagoniense beds in the San Jorge Basin (Legarreta and Uliana, 1994). In the Austral Basin, this boundary is not well defined and the ages obtained for the possible Superpatagoniense beds are younger than predicted by the sea level curve. This, plus the fact that Superpatagoniense deposits are located in the Andean foothills in a "foreland location", suggest that overprint of a tectonic control on the long term eustatic sea level variations is feasible. In addition, Andean uplift during early Miocene times is closely related to the progradation of the fluvial deposits of the Santa Cruz Formation over the Patagoniense (s.l.) marine deposits, especially in the west border of the Austral Basin. In the study area and in all the western part of the Santa Cruz province both units appear forming a conformable thick prograding pile of strata of about 600–800 m. The Andean belt reached enough altitude to form a topographic barrier to atmospheric circulation at about 16 Ma (Blisniuk et al., 2005) and a 20–16 Ma arc migration to the east is recorded in plutonic intrusions of the same area (Hervé et al., 2007; Ramírez de Arellano et al., 2011). In the Aysen region of Chile, Flynn et al. (2002) recognize this prograding pile of strata and estimate a contemporaneous Andean uplift as the consequence of a tectonic event related to the Chile Margin Triple Junction. The Superpatagoniense transgression occurred at the beginning (20–19 Ma) of these tectonic episodes, and it could be interpreted as a consequence of a fast subsidence triggered by tectonic loading, which creates an associated lowland area that served the transgression to reach the foothills of the Andes. Moreover, paleoenvironmental reconstructions in Lago Argentino region point to a northeastward shallowing of the sea, from nearshore deposits to the northeast grading to muddy marine offshore sediments to the southwest, part of which has been removed by subsequent erosion during uplift (Cuitiño, 2011). Fast infilling of the accommodation space created by tectonics resulted in the subsequence progradation of fluvial deposits of the Santa Cruz Formation over the Patagoniense (s.l.) beds. These are common features in foreland basins (Flemings and Jordan, 1990; Cant and Sotckmal, 1993).

New isotopic ages, detailed sedimentologic and sequence stratigraphic analysis are needed in order to account for paleogeographic reconstructions and eustatic vs. subsidence controls over Patagoniense stages in other areas of Patagonia.

8. Conclusions

U–Pb analysis carried out in two pyroclastic levels at the base and top of the conformable succession formed by the marine Estancia 25 de Mayo Formation and the lower part of the overlying fluvial Santa Cruz Formation indicate ages of 19.14 ± 0.5 and 18.85 ± 0.3 Ma respectively. $^{87}Sr/^{86}Sr$ ages measured in pristine carbonate layers of oysters from the same stratigraphic column agree well with those obtained through U–Pb dating, giving for the first time reliable ages for the marine beds that represent the Patagoniense transgression in the Lago Argentino region. Age data integration indicates a maximum of 1 Ma interval of deposition for the Estancia 25 de Mayo Formation, from 20 to 19 Ma, pointing to high sedimentation rates for the unit. The basal section of the Santa Cruz Formation in this area is situated at 18.8 Ma and marks the beginning of terrestrial sedimentation in the area.

These new ages have an important stratigraphic significance because place the Patagoniense beds of Lago Argentino entirely in the Burdigalian stage, younger than previous age determinations. According to the stratigraphic subdivisions made in other areas of Patagonia, the marine beds analyzed here would correspond to the Superpatagoniense transgression and not to the Leonense transgression as it was formerly suggested on the basis of the faunal affinities.

The age and geographic distribution of the Patagoniense deposits of Lago Argentino suggest sedimentation in a shallow sea developed in a foreland basin related to Andean thrusting during early Miocene times. Local tectonic subsidence probably overprinted eustatic sea level fluctuations and were the main control for sedimentation.

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