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Correlation of marine beds based on Sr- and Ar-date determinations and faunal affinities across the Paleogene/Neogene boundary in southern Patagonia, Argentina

Ana Parras^{a,b,*}, Miguel Griffin^{a,b}, Rodney Feldmann^c, Silvio Casadío^{a,b}, Carrie Schweitzer^d, Sergio Marensi^{b,e}

^a Facultad de Ciencias Exactas y Naturales, Universidad Nacional de La Pampa, Uruguay 151, 6300 Santa Rosa, La Pampa, Argentina

^b CONICET Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina

^c Department of Geology, Kent State University, Kent, OH 44242, USA

^d Department of Geology, Kent State University, Stark Campus, Canton, OH 44720, USA

^e Instituto Antártico Argentino, Cerrito 1248, Buenos Aires (1010), Argentina

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ABSTRACT

The San Julián and Monte León formations ("Patagonian") are exposed along the Atlantic coast of Patagonia, whereas in the west equivalent rocks are known as Centinela Formation. Sixteen ⁸⁷Sr/⁸⁶Sr measurements on the oyster *Crassostrea? hatcheri* (Ortmann) from the San Julián and Centinela formations and an ⁴⁰Ar/³⁹Ar-date from a whole-rock sample from the Centinela Formation yielded ages that allow more precise correlation between the two areas. ⁸⁷Sr/⁸⁶Sr measurements from the San Julián Formation yielded ages between 23.83 and 25.93 Ma, while for the Centinela Formation the ages ranged between 21.24 and 26.38 Ma. The ⁴⁰Ar/³⁹Ar analysis of a sample of the Centinela Formation yielded an age of 20.48 ± 0.27 Ma. The age data suggest a late Oligocene (Chattian) age for the San Julián Formation and the lowermost beds of the Centinela Formation (northernmost exposures). The Monte León Formation along the East coast and the entire section of the Centinela Formation in the southern area – and the middle and upper beds of this same unit in the northernmost localities – were deposited at the end of the Oligocene and early Miocene (Chattian–Burdigalian). The invertebrate fauna present in these units shows diverse preservation patterns that makes these fossils, especially the mollusks, not useful – at this stage – for correlation purposes.

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1. Introduction

During the Late Cretaceous–Neogene interval Patagonia experienced alternating periods of sedimentation associated with transgressions of the Atlantic Ocean and periods of non-marine sedimentation and erosion (Malumián, 1999). Two of these Atlantic transgressions resulted in the deposition of marine sediments grouped under the informal name of "Patagoniano" (Patagonian).

Sediments deposited in the "Patagonian" sea extend from the present-day Atlantic coast to the foothills of the Andes. Unfortunately, exposures of these rocks are separated by broad expanses of grassland. This makes it difficult to establish correlations among the various outcrops. Therefore, correlation and age of the widely separated exposures have been controversial and poorly con-

strained ever since d'Orbigny (1842) and Darwin (1846) first assigned them to the Tertiary. Modern estimated ages range from middle Eocene to early Miocene (Bertels, 1970, 1975, 1977; Furque and Camacho, 1972; Furque, 1973; Camacho, 1974, 1979; Riccardi and Rolleri, 1980; Zinsmeister, 1981; Ramos, 1982; Náñez, 1988; Parma, 1989; Griffin, 1990; Barreda, 1997; Casadío et al., 2000a,b, 2001; Parras and Casadío, 2002). Such discrepant ages have made it difficult to elucidate the Cenozoic geologic history of Patagonia and thus to establish a temporal framework for paleo-environmental and paleogeographic reconstructions.

Recent progress in the correct age determination of these marine deposits has been based on data drawn from micropaleontological and isotopic studies (Náñez, 1988; Barreda, 1997; Casadío et al., 2000b, 2001; Parras and Casadío, 2002; Guerstein et al., 2004). The age of associated terrestrial beds has been based mainly on radiometric and magnetostratigraphic data (Marshall et al., 1986; Fleagle et al., 1995). While radiometric ages proved useful in dating terrestrial facies, these rocks have eluded correlation with the Paleogene–Neogene marine beds (Legarreta and Uliana, 1994).

* Corresponding author. Address: Facultad de Ciencias Exactas y Naturales, Universidad Nacional de La Pampa, Uruguay 151, 6300 Santa Rosa, La Pampa, Argentina. Tel.: +54 2954 453943; fax: +54 2954 432535.

E-mail address: aparras@exactas.unlpam.edu.ar (A. Parras).

Disagreement over the stratigraphic relationships between the terrestrial and marine beds still remains one of the most controversial aspects of Patagonian geology.

The dating of the marine beds are problematic and one way to address this is through the use of Sr and Ar isotope ratios. At other localities, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in rock and fossil samples have been used successfully to date and correlate marine sediments, estimate the duration of stratigraphic gaps, underpin speculations about major geochemical cycles, estimate the duration of biozones and stages, and distinguish between marine and non-marine environments (McArthur et al., 2001). Burke et al. (1982) demonstrated that Sr-isotope stratigraphy provides a precise means of correlating and dating marine carbonates for certain periods within the past 100 Ma, and they compiled the Phanerozoic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios then available. From that moment onwards, $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic variations in marine carbonates have received growing attention as a valuable chronostratigraphic tool (DePaolo and Ingram, 1985; Elderfield, 1986; Howarth and McArthur, 1997; Veizer et al., 1997, 1999; McArthur et al., 2001). Most of the advances have been particularly valuable for the Cenozoic, due to the more precise and definitive geochronology and biostratigraphy for all Cenozoic time intervals except for the early Eocene. The results obtained from low-Mg calcite shells, such as foraminifers, belemnites, brachiopods and oysters, are typically more reliable than those from phosphatic skeletal components (Veizer et al., 1997).

Here, we show that measurements of $^{87}\text{Sr}/^{86}\text{Sr}$ in the oyster *Crassostrea? hatcheri* (Ortmann) from the “Patagonian” rocks assigned to the San Julián and Centinela formations, and a $^{40}\text{Ar}/^{39}\text{Ar}$ -dating from a whole-rock sample from the Centinela Formation, yield ages for sections exposed in the eastern and western parts of Patagonia, enabling correlation between the two areas. In order to establish the faunal relationships and adjust correlations, we compared the invertebrate content of the two formations at different locations with each other and with those present in other Paleogene and Neogene units exposed in Patagonia. Such a correlation allows more precise adjustment of the relative sea-level changes and paleoenvironmental conditions during the Paleogene–Neogene interval in southern Patagonia.

2. Geological setting and previous age determinations

Along the eastern seaboard of southern Patagonia (Fig. 1), in the areas known as Gran Bajo de San Julián and Cabo Curioso, the well-exposed lower part of the “Patagonian” beds is referred to as the San Julián Formation (Bertels, 1970). This is a shallow marine unit that includes both siliciclastic and calcareous sediments and represents upward-shoaling cycles developed in a sand-dominated shelf sequence (Manassero et al., 1997). Bertels (1977) divided this unit into two members, the lower Gran Bajo Member and the upper Meseta Chica Member. The former is characterized by yellowish to dark-red mudstones, siltstones, and sandstones and the second by green-yellowish and brown-greenish sandstones and coquinas. The San Julián Formation unconformably overlies the Jurassic volcanic and sedimentary rocks of the Bahía Laura Group, and is overlain by the marine Monte León Formation (late Oligocene–early Miocene).

In the stratigraphic sections considered in this study (Gran Bajo, Nido de Águila, La Colmena and Cabo Curioso, Fig. 2), the San Julián Formation consists of up to 34 m of yellowish-brown sandstone and mudstone (Gran Bajo Member), and up to 28.5 m of yellowish-brown and green sandstone and limestone (Meseta Chica Member). The massive, laminated and trough-cross bedded, bioturbated sandstones and heterolithic carbonaceous mudstones with wood and leaf fragments and coal beds of the lower part of the San Julián Formation are associated with a sea-level rise and

infilling of an incised topography. They are interpreted as the beginning of a transgressive system tract (Parras and Casadío, 2002, 2005), and were deposited in a marshy environment under warm and humid climatic conditions (Barreda, 1997). The overlying part of the San Julián Formation is characterized by a flooding surface, corresponding to a ravinement surface, formed by shoreface erosion within the transgressive system tract. This surface was interpreted by Parras and Casadío (2002, 2005) as a sedimentological concentration deposited in an upper shoreface environment. Overlying the flooding surface, marine transgression and facies retrogradation resulting from continued sea-level rise are represented by another sedimentological concentration deposited in intermediate energy conditions in a lower shoreface environment (Parras and Casadío, 2002). The maximum flooding surface separating the transgressive system tract from the highstand system tract reflects maximum water depths and associated sediment starvation on the shelf and is represented by a biogenic concentration of articulated adult and juvenile *Crassostrea? hatcheri* (Ortmann) in life position, forming bunches. Parras and Casadío (2002, 2005) interpreted this level as deposited in a lower shoreface to offshore environment, with a low sedimentation rate. Finally, the highstand system tract is represented by several sedimentological concentrations interpreted as storm events, which are common in this part of the sequence. This part of the section was interpreted as deposited in a shallow shelf storm-wave dominated depositional environment (Manassero et al., 1997; Parras and Casadío, 2002, 2005).

Different opinions exist regarding the age of the San Julián Formation (Fig. 3). Based on the invertebrate fauna it contains, Camacho (1974) and Zinsmeister (1981) proposed a middle-late Eocene age for the San Julián Formation. According to Camacho (1979, 1985) an Eocene age is supported by the presence of the bivalves *Parinomya patagonensis* (Ihering) and *Neoinoceramus ameghinoi* Ihering. A late Eocene–early Oligocene age is suggested by the foraminiferans (according to Bertels, 1975, 1977 and Nández, 1988) and echinoderms (Parma, 1989). A late Oligocene (Chattian) age was suggested by Bertels (1970), also based on foraminifera, and by Casadío et al. (2001) and Parras and Casadío (2002), based on $^{87}\text{Sr}/^{86}\text{Sr}$ datings drawn from shells of the oyster *Crassostrea? hatcheri* (Ortmann). An Oligocene age was proposed by Barreda (1997), who studied the spore–pollen assemblages. Such an age was based on the ranges of known species and the similarity with associations from other areas, stating that the samples examined by her could be as young as late Oligocene.

Overlying the San Julián Formation are yellowish-gray, fine-tuffaceous sandstones and tuffaceous siltstones, tuffs, and coquinas of the upper part of the “Patagonian”. These are included in the Monte León Formation (Bertels, 1970), which is exposed along a large portion of the eastern seaboard. This unit records the highest relative sea-level and the influx of Antarctic waters onto the Argentine Continental Shelf (Malumián, 2002). Although some discrepancies still persist about the age of this unit, most authors consider it to be late Oligocene (Bertels, 1970) or late Oligocene–early Miocene (Malumián, 1999) (Fig. 3). Based on foraminifera, Nández (1988) restricted its age to the Oligocene (middle section of Zone P19 and top of Zone P21), although she indicated that the top beds could extend into the early Miocene. A radiometric $^{40}\text{Ar}/^{39}\text{Ar}$ age of the Monte León Formation at the Monte León locality indicated 19.33 Ma (Burdigalian, early Miocene) for the top of this unit (Fleagle et al., 1995).

Although not exposed in central Patagonia, the “Patagonian” beds have been recorded there in subsurface samples (Malumián, 2002). They outcrop again in the west along the foothills of the Andes (Fig. 1), between Lago Posadas and Río Turbio. In this area, the “Patagonian” is known under the formal name of Centinela Formation (Furque and Camacho, 1972). Furque and Camacho (1972)

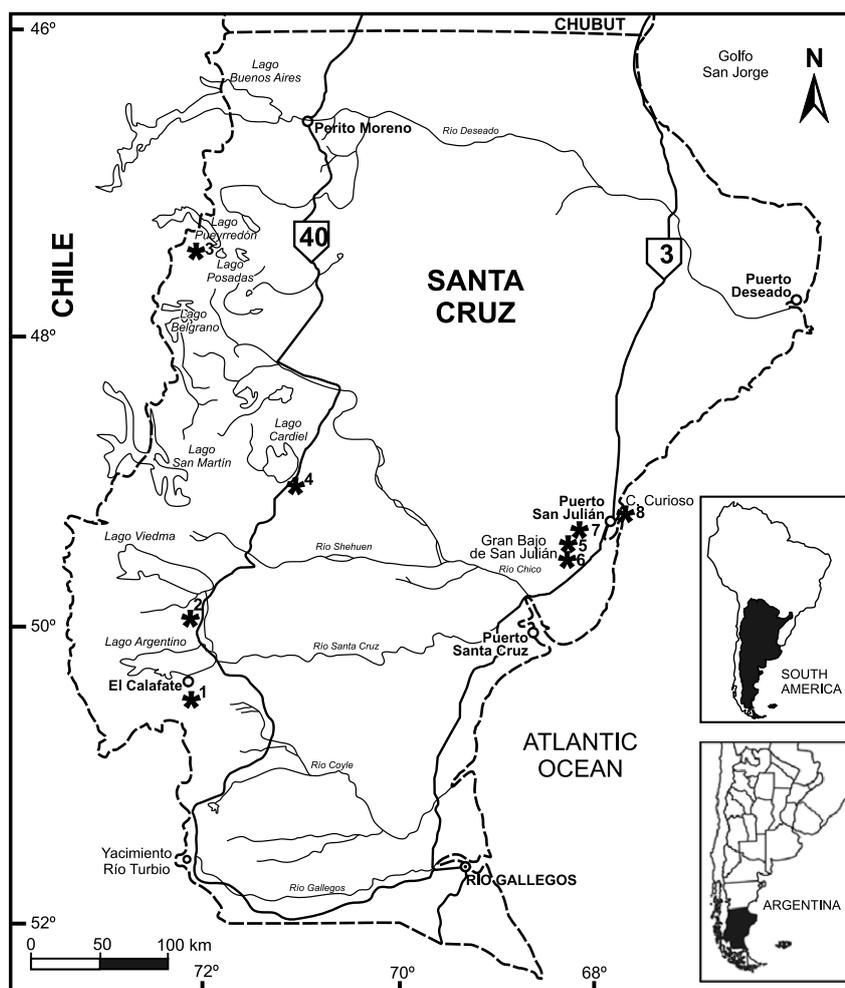


Fig. 1. Map showing the location of the studied sections and sites. (1) Estancia 25 de Mayo, (2) Cerro Pirámides, (3) Veranada de Cárcamo, (4) Estancia La Siberia, (5) Gran Bajo, (6) Nido de Águila, (7) La Colmena, (8) Cabo Curioso. Localities: 1–4, Centinela Formation; 5–8, San Julián Formation.

proposed this name for the marine beds exposed in the Lago Argentino area and intercalated between the terrestrial Río Leona Formation below and the overlying terrestrial Santa Cruz Formation. Later, Riccardi and Rolleri (1980) extended this use also to the marine deposits exposed in the Patagonian Cordillera in north-western Santa Cruz, and intercalated between the Paleocene–Eocene Posadas Basalt and the terrestrial middle Miocene Santa Cruz Formation. In this study, we follow the stratigraphic nomenclature proposed by the latter authors.

The preserved Oligocene–early Miocene section in the Lago Argentino area at Estancia 25 de Mayo (Fig. 2), south of El Calafate city, comprises a vertical arrangement of facies passing upwards from high-energy fluvial to low-energy fluvial-coastal plain environments included in the Río Leona Formation (Marenssi et al., 2005). These are covered by marine deposits of the Centinela Formation. The lower Centinela Formation is composed of fine sandstones, siltstones and claystones with calcareous concretions containing mollusks, echinoderms, and a diverse fauna of crustaceans, including nine families of Decapoda and one of Isopoda (Casadío et al., 2000a). This part of the section is interpreted to be a biogenic concentration, characterized by articulated *Crassostrea? hatcheri* (Ortmann) forming bunches in life position. A layer of white, massive tuff overlies these rocks, followed by siltstones, tuffs, and fine-grained sandstones with decapods and the bivalve *Panopea* sp. in life position. These sediments were deposited in predominantly subtidal environments (Casadío et al., 2000a). The

upper part of the Centinela Formation comprises fine- to medium-grained sandstones with intercalated siltstones showing sigmoid and planar bi-directional cross stratification and also biogenic concentrations of oysters, characterized by articulated specimens forming bunches in life position, and a few convex-up and convex-down disarticulated valves. Assemblages from the lower part of the section suggest that the beds were deposited under marine, nearshore paleoenvironmental conditions with a strong continental influence; in the middle part, the dinoflagellate cyst ratios mark the highest relative sea-level rise, and toward the top the sporomorph assemblage reflects the development of vegetation adapted to coastal environments (Guerstein et al., 2004).

In the Lago Viedma area, at the locality known as Cerro Pirámides (Fig. 2), the Centinela Formation is at the top of the section and consists of only 3 m of fine sandstone and muddy sandstone, massive or with trough-cross stratification, and undulose and flaser lamination (Marenssi et al., 2003). At this locality, the formation contains specimens of *Crassostrea? hatcheri* (Ortmann) and wood fragments. It was deposited in a shallow marine environment and probably represents sandy and mixed subtidal flats (Marenssi et al., 2003).

Southeast of Lago Cardiel, at Estancia La Siberia (Fig. 2), the exposures of the “Patagonian” comprise 100 m of medium sandstones with trough-cross, planar cross, and hummocky cross stratification, with lenses and beds of medium massive sandstones that constitute biogenic concentrations dominated by *Crassostrea?*

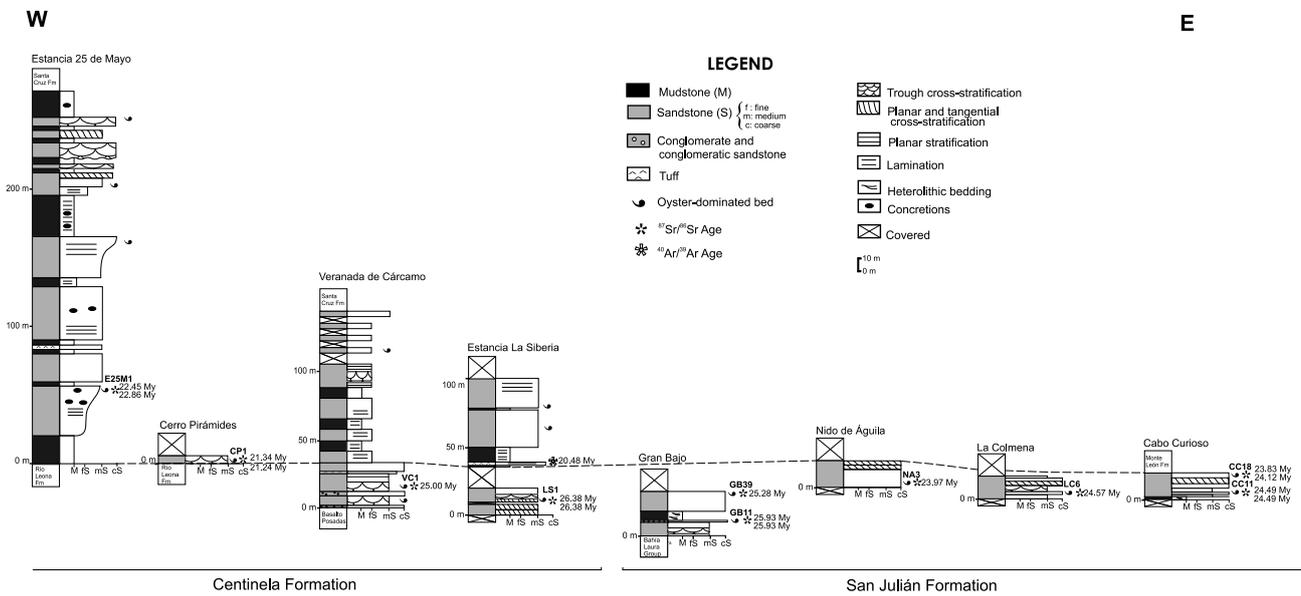


Fig. 2. Studied stratigraphic sections of the San Julián and Centinela formations, showing provenance of the samples and $^{87}\text{Sr}/^{86}\text{Sr}$ ages (Ma). Dashed line shows boundary between rocks deposited during the late Oligocene and the latest Oligocene–early Miocene.

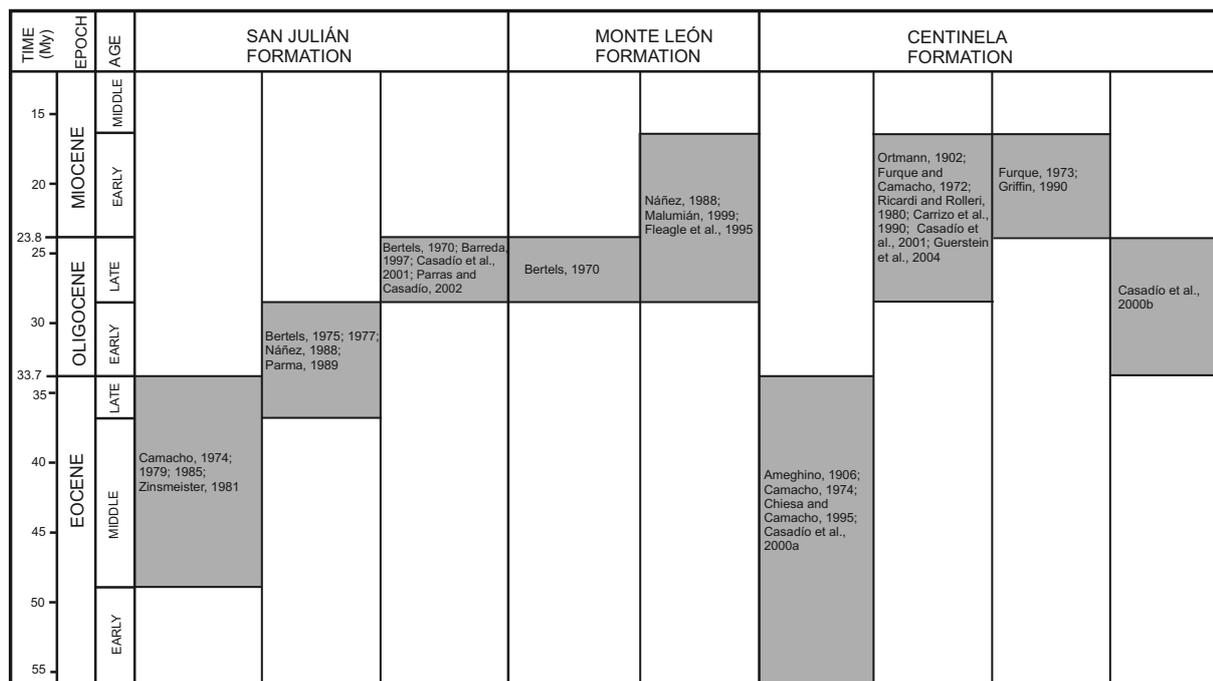


Fig. 3. Diagram showing the different ages of the stratigraphic units considered, according to various authors.

hatcheri (Ortmann) in life position. Intercalated are a few beds of massive and laminated mudstones, tuffs, and chonites. We interpret the section as deposited in a shallow shelf, storm-dominated depositional environment, with facies of bars and channels and frequent storm events. These were deposited under intertidal to subtidal conditions. Ostracods studied by Echeverría (1998) in this area suggest a shelf environment with moderately high-energy conditions, shallow depths (0–20 m), sandy substrate, and warm waters with normal salinity.

In the Lago Posadas area, at Veranada de Cárcamo (Fig. 2), the Centinela Formation is characterized by 145 m of sandstones and mudstones overlying the volcanic rocks of the Basalto Posadas (Paleocene–Eocene). At the base of the section there are conglomerates and conglomeratic sandstones, massive or with trough-cross or planar cross stratification, with marine invertebrates and intraclasts of the underlying volcanic rocks. Biogenic concentrations formed mostly by *Crassostrea? hatcheri* (Ortmann) and a bed of tuff with specimens of *Pinna* sp. in life position are intercalated. Fine-grained sandstone and mudstone characterize the middle part of the section with concretions containing very well preserved marine invertebrates. The upper part is characterized by medium to coarse-grained sandstone with biogenic and sedimentological concentrations formed mostly by *C.? hatcheri* and *C. orbigny* (Ihering). Towards the top, there are frequent plant fragments. We interpret these rocks as deposited in a nearshore, shallow marine environment.

There are different opinions regarding the age of the Centinela Formation too (Fig. 3). Based on the invertebrates collected by Hatcher south of Santa Cruz, Ortmann (1902) concluded that the marine fossiliferous rocks had been deposited during the late Oligocene–early Miocene. Ameghino (1906) supported an Eocene age based on the studies undertaken by Ihering (1897) on the molluscan fauna. An Eocene age was also proposed by Camacho (1974) due to the presence of the bivalve *Venericor*. A similar age was inferred by Chiesa and Camacho (1995) based on molluscan assemblages, and by Casadio et al. (2000a) by means of a $^{40}\text{Ar}/^{39}\text{Ar}$ determination of about 46 Ma in a tuff layer at the lower part of the unit at Estancia 25 de Mayo. Furque and Camacho (1972), Ric-

cardi and Rolleri (1980), and Carrizo et al. (1990) suggested a late Oligocene–early Miocene age for this unit based on its molluscan and foraminiferan assemblages, whereas Furque (1973) and Griffin (1990) placed it in the Miocene. Palynological data (Guerstein et al., 2004) and a $^{87}\text{Sr}/^{86}\text{Sr}$ age of 23.19 Ma on a valve of *Crassostrea? hatcheri* (Ortmann) collected at Estancia 25 de Mayo (Casadio et al., 2000b) yielded a late Oligocene–early Miocene age.

3. Materials and methods

3.1. Samples

We measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of biogenic carbonate from 16 samples of *Crassostrea? hatcheri* (Ortmann), which is one of the more characteristic fossils of the Cenozoic marine deposits in Patagonia (Table 1). We also measured $^{40}\text{Ar}/^{39}\text{Ar}$ ratios in a whole-rock sample from the Centinela Formation at the La Siberia locality.

Each of the localities from which oysters were collected was also carefully examined for the presence of decapod crustaceans, fossil crabs and lobsters. Extensive work on this group of organisms throughout Patagonia has made it possible to develop models of paleobiogeographic patterns that can serve as a test for models based upon studies of mollusks (Feldmann and Schweitzer, 2006). In the present study, it was anticipated that the decapods could provide independent, useful information regarding distributional patterns and temporal relationships. The specimens collected were studied in the laboratories at Kent State University, several papers describing the identification and classification of the material have either been published (Feldmann et al., 1995, 1997; Schweitzer and Feldmann, 2000; Casadio et al., 2004, and others) or are in progress. This work, coupled with the extensive published record of Aguirre-Urreta (1987, 1990, 1992) is summarized in Table 2.

Likewise, the mollusk content of the localities where the oysters were collected was recorded in order to identify as closely as possible the mollusk fauna associated with the dated oysters. The geographic and stratigraphic distributions of the bivalves and gastropods reflect the different temporal and paleobiogeographic settings in which the rocks involved were deposited and agree well

Table 1
 $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and calculated age

Locality	Sample	Formation	Sr (ppm) ^a	$^{87}\text{Sr}/^{86}\text{Sr}^b$	N	$^{87}\text{Sr}/^{86}\text{Sr}^c$	$^{87}\text{Sr}/^{86}\text{Sr}^d$	Limiting ages (Ma) ^e	Age (Ma) ^f
Cabo Curioso	CC11 (*)	San Julián	487.1	0.708215 (9) 0.708224 (8)	17	0.708220	0.708226 (0.708206–0.708246)	24.05–24.92	24.49
Cabo Curioso	CC11 (*)	San Julián	531.0	0.708243 (8) 0.708216 (8) 0.708200 (7)	23	0.708220	0.708226 (0.708206–0.708246)	24.05–24.92	24.49
Cabo Curioso	CC18	San Julián	624.0	0.708240 (9) 0.708247 (6)	15	0.708244	0.708250 (0.70823–0.70827)	23.63–24.56	24.12
Cabo Curioso	CC18 (*)	San Julián	619.0	0.708266 (13) 0.708261 (7) 0.708257 (8)	28	0.708261	0.708267 (0.708287–0.708247)	23.30–24.30	23.83
La Colmena	LC6	San Julián	288.0	0.708214 (10) 0.708216 (9)	19	0.708215	0.708221 (0.708241–0.708201)	24.13–25.00	24.57
Nido de Águila	NA3	San Julián	582.0	0.708258 (8) 0.708248 (8)	16	0.708253	0.708259 (0.708279–0.708239)	23.46–24.42	23.97
Gran Bajo	GB11	San Julián	678.0	0.708132 (6) 0.708147 (6)	12	0.708137	0.708143 (0.708163–0.708123)	25.35–26.60	25.93
Gran Bajo	GB11 (*)	San Julián	680.0	0.708137 (7)	7	0.708137	0.708143 (0.708163–0.708123)	25.35–26.60	25.93
Gran Bajo	GB39	San Julián	324.0	0.708169 (7) 0.708171 (11)	18	0.708170	0.708176 (0.708196–0.708156)	24.81–25.86	25.28
La Siberia	LS1	Centinela	411.0	0.708117 (9)	9	0.708116	0.708122 (0.708142–0.708102)	25.76–27.18	26.38
La Siberia	LS1 (*)	Centinela	402.0	0.708116 (10)	10	0.708116	0.708122 (0.708142–0.708102)	25.76–27.18	26.38
Veranada de Cárcamo	VC1 (*)	Centinela	518.3	0.708187 (7) 0.708179 (7) 0.708193 (11)	25	0.708186	0.708192 (0.708212–0.708172)	24.58–25.53	25.00
Cerro Pirámides	CP1 (*)	Centinela	636.9	0.708378 (8) 0.708362 (7)	15	0.708370	0.708376 (0.708396–0.708356)	20.83–22.00	21.34
Cerro Pirámides	CP1 (*)	Centinela	665.8	0.708371 (7) 0.708379 (7)	14	0.708375	0.708381 (0.708401–0.708361)	20.75–21.88	21.24
Estancia 25 de Mayo	E25M1 (*)	Centinela	453.9	0.708316 (7) 0.708328 (8) 0.708324 (8)	23	0.708323	0.708329 (0.708349–0.708309)	21.72–23.16	22.45
Estancia 25 de Mayo	E25M1 (*)	Centinela	396.2	0.708309 (9) 0.708318 (10) 0.708298 (6)	25	0.708308	0.708314 (0.708334–0.708294)	22.05–23.48	22.86

Each entry with a sample number represents a separate dissolution. When two fragments from the same sample were analyzed, the one indicated by the asterisk (*) was dissolved using acetic acid while the other one was dissolved in dilute HCL.

^a Minimum concentrations of Sr for the sample used for analysis.

^b Measured values of $^{87}\text{Sr}/^{86}\text{Sr}$ normalized assuming normal Sr with $^{86}\text{Sr}/^{88}\text{Sr} = 0.119400$ and using a reference value of the SRM987 = 0.710242.

^c Average $^{87}\text{Sr}/^{86}\text{Sr}$ from measured values and recommended value for that dissolution considering replication of $^{87}\text{Sr}/^{86}\text{Sr}$ determinations.

^d Reference value $^{87}\text{Sr}/^{86}\text{Sr}$ corrected to make the data concordant with SRM987 = 0.710248 used in the construction of used Look-Up Table (number in parentheses is 2σ of the mean).

^e Calculated limiting ages using the SIS Look-Up Table Version 3:10/99 of McArthur et al. (2001), at 95% confidence limits.

^f Preferred numerical age.

with the patterns shown by the decapod fauna. Table 3 summarizes the distribution of mollusks in the two stratigraphic units considered in this work (i.e., San Julián and Centinela formations) and in the other equivalent units exposed in the area (i.e., Monte León and Guadal formations). Uneven preservation of the material and inaccurate identifications cloud the true affinities among the marine faunas contained in these formations. Therefore, we have only included in the table those taxa that could be positively identified and that occur in at least two of the lithostratigraphic units. Data on Table 3 was compiled from a number of sources (Sowerby, 1846; Philippi, 1887; Ihering, 1897, 1907, 1914; Ortmann, 1897, 1902; Feruglio, 1937, 1954; Zinsmeister, 1981; Camacho, 1985; Camacho and Zinsmeister, 1989; Erdmann and Morra, 1985; Morra, 1985; Olivera et al., 1994; Chiesa et al., 1995; del Río, 1995, 2004a,b; del Río and Camacho, 1996, 1998; Frassinetti and Covacevich, 1999) and from our own field observations.

3.2. Sample preparation and analytical techniques

Oyster samples were collected from sections of the San Julián Formation measured at Cabo Curioso (49°12'S; 67°39'W), Gran Bajo (49°31'S; 68°14'W), La Colmena (49°27'S; 68°5'W), and Nido de Águila (49°36'S; 68°14'W) along the Atlantic coast, and from sections of the Centinela Formation exposed at Estancia 25 de Mayo (50°30'S; 72°15'W), Estancia La Siberia (49°00'S; 71°05'W), Veranada de Cárcamo (47°29'S; 71°13'W), and Cerro Pirámides (49°52'S; 72°13'W) along the foothills of the Andes (Figs. 1 and 2). Almost all of the samples were from biogenic or biogenic-sedimentological concentrations with oysters in life position (Fig. 4).

For each sample, a small piece of the hinge area of a shell was broken off and manually crushed. One of the resulting fragments was selected and part of it was used for thin-section petrographic analysis under a petrographic microscope in order to determine

Table 2
Stratigraphic array of decapod crustacean taxa known from the Cenozoic of Argentina

TAXON	Maast/Danian	Oligocene	Oligocene/Miocene	Miocene	Late Miocene
Nephropidae					
<i>Hoploparia</i> cf. <i>H. arbei</i> Aguirre-Urreta, 1989	R				
Parastacidae Huxley, 1879					
<i>Lammuastracus longirostris</i> Aguirre-Urreta, 1992		FW			
Callianassidae Dana, 1852					
<i>Callianassa burkhardi</i> Böhm, 1911	R				
<i>Callianassa</i> sp. Aguirre-Urreta, 1990			P		
<i>Protocallianassa</i> sp.	R				
<i>Callianopsis australis</i> Casadío et al., 2004		F			
Ctenochelidae Manning and Felder, 1991					
<i>Ctenocheles</i> sp.	R			N	
Galatheididae					
<i>Munida casadioi</i> (Schweitzer and Feldmann, 2000)		F	C		
Paguroidea Latreille, 1802					
Paguroidea, family and species undetermined		J			
Family Raninidae de Haan, 1833					
<i>Raninoides</i> sp.			C		
Majidae Samouelle, 1819					
<i>Eoinachoides</i> cf. <i>E. senni</i> Van Straelen, 1933			G		
<i>Leurocyclus primigenius</i> Aguirre-Urreta, 1990			P		
<i>Notomithrax</i> sp.		J	C		
<i>Rochinia</i> sp.			C		V
Calappidae Milne Edwards, 1837					
? <i>Calappilia</i> n.sp.				N	
Hepatidae Stimpson, 1871					
<i>Hepatus</i> n. sp.				N	
Aethridae Dana, 1851					
<i>Osachila</i> n. sp.					V
Retroplumidae Gill, 1894					
<i>Costacopluma australis</i> Feldmann et al., 1995	R				
<i>Costacopluma salamanca</i> Feldmann et al., 1997	S				
Atelecyclidae Ortmann, 1893					
<i>Trichopeltarion levis</i> Casadío et al., 2004		F		N	
Cancridae Latreille, 1802					
<i>Metacarcinus</i> sp.			C		
<i>Notocarcinus sulcatus</i> Schweitzer and Feldmann, 2000			C		
<i>Romaleon</i> n. sp.					V
Geryonidae Colosi, 1923					
<i>Chaceon peruvianus</i> (d'Orbigny, 1842)			C		V
<i>Chaceon fuegianum</i> (Colosi, 1823)			T		
Portunidae Rafinesque, 1815					
<i>Proterocarcinus lophos</i> Feldmann et al., 1995	R				
<i>Proterocarcinus latus</i> (Glaessner, 1933)		J	C, G		V
<i>Proterocarcinus corsolini</i> Casadío et al., 2004		F			
<i>Proterocarcinus</i> n. sp.				N	
Portunidae, genus and species undetermined		J			
Palaeoxanthopsidae Schweitzer, 2003					
<i>Lobulata lobulata</i> (Feldmann et al., 1995)	R				
<i>Rocacarcinus gerthi</i> (Glaessner, 1930)	R				
Hexapodidae Miers, 1886					
<i>Palaeopinnixa rocaensis</i> (Feldmann et al., 1995)	R				
Panopeidae Ortmann, 1893					
<i>Chirinocarcinus wichmanni</i> (Feldmann et al., 1995)	R				
<i>Panopeus</i> n. sp.					V
Pilumnidae Samouelle, 1819					
<i>Baricarcinus mariae</i> Casadío et al., 2004		F			
<i>Pilumnus</i> n. sp.				N	
Rhizopinae, genus and species undetermined				N	
Pseudorhombilidae Alcock, 1900					
<i>Pseudorhombilia patagonica</i> Glaessner, 1933				?	
Xanthidae MacLeay, 1838, sensu stricto					
<i>Atergatis</i> sp.			C		
Pinnotheridae de Haan, 1833					
<i>Asthenognathus microspinus</i> Casadío et al., 2004		F			
<i>Asthenognathus urretae</i> Schweitzer and Feldmann, 2001			C		
<i>Pinnixa</i> n. sp.				N	
Ocypodidae Rafinesque, 1815					
<i>Ocypode</i> n. sp.					V

Footnotes: C, Centinela Formation; F, Río Foyel Formation; G, Gran Bajo del Gualicho Formation; N, Navidad Formation (Chile); P, Patagoniano undifferentiated; R, Roca Formation; T, Tierra del Fuego unit undifferentiated; V, Puerto Madryn Formation, Península Valdés; J, San Julián Formation, Gran Bajo de San Julián; S, Salamanca Formation; FW, Fresh water.

the state of textural preservation; small chips of about 100 mg were taken from the remaining part of it for isotopic analysis. Petrographic analysis showed that shell structure is well preserved

and retains the original calcitic composition and foliated microstructure. Evidence of postdepositional diagenesis could not be detected. The chips were washed in water, alcohol, and acetone prior

Table 3

Stratigraphic array of mollusk taxa in the San Julián, Monte León, and Centinela formations and in the Guadal Formation in southern Chile which is at least partly equivalent to the Centinela Formation

TAXON		Centinela Fm. (North)	Centinela Fm. (South)	San Julián Fm. (at Bahía San Julián)	Monte León Fm. (at M.León)	Guadal Fm. (southern Chile)
Bivalvia	<i>Neilo</i> sp.	*	*		*	
	<i>Glycymeris cuevensis</i> (Ihering, 1897)	*	*		*	
	<i>Cucullaea alta</i> Sowerby, 1846	*	*		*	*
	<i>Lithophaga patagonica</i> d'Orbigny, 1846		*		*	
	<i>Modiolus arctus</i> Feruglio, 1937		*		*	
	<i>Atrina magellanica</i> (Ihering, 1899)	*	*		*	*
	<i>Neopanias quadrisulcatum</i> (Ihering, 1897)	*	*		*	*
	<i>Reticulochlamys proxima</i> (Sowerby, 1846)	*	*		*	*
	<i>Zygochlamys geminata</i> (Sowerby, 1846)	*	*		*	*
	<i>Zygochlamys jorgensis</i> (Ihering, 1907)	*	*		*	*
	<i>Zygochlamys sebastiani</i> Morra, 1985	*	*		*	*
	<i>Crassostrea orbigny</i> (Ihering, 1897)	*	*	*	*	*
	<i>Crassostrea? hatcheri</i> (Ortmann, 1897)	*	*	*	*	*
	<i>Pteromyrtea crucialis</i> (Ihering, 1907)	*	*	*	*	*
	<i>Macoma santacruzensis</i> (Ihering, 1899)	*	*		*	
	<i>Patagonocardium? guadalense</i> Frassinetti and Covacevich, 1999	*				*
	<i>Patagonocardium iheringi</i> Frassinetti and Covacevich, 1999	*	*			*
	<i>Patagonocardium philippii</i> (Ihering, 1897)	*	*		*	*
	<i>Trachycardium puelchum</i> (Sowerby, 1846)	*	*		*	*
	<i>Cardium patagonicum</i> Ihering, 1907	*	*		*	*
	<i>Lahilla patagonica</i> Ihering, 1907	*	*		*	*
	<i>Fasciculocardia patagonica</i> (Sowerby, 1846)	*	*		*	*
	<i>Dosinia meridionalis</i> Ihering, 1897	*	*		*	*
	<i>Eumarcia arenosa</i> (Ortmann, 1899)	*	*		*	*
	<i>Eurhomalea? navidadiformis</i> Frassinetti and Covacevich, 1999	*			*	*
	<i>Chione patagonica</i> (Philippi, 1887)	*			*	*
	<i>Ameghinomya argentina</i> (Ihering, 1897)	*			*	*
	<i>Ameghinomya meridionalis</i> (Sowerby, 1846)	*			*	*
	<i>Ameghinomya darwini</i> (Philippi, 1887)	*			*	*
	<i>Panopea quemadensis</i> (Ihering, 1897)	*	*		*	*
	" <i>Panopea</i> " cf. <i>nucleus</i> (Ihering, 1899)	*	*		*	*
	<i>Pholadidea patagonica</i> (Philippi, 1887)	*		*	*	*
	Gastropoda	<i>Valdesia dalli</i> (Ihering, 1897)	*	*		*
<i>Calyptrea pileolus</i> d'Orbigny, 1841		*	*		*	*
<i>Crepidula gregaria</i> Sowerby, 1846			*		*	*
<i>Cirsotrema rugulosa</i> (Sowerby, 1846)			*	*	*	
<i>Turritella ambulacrum</i> Sowerby, 1846		*	*		*	
<i>Struthiolarella ameghinoi</i> (Ihering, 1897)		*	*		*	*
<i>Ficus? carolina</i> (d'Orbigny, 1847)		*	*		*	*
<i>Trophon santacruzensis</i> Ihering, 1897		*	*		*	*
" <i>Siphonalia</i> " sp.		*	*	*	*	
<i>Aeneator? annae</i> (Ortmann, 1900)		*	*		*	
<i>Penion subrectus</i> Ihering, 1899		*	*		*	
<i>Neoimbricaria patagonica</i> (Ihering, 1897)		*	*	*	*	
<i>Proscaphella cossmanni</i> Ihering, 1907		*	*		*	*
<i>Proscaphella quemadensis</i> (Ihering, 1897)		*	*		*	*
<i>Proscaphella santacruzensis</i> Chiesa, Parma and Camacho, 1995		*	*		*	*
<i>Adelomelon? burmeisteri</i> (Ihering, 1907)		*	*	*	*	*
<i>Sigapatella americana</i> (Ortmann, 1900)		*	*	*	*	*
<i>Peonza torquata</i> Olivera et al., 1994		*	*		*	*

Only the species in common from one locality to another are included. Not included in the table are most of the mollusk species of the Monte León Formation, which are known to occur only within this unit in which the preservation of aragonitic shells in some beds results in a large number of "exclusive" taxa. The mollusk taxa contained in the Centinela and San Julián formations are relatively few and comprise either species with calcitic shells or molds. Of these, only the taxa positively identifiable are included in the tables. A significant number of the specimens collected are impossible to identify adequately for meaningful comparisons between these two units.

to dissolution. Carbonate was dissolved with dilute acetic or hydrochloric acid. For hydrochloric acid dissolution, aliquots of 2 N HCl were incrementally added to the carbonate samples for 15 min until visible reaction ceased. For acetic acid dissolution, 4 N acetic acid was added to the carbonate for two days. After dissolution, the solution was centrifuged to separate any residue, and the supernatant was spiked with a highly enriched ^{84}Sr tracer, decanted and evaporated. Then the Sr was isolated from this fraction by ion-exchange chromatography. All chemical preparations were carried out with low blank procedures in a clean laboratory, following the general analytical procedures for Sr isolation, isotope dilution, and mass spectrometry separation described by Foland and Allen (1991). The Radiogenic Isotopes Laboratory in the

Department of Geological Sciences of the Ohio State University performed the $^{87}\text{Sr}/^{86}\text{Sr}$ analyses.

$^{87}\text{Sr}/^{86}\text{Sr}$ determinations were made using dynamic multicollection of all Sr-isotopes on a Finnigan MAT 261A thermal ionization mass spectrometer as outlined by Foland and Allen (1991). Measured values of $^{87}\text{Sr}/^{86}\text{Sr}$ were normalized assuming normal Sr with $^{86}\text{Sr}/^{88}\text{Sr} = 0.119400$. Data are presented in Table 1, where each entry with a sample number represents a different sample dissolution and replicate entries indicate complete replicate analyses. Multiple entries for $^{87}\text{Sr}/^{86}\text{Sr}$ values for a given dissolution represent replicate mass spectrometer analyses. Each entry is for a separate loaded filament and represents a run of 100 ratio measurements with an ^{88}Sr ion signal intensity of approximately



Fig. 4. Field photograph of a biogenic concentration at Cabo Curioso, consisting of a 20 cm-thick continuous bed of *Crassostrea? hatcheri* (Ortmann) in life position, forming clumps.

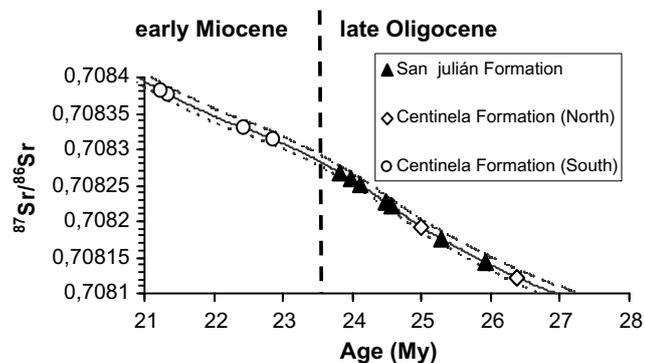


Fig. 5. $^{87}\text{Sr}/^{86}\text{Sr}$ average compositions of 16 *Crassostrea? hatcheri* (Ortmann) shells from the San Julián and Centinela formations plotted on the secular Sr-isotope curve for marine water (solid line) showing 95% confidence interval (shaded lines) of McArthur et al. (2001).

6×10^{-11} to 5×10^{-11} amps. Uncertainties refer to the last digit(s) and are two standard deviations of the mean within-run uncertainties. The reference value of $^{87}\text{Sr}/^{86}\text{Sr}$ for the SRM987 is 0.710242 ± 0.000010 (one sigma external reproducibility).

The $^{87}\text{Sr}/^{86}\text{Sr}$ values of the samples were converted to numerical ages using the SIS (Strontium Isotope Stratigraphy) Version 3:10/99 of the Look-Up Table of McArthur et al. (2001). The reference value $^{87}\text{Sr}/^{86}\text{Sr}$ used ($=0.710242$) was corrected to make the data concordant with SRM987 of 0.710248 used in the construction of this Look-Up Table. The time scale used is that of Berggren et al. (1995). Results are plotted in Fig. 5.

The Nevada Isotope Geochronology Laboratory of the University of Nevada, Las Vegas, made the $^{40}\text{Ar}/^{39}\text{Ar}$ analyses. A rock sample taken at 35 m from the bottom of the section at Estancia La Siberia was analyzed by the furnace step heating method on crushed and sieved whole rock material. The sample was wrapped in Al foil and stacked in 6 mm inside diameter Pyrex tubes. It was in-core for 14 h in the D3 position on the core edge of the 1 MW TRIGA type reactor. Correction factors for interfering neutron reactions on K and Ca were determined by repeated analysis of K-glass and CaF_2 fragments. Correction factors were $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.00 \pm 0.0002$, $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 2.78 \pm 2.99 \times 10^{-4}$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 6.81 \pm 2.94 \times 10^{-4}$. J factors were determined by fusion of 3–5 individual crystals of neutron fluence monitors which gave reproducibilities of 0.09–0.29% at each stan-

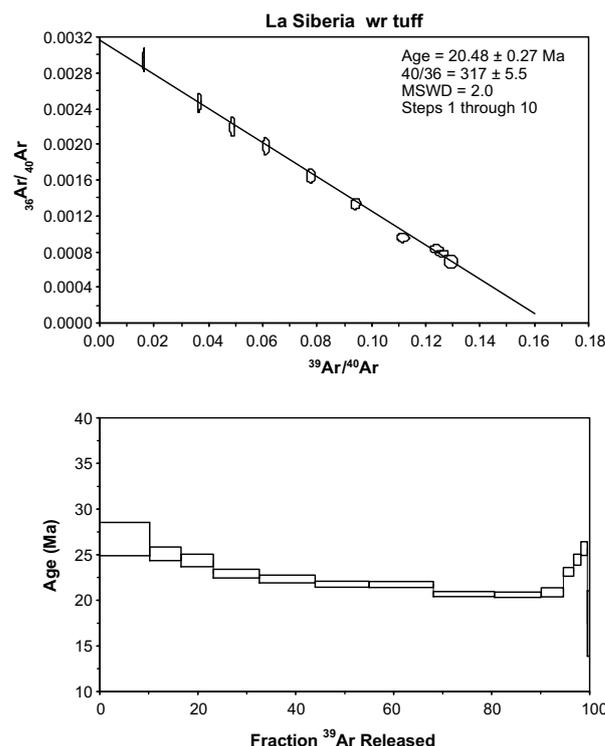


Fig. 6. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum of the tuff from the Centinela Formation, based upon total fusion and incremental heating procedures, and isotope correlation.

dard position. An error in J of 0.5% was used in age calculations. Irradiated crystals together with CaF_2 and K-glass fragments were placed in a Cu sample tray in a high vacuum extraction line and were fused using a 20WCO_2 laser. Measured $^{40}\text{Ar}/^{36}\text{Ar}$ ratios were $290.12 \pm 0.38\%$ during this work, thus a discrimination correction of 1.01857 (4 AMU) was applied to measured isotope ratios. Computer automated operation of the sample stage, laser extraction line, and mass spectrometer as well as final data reduction and age calculations were done using LabSPEC software written by B. Idleman (Lehigh University). An age of 27.9 Ma was used for the Fish Canyon Tuff sanidine flux monitor in calculating age for the sample. Results of the analyses are given in Fig. 6.

4. Results and discussion

4.1. Isotopic and radiometric ages

Although the samples have less Sr content (<800 ppm) than modern low-Mg calcitic shells, it is still possible that they may not have suffered diagenetic loss of Sr, since concentrations <800 ppm have been reported in oyster samples from Upper Cretaceous and Miocene deposits (McArthur et al., 2000; Scasso et al., 2001). Veizer et al. (1999) stated that the lower Sr concentration may be in part due to the inclusion of distinct small domains of secondary calcite, and not to partial re-crystallization, leaving the bulk of the shell unaltered.

Nine measurements were performed using six oyster valves (three were analyzed twice) from the San Julián Formation (Table 1, Fig. 5). The ages range between 23.83 and 25.93 Ma (late Oligocene), and Sr contents lie between 288 and 680 ppm. Seven measurements were performed using four oyster valves (three were analyzed twice) from the Centinela Formation. The ages range between 21.24 and 26.38 Ma (late Oligocene to early Miocene), and Sr content ranges between 396.2 and 665.8 ppm.

The results provide a well-constrained depositional age for the “Patagonian” deposits examined here. The $^{87}\text{Sr}/^{86}\text{Sr}$ ages suggest that in the eastern areas of Patagonia, the rocks included in the San Julián Formation were deposited during the late Oligocene (Chattian). In the west, the rocks belonging in the Centinela Formation were deposited between the late Oligocene and the early Miocene (Chattian–Aquitania). At the two northernmost sections where this unit is exposed (Veranada de Cárcamo and Estancia La Siberia), $^{87}\text{Sr}/^{86}\text{Sr}$ data from oysters collected in the lowermost beds suggest a late Oligocene age. Samples from further South – also from the base of the sections – at Cerro Pirámides and Estancia 25 de Mayo, yielded younger (early Miocene) ages.

The sample of the tuff from the Centinela Formation, based upon the furnace step heating method, exhibits a discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum (Fig. 6) with high initial ages (~ 27 Ma), falling to ages of ~ 21 Ma at ~ 50 – 90% gas released, and then rising again to older final step ages. This type of age spectrum (called U-shaped, or saddle-shaped) is associated with excess argon, which can cause anomalously old ages for samples. The total gas age of 22.64 ± 0.25 Ma is equivalent to conventional K/Ar age and is likely an overestimate of the true eruptive event. This sample has a valid isochron, using the first 10 out of 14 steps, which defines an age of 20.48 ± 0.27 and does confirm some initial excess argon present, as the y-intercept is 317. We considered that this isochron is the best estimate of the age of the Estancia La Siberia sample.

A strong discrepancy exists between the ages derived from $^{87}\text{Sr}/^{86}\text{Sr}$ (this study) and $^{40}\text{Ar}/^{39}\text{Ar}$ dating methods (Casadio et al., 2000a) on the Centinela Formation at Estancia 25 de Mayo, near Calafate. The initial radiometric age published for the Centinela Formation was based upon an $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of a thick volcanic ash bed within the formation and bounded above and below by fossiliferous sediments (Casadio et al., 2000a). The age of approximately 46 Ma was judged to be a minimum age. Subsequently, multiple $^{87}\text{Sr}/^{86}\text{Sr}$ ages taken on oyster shells from the same stratigraphic section, and reported herein (Table 1) document a much younger age. In an attempt to resolve this difference, another $^{40}\text{Ar}/^{39}\text{Ar}$ analysis was conducted at a different laboratory on a different split of the same sample of the volcanic ash, and the resultant age was not conclusive. The youngest age on the age spectrum, presumed to be the minimum age, was 30.2 Ma, whereas the statistically valid isochron yielded an age of 64.8 ± 1.6 Ma (T. Spell, personal communication to RMF). Although this age determination embraced the previous $^{40}\text{Ar}/^{39}\text{Ar}$ determination, the uncertainty in the results, coupled with the similarity of the $^{87}\text{Sr}/^{86}\text{Sr}$ ages taken on multiple oyster shells from the same stratigraphic section leads us to the conclusion that the latter ages are a more reliable estimate of the age of the Centinela Formation.

4.2. Paleontological affinities

In the Monte León Formation, most of the mollusk and decapod fauna is exquisitely preserved, showing a high diversity with a large number of mollusk taxa represented. In contrast, the San Julián Formation yields mostly taxa with calcitic shells such as oysters, pectinids, muricids, epitonids, bryozoans, barnacles, and echinoids, among others. Very rarely are aragonitic shells preserved and only as calcite replacements or molds. The Centinela Formation is somewhat intermediate, although most of the aragonitic shells have suffered a fair degree of diagenetic alteration. Consequently, comparison among the faunas from different localities must by necessity take into account the preservation of the fossils considered, in order to avoid taxonomic misplacements that may artificially cloud or enhance any existing affinities.

The decapod record (Table 2) suggests that different geographic regions, for example the areas of Calafate and Gran Bajo de San

Julián, had some affinities. Both areas yielded *Proterocarcinus latus* (Glaessner); however, this species was extremely common at the former locality and rare at the latter. Furthermore, the species is widespread geographically and temporally. *Notomithrax* sp. was also present at both localities but the material collected from Calafate is fragmentary and it may not be possible to determine whether it is the same species as that from Gran Bajo de San Julián. Unfortunately, no decapods were collected at the other localities from which age determinations were made.

Although decapods are not typically considered to be good stratigraphic indices, the more detailed analysis of ages of Paleogene rock units does permit description of one morphological trend that may have stratigraphic implications. *Proterocarcinus* Feldmann, Casadio, Chirino-Gálvez and Aguirre-Urreta, is a genus of primitive portunids, or swimming crabs, that first appear in the fossil record in the Paleocene Roca Formation of central Argentina. The geologically oldest species, *P. lophos* Feldmann, Casadio, Chirino-Gálvez and Aguirre-Urreta, is characterized by having four well-developed anterolateral spines. Another species within the genus, *P. latus* (Glaessner), is distinguished from the type species in having the central two anterolateral spines reduced to small protuberances. As can be seen in Table 2, that genus is geographically widespread and geologically long-ranging with representatives known from the Oligocene and the Miocene. The trend in reduction of the medial spines is apparently reflected in two other species. *Proterocarcinus corsolini* Casadio, de Angeli, Feldmann, Garassino, Hetler, Parras and Schweitzer, from the Oligocene Río Foyel Formation near Bariloche exhibits only three anterolateral spines, the central one of which is strongly reduced. Finally, a newly discovered species, yet to be named, from the Miocene Navidad Formation in Chile, bears all the diagnostic features of *Proterocarcinus* except that the medial spine(s) are absent altogether. The age of the part of the Navidad Formation from which crabs were collected is Tortonian (late Miocene, ca. 10–11 Ma) (Finger et al., 2003). Thus, there seems to be one lineage of *Proterocarcinus*, including *P. lophos* and *P. latus*, that retains the original condition of four anterolateral spines, although the latter exhibits reduced medial spines, whereas a second lineage, characterized by *P. corsolini* and the new species from the Navidad Formation, has experienced reduction and ultimate loss of the medial anterolateral spines. Additional studies of its presence both in Argentina and Chile will permit testing this hypothesis. The occurrence of *Proterocarcinus* spp. on both sides of the Andes suggests that there may have been a connection through the Andes at this time such that faunal mixing of Pacific and Atlantic faunas was possible.

That potential connection is further reinforced by the distributional patterns of two other taxa. The Cancridae is represented by three genera, two noted from the Centinela Formation and one from the late Miocene Puerto Madryn Formation. Examination of the geographic distribution of extant members of the family indicates that none is known from the eastern coast of South America, south of the Caribbean (Nations, 1975; Boschi, 2000). The occurrence of representatives of this family in the Oligocene and Miocene of Argentina suggests either that the family was formerly more widespread in the Atlantic Ocean or that the fossil species document a Pacific connection through the Andes during this time. These possibilities can be explored by additional studies in both Chile and Argentina to develop a more detailed history of the Cancridae in South America. Perhaps even more striking is the occurrence of the atelecyclid species, *Trichopeltarion levis* Casadio, de Angeli, Feldmann, Garassino, Hetler, Parras and Schweitzer, in the Río Foyel Formation in Argentina and in the Navidad Formation in Chile. Recent studies on the Atelecyclidae (Schweitzer and Salva, 2000; Salva and Feldmann, 2001) document a fossil record of the family that is strictly circum-Pacific so the occurrence in Argentina represents the first fossil record in rocks presumed to have been

connected to the Atlantic basin. Extant atelecyclids are known from both coasts of South America and the Caribbean (Boschi, 2000), as well as West Africa (Crosnier, 1981).

Finally, another decapod taxon of interest is *Chaceon peruvianus* (d'Orbigny). Although it is formally recognized from only two occurrences herein (Table 2), it probably has a wider occurrence. The species occurs in museum collections around the world and is probably the best known fossil crab from South America. Unfortunately, the stratigraphic and geographic information accompanying most of the material is inadequate to locate the collecting sites and verify the occurrences. The known occurrences of the species in the Centinela and the Puerto Madryn formations, however, do document a range extending from the late Oligocene to the late Miocene, suggesting that additional studies could yield more occurrences.

A survey of the mollusk taxa collected from the four stratigraphic units (i.e., San Julián, Monte León, Centinela, and Guadal formations; Table 3) reveals that forty-one taxa are common to the Monte León and Centinela formations; in contrast, only six are in common between the Centinela and San Julián formations. If the Centinela Formation is divided into North and South (according to the area where the samples were taken) then the species in common differ slightly. A cluster analysis using Euclidean Distance (Simple Linkage), and considering the Centinela Formation as a unit (Fig. 7A) or separated into North and South (Fig. 7B), reveals divergent clustering patterns that in some cases agree well – but not always – with the accepted paleobiogeographic and biostratigraphic patterns for the Patagonian marine Paleogene–Neogene faunas proposed by del Río (2004b). These patterns are not always consistent with the $^{87}\text{Sr}/^{86}\text{Sr}$ ages distribution obtained from oyster shells from these localities. The most obvious reason for this are the strong preservational bias resulting from the absence of aragonitic shells in the San Julián Formation and the generally poor preservation in the Centinela Formation, which produce a significant distortion of the record. Therefore, as only relative proportions can be used in estimating any possible affinities, the evidence provided by mollusks regarding the affinities between the different faunas must remain presently inconclusive. Nevertheless, it is interesting to note some peculiarities in the distribution of certain well preserved mollusks. Such is the case of the distribution of the large pectinids from Patagonia. *Reticulochlamys proxima* (Sowerby) is a species that appears in the Monte León Formation and also occurs in the Centinela Formation but is entirely missing from the San Julián Formation, despite the fact that pectinids are among the most conspicuous elements in the latter unit. A similar stratigraphic distribution is also shown by *Zygochlamys geminata* (Sow-

erby). Conversely, the most abundant pectinid in the San Julián Formation, i.e., *Zygochlamys dominator* Morra, is never present in the overlying Monte León Formation and is also missing in the Centinela Formation and the equivalent Guadal Formation in southern Chile. Likewise, *Crassostrea orbigny* (Hering) is only found within the uppermost beds of the Monte León and Centinela formations, whereas it is missing in the lower part of these units and is not present at all in the San Julián Formation. Further collections and study of different sections within the area will be instrumental in elucidating whether these differences can be attributed to age or else to different paleoecological conditions.

5. Conclusions

The $^{87}\text{Sr}/^{86}\text{Sr}$ data from the lower part of the Centinela Formation at the northernmost localities – Estancia La Siberia and Veranada de Cárcamo (25.00 and 26.38 Ma) – suggest that these rocks temporally correlate in part with the San Julián Formation (23.83–25.93 Ma; see Table 1 for localities) exposed in the eastern areas of southern Patagonia. Despite the agreement between Sr-isotope data there are insufficient species in common to establish a close paleontological correlation between the San Julián Formation and the lower part of the Centinela Formation at the northernmost localities. $^{87}\text{Sr}/^{86}\text{Sr}$ data from the lower part of the Centinela Formation at the southern localities – Estancia 25 de Mayo and Cerro Pirámides – yield younger ages (21.24 to 22.86 Ma), suggesting a possible correlation with the Monte León Formation exposed in the eastern part of southern Patagonia and there overlying the San Julián Formation. No isotopic data are available on the lower part of the Monte León Formation, and the only radiometric $^{40}\text{Ar}/^{39}\text{Ar}$ age of 19.33 Ma is from the top of the unit (Fleagle et al., 1995). The $^{87}\text{Sr}/^{86}\text{Sr}$ age of 23.83 and 24.12 Ma (latest Oligocene) drawn from top of the San Julián Formation immediately below its contact with the overlying Monte León Formation at Cabo Curioso, suggest that the age of the latter at the localities along the coast should lie between 24.12 and 19.33 Ma, i.e., latest Oligocene or more probably early Miocene (see Fig. 8). The faunal affinities among the Centinela Formation at its southernmost localities, the upper part of the same unit at its northernmost localities, and the Monte León Formation agree with this correlation. It should be noted, however, that the present state of knowledge on the faunas from all these units is inconclusive.

The isotopic data obtained and the identification and comparison of the taxa present in the different units somewhat modifies the extent of the “Patagonian” transgressions as described by previous authors (Camacho, 1974; Malumián, 1999, 2002), and refines

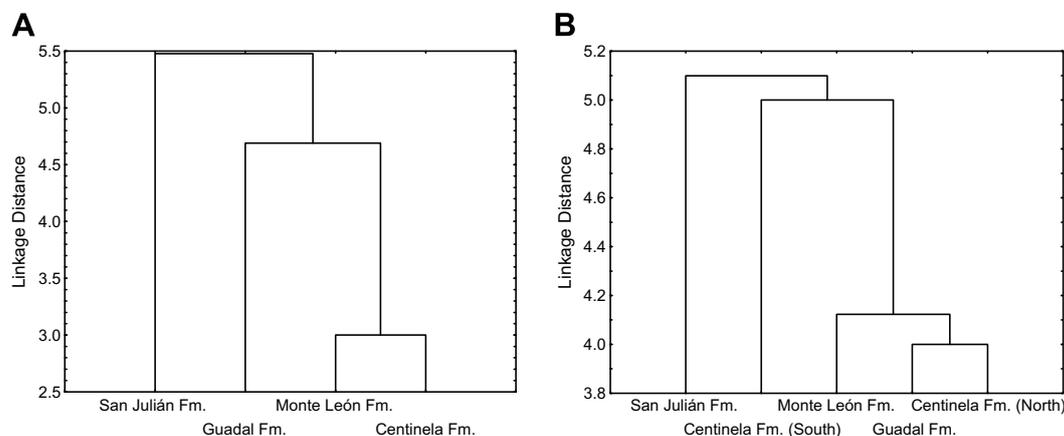


Fig. 7. Tree diagrams illustrating association of lithostratigraphic units based on cluster analysis (single linkage) of the mollusk fauna using Euclidean distance indexes; (A) considering the entire Centinela Formation as a unit; (B) discriminating the Centinela Formation into northern and southern exposures.

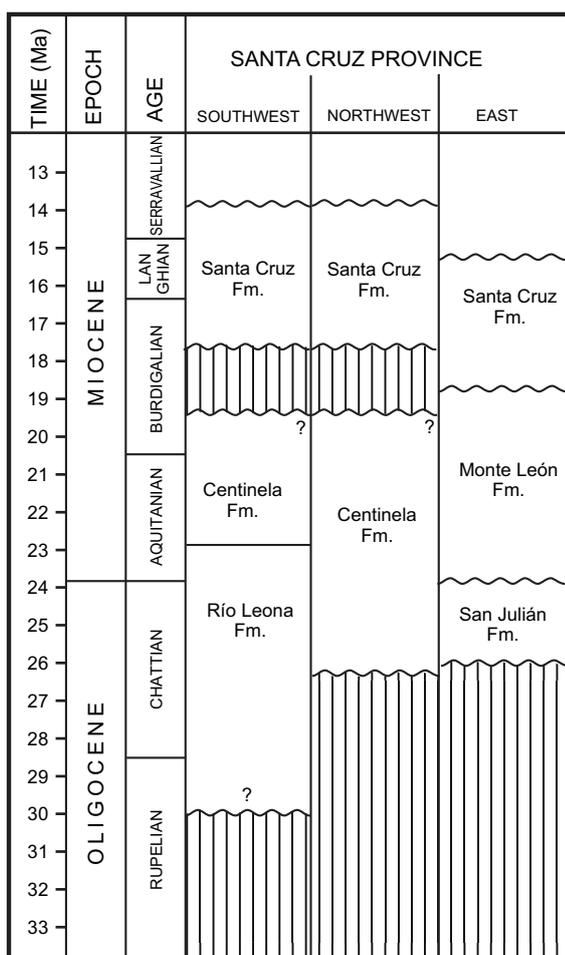


Fig. 8. Proposed lithostratigraphic correlation of units exposed in the western part of Santa Cruz province with those exposed along the Atlantic coast.

the age of "Patagonian" rock units and the Oligocene–Miocene paleogeographic boundaries.

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References

Aguirre-Urreta, M.B., 1987. La familia Geryonidae (Crustacea: Brachyura) en el Terciario de Patagonia y Tierra del Fuego, Argentina. *Actas 4º Congreso Latinoamericano de Paleontología* 1, 459–484.

Aguirre-Urreta, M.B., 1990. Nuevos crustaceos decapodos (Brachyura y Anomura) en el Terciario de Patagonia, Argentina. *Actas 5º Congreso Argentino de Paleontología y Bioestratigrafía* 1, 149–154.

Aguirre-Urreta, M.B., 1992. Tertiary freshwater Decapoda (Crustacea: Parastacidae) from the Nirihuau Basin, Patagonia, Argentina. *Journal of Paleontology* 66, 817–825.

Ameghino, F., 1906. Les formations sedimentaires du Cretace superieur et du Tertiariere de Patagonie. *Anales Museo Nacional de Historia Natural de Buenos Aires, Serie 3* (8), 1–568.

Barreda, V.D., 1997. Palinoestratigrafía de la Formación San Julián en el área de Playa La Mina (provincia de Santa Cruz), Oligoceno de la cuenca Austral. *Ameghiniana* 34 (3), 283–294.

Berggren, W.A., Kent, D.V., Swisher III, C.C., Aubry, M.P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.P., Hardenbol, J. (Eds.), *Geochronology Time Scales and Global Stratigraphic Correlation*. Society for Sedimentary Geology, Special Publication 54, pp. 129–212.

Bertels, A., 1970. Sobre el "Piso Patagoniano" y la representación de la época del Oligoceno en Patagonia Austral, República Argentina. *Revista de la Asociación Geológica Argentina* 25 (4), 495–501.

Bertels, A., 1975. Bioestratigrafía del Paleógeno en la República Argentina. *Revista Española de Micropaleontología* 7 (3), 429–450.

Bertels, A., 1977. Estratigrafía y micropaleontología de la Formación San Julián en su área tipo, provincia de Santa Cruz, República Argentina. *Ameghiniana* 14 (1–4), 233–293.

Boschi, E.E., 2000. Species of decapod crustaceans and their distribution in the American marine zoogeographic provinces. *Revista de Investigación y Desarrollo Pesquero* 13, 1–136.

Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F., Otto, J.B., 1982. Variaton of seawater ⁸⁷Sr/⁸⁶Sr throughout Phanerozoic time. *Geology* 10, 516–519.

Camacho, H.H., 1974. Bioestratigrafía de las formaciones marinas del Eoceno y Oligoceno de la Patagonia. *Anales de la Academia Nacional de Ciencias Exactas, Físicas y Naturales* 26, 39–57.

Camacho, H.H., 1979. Significados y usos de "Patagoniano", "Patagoniense", "Formación Patagónica", "Formación Patagonia" y otros términos de la estratigrafía del Terciario marino argentino. *Revista de la Asociación Geológica Argentina* 34 (3), 235–242.

Camacho, H.H., 1985. Presencia del género *Parynomya* Olsson, 1928 (Mollusca, Bivalvia) en la Formación San Julián (Eoceno) de la provincia de Santa Cruz, Argentina. *Boletín de la Academia Nacional de Ciencias de Córdoba* 56, 119–125.

Camacho, H.H., Zinsmeister, W., 1989. La Familia Struthiolariidae Fischer, 1884 (Mollusca: Gastropoda) y sus representantes del Terciario Patagónico. *Actas 4º Congreso Argentino de Paleontología y Bioestratigrafía* 4, 99–110.

Carrizo, R., Malumián, N., Nández, C., Caramés, A., Concheyro, A., 1990. Micropaleontología y correlación del Terciario del área carbonífera de Río Turbio, provincia de Santa Cruz. *Actas 2º Simposio sobre el Terciario de Chile* 1, 29–50.

Casadío, S., De Angeli, A., Feldmann, R.M., Garassino, A., Hetler, A.L., Parras, A., Schweitzer, C., 2004. New decapod crustaceans (Thalassinidea, Galatheoidea, Brachyura) from the middle Oligocene of Patagonia, Argentina. *Annals of Carnegie Museum* 73 (2), 25–47.

Casadío, S., Feldmann, R.M., Foland, K.A., 2000a. ⁴⁰Ar/³⁹Ar age and oxygen isotope temperature of the Centinela Formation, southwestern Argentina: an Eocene age for crustacean-rich Patagonian beds. *Journal of South America Earth Sciences* 13, 123–132.

Casadío, S., Guerstein, G.R., Marensi, S., Santillana, S., Feldmann, R., Parras, A., Montalvo, C., 2000b. Evidencias para una edad oligocena de la Formación Centinela, suroeste de Santa Cruz, Argentina. *Ameghiniana* 37, 71R.

Casadío, S., Parras, A., Marensi, S.A., Griffin, M., 2001. Edades ⁸⁷Sr/⁸⁶Sr de *Crassostrea? hatcheri* (Ortmann) – Bivalvia, Ostreoidea- en el "Patagoniano" de Santa Cruz, Argentina. *Ameghiniana* 38, 30R.

Chiesa, J.O., Camacho, H.H., 1995. Litoestratigrafía del Paleógeno marino en el noroeste de la provincia de Santa Cruz, Argentina. *Monografías de la Academia Nacional de Ciencias Exactas, Físicas y Naturales de Buenos Aires* 11, 9–15.

Chiesa, J.O., Camacho, H.H., Parma, S.G., 1995. Invertebrados marinos de la Formación El Chacay (Eoceno), provincia de Santa Cruz, Argentina. *Sistemática y bioestratigrafía*. *Monografías de la Academia Nacional de Ciencias Exactas, Físicas y Naturales* 11, 17–68.

Crosnier, A., 1981. Découverte du genre *Trachycarcinus* dans l'Atlantique oriental. *Description de T. intesi* sp. nov. (Decapoda Brachyura). *Crustaceana* 40, 303–306.

d'Orbigny, A., 1842. Voyage dans l'Amérique meridionale. *Paleontologie et Geologie* 3 (3), 245–247.

Darwin, Ch., 1846. *Geological Observations on South America, Being the Third Part of the Geology of the Voyage of the Beagle*. Smith Elder & Co., London. pp. 617.

del Río, J.C., 1995. The genus *Swiftopecten* Hertlein, 1936 (Bivalvia: Pectinidae) in the Tertiary of Southern South America. *Journal of Paleontology* 69 (6), 1054–1059.

del Río, C.J., 2004a. Revision of the large Neogene pectinids (Mollusca: bivalvia) of eastern Santa Cruz and Chubut provinces (Patagonia: Argentina). *Journal of Paleontology* 78 (4), 690–699.

del Río, C.J., 2004b. Tertiary marine molluscan assemblages of eastern Patagonia (Argentina): a biostratigraphic analysis. *Journal of Paleontology* 78 (6), 1097–1122.

del Río, J.C., Camacho, H.H., 1996. *Iheringinuclula*, a new genus of the Family Nuculidae (Mollusca: Bivalvia) from the Tertiary of Patagonia (Argentina). *Journal of Paleontology* 70 (6), 935–940.

del Río, J.C., Camacho, H.H., 1998. Tertiary nuculoids and arcoids of eastern Patagonia (Argentina). *Palaeontographica Abteilung A, Band* 250, 47–88.

DePaolo, D.J., Ingram, B.L., 1985. High-resolution stratigraphy with strontium isotopes. *Science* 227 (4689), 938–941.

Echeverría, A.E., 1998. Ostrácodos marinos del Paleógeno del sud-sudeste del Lago Cardiel, Santa Cruz, Argentina. In: Casadío, S., (Ed.), *Paleógeno de América del Sur y de la Península Antártica*, *Publicación Especial de la Asociación Paleontológica Argentina*, vol. 5, pp. 109–127.

Elderfield, H., 1986. Strontium isotope stratigraphy. *Palaeogeography, Palaeoclimatology, Palaeoecology* 57, 71–90.

- Erdmann, S., Morra, G.A., 1985. Nuevos moluscos de la Formación San Julián, Provincia de Santa Cruz. *Ameghiniana* 22, 289–295.
- Feldmann, R.M., Schweitzer, C.E., 2006. Paleobiogeography of southern hemisphere decapod Crustacea. *Journal of Paleontology* 80, 83–103.
- Feldmann, R.M., Casadío, S., Chirino-Gálvez, L., Aguirre-Urreta, M., 1995. Fossil decapod crustaceans from the Jagüel and Roca formations (Maastrichtian-Danian) of the Neuquén Basin, Argentina. *Memoir of Paleontological Society* 43, 1–22.
- Feldmann, R.M., Aguirre-Urreta, M., Chirino-Gálvez, L., Casadío, S., 1997. Paleobiogeography of Cretaceous and Tertiary decapod crustaceans from southern South America: the link with Antarctica. In: Ricci, C.A. (Ed.), *The Antarctic Region: Geological Evolution and Processes*. Antarctic Geology and Geophysics, pp. 1007–1016.
- Feruglio, E., 1937. *Palaeontographia Patagonica*, vol. 11–12. Memoire Istituto Geologico Realle Università Padova. pp. 1–384.
- Feruglio, E., 1954. Alcune nuove forme di brachiopodi e moluschi del Terziario e Crétaceo superiore della Patagonia, vol. 2. Pubblicazioni Istituto Geologico Università Torino, Fascicolo. pp. 1–45.
- Finger, K., Encinas, A., Nielsen, S., Peterson, D., 2003. Microfaunal indications of late Miocene deep-water basins off the central coast of Chile. *Actas 10° Congreso Geológico Chileno, Concepción, Chile, Abstract Volume CD-ROM*, 8 p.
- Feagle, J.G., Bown, T.M., Swisher, C., Buckley, G., 1995. Age of the Pinturas and Santa Cruz formations. *Actas 6° Congreso Argentino de Paleontología y Bioestratigrafía*, 129–135.
- Foland, K.A., Allen, J.C., 1991. Magma sources for Mesozoic anorogenic granites of the White Mountain magma series, New England USA. *Contributions to Mineralogy and Petrology* 109 (2), 195–211.
- Frassinetti, D., Covacevich, V., 1999. Invertebrados fósiles marinos de la Formación Guadal (Oligoceno superior-Mioceno inferior) en Pampa Castillo, Región de Aisén, Chile. *Boletín del Servicio Nacional de Geología y Minería, Chile* 51, 1–96.
- Furque, G., 1973. Descripción geológica de la Hoja 58b, Lago Argentino, provincia de Santa Cruz. *Boletín Servicio Nacional Minero Geológico* 140, 1–51.
- Furque, G., Camacho, H.H., 1972. El Cretácico Superior y Terciario de la región austral del Lago Argentino (provincia de Santa Cruz). *Actas 4° Jornadas Geológicas Argentinas* 3, 61–75.
- Griffin, M., 1990. *Modiomylus*, a new mytilid bivalve from the Tertiary of southern Patagonia. *Journal of Paleontology* 64, 377–382.
- Guerstein, G.R., Guler, M.V., Casadío, S., 2004. Palynostratigraphy and palaeoenvironments of the Oligocene/Miocene boundary from the Centinela Formation, southwestern Argentina. In: Beaudoin, A.B., Head, M.J. (Eds.), *The Palynology and Micropalaeontology of Boundaries*. Geological Society Special Publication 230, pp. 325–343.
- Howarth, R.J., McArthur, J.M., 1997. Statistics for strontium isotope stratigraphy; a robust LOWESS fit to marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age. *Journal of Geology* 105 (4), 441–456.
- Ihering, H. von., 1897. Os molluscos dos terrenos terciarios de Patagonia. *Revista Museo Paulista* 2, 217–382.
- Ihering, H. von., 1907. Les Mollusques fossiles du Tertiaire et du Crétacé supérieur de l'Argentine. *Anales del Museo Nacional de Buenos Aires* 3 (7), 1–611.
- Ihering, H. von., 1914. Catalogo de molluscos Cretáceos e terciarios da colleção do auctor. *Notas do Museu Paulista* 1, 1–113.
- Legarreta, L., Uliana, M.A., 1994. Asociaciones de fósiles y hiatos en el Supracretácico-Neogeno de Patagonia: una perspectiva estratigráfico-secuencial. *Ameghiniana* 31 (3), 257–281.
- Malumián, N., 1999. La sedimentación y el volcanismo terciarios en la Patagonia Extraandina. In: Caminos, R. (Ed.), *Geología Argentina. Anales Instituto de Geología y Recursos Minerales, SEGEMAR, Buenos Aires*, vol. 29 (18), pp. 557–612.
- Malumián, N., 2002. El Terciario marino. Sus relaciones con el eustatismo. In: Haller, M.J. (Ed.), *Geología y Recursos Naturales de Santa Cruz. Relatorio 15° Congreso Geológico Argentino* (1–15), pp. 237–244.
- Manassero, M., Griffin, M., Pastorino, G., 1997. Coquinas and shelf deposits of the San Julián Formation (upper Eocene–lower Oligocene) southern Patagonia, Argentina. *Revista de la Asociación Geológica Argentina* 52 (3), 286–296.
- Marensi, S.A., Casadío, S., Santillana, S.N., 2003. Estratigrafía y sedimentología de las unidades del Cretácico Superior-Paleógeno aflorantes en la margen sureste del lago Viedma, provincia de Santa Cruz, Argentina. *Revista de la Asociación Geológica Argentina* 58 (3), 403–416.
- Marensi, S.A., Limarino, C.O., Tripaldi, A., Net, L., 2005. Fluvial systems variations in the Rio Leona Formation: tectonic and eustatic controls on the Oligocene evolution of the Austral (Magallanes) basin, southernmost Argentina. *Journal of South American Earth Sciences* 19 (3), 359–372.
- Marshall, L.G., Drake, R.R., Curtis, G.H., Butler, R.F., Glanagan, K.M., Naeser, C.W., 1986. Geochronology of type Santecrucian (middle Tertiary) land mammal age, Patagonia, Argentina. *Journal of Geology* 94, 449–457.
- McArthur, J.M., Crame, J.A., Thirlwall, M.F., 2000. Definition of Late Cretaceous stage boundaries in Antarctica using strontium isotope stratigraphy. *Journal of Geology* 108, 623–640.
- McArthur, J.M., Howarth, R.J., Bailey, T.R., 2001. Strontium isotope stratigraphy: LOWESS version 3: best fit to the Marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. *Journal of Geology* 109 (2), 155–169.
- Morra, G.A., 1985. Revisión de *Zygochlamys* (Mollusca: Bivalvia). *Ameghiniana* 22, 300–308.
- Náñez, C., 1988. Foraminíferos y bioestratigrafía del Terciario Medio de Santa Cruz oriental. *Revista de la Asociación Geológica Argentina* 43 (4), 493–517.
- Nations, D., 1975. The genus *Cancer* (Crustacea: Brachyura): systematics, biogeography and fossil record. *Natural History Museum of Los Angeles County, Science Bulletin* 23, 1–104.
- Olivera, A., Zinsmeister, W., Parma, G., 1994. *Peonza*: a new gastropod genus from the middle Tertiary of Patagonia and Chile. *Journal of Paleontology* 68 (2), 279–286.
- Ortmann, A.E., 1897. On some of the large oysters of Patagonia. *American Journal of Sciences* 4, 355–357.
- Ortmann, A., 1902. Tertiary invertebrates. Reports on the Princeton University Expedition to Patagonia 4 (2), 45–332.
- Parma, S.G., 1989. El género *Platipygus* (Echinoidea: Cassiduloidea) en el Terciario de la provincia de Santa Cruz, República Argentina. *Ameghiniana* 25 (3), 213–224.
- Parras, A., Casadío, S., 2002. Oyster concentrations from the San Julián Formation, Paleogene of Patagonia, Argentina: taphonomic analysis and paleoenvironmental implications. In: De Renzi, M., Pardo Alonso, M.V., Belinchón, M., Peñalver, E., Montoya, P., Márquez-aliaga, A. (Eds.), *Currents Topics on Taphonomy and Fossilization 3, Taphonomy of the shell concentrations*. Ajuntament de Valencia, Valencia, pp. 207–213.
- Parras, A., Casadío, S., 2005. Taphonomy and sequence stratigraphic significance of oyster-dominated concentrations from the San Julián Formation, Oligocene of Patagonia, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology* 217 (1–2), 47–66.
- Philippi, R.A., 1887. Die Tertiären und Quartären Versteinerungen von Chile. F.A. Brockhaus, Leipzig. pp. 1–256.
- Ramos, V., 1982. Geología de la región del Lago Cardiel, provincia de Santa Cruz. *Revista de la Asociación Geológica Argentina* 37 (1), 23–49.
- Riccardi, A.C., Roller, E.O., 1980. Cordillera Patagónica Austral. *Actas Segundo Simposio de Geología Regional Argentina* 2, 1173–1306.
- Salva, E.W., Feldmann, R.M., 2001. Reevaluation of the family Ateleyclidae (Decapoda: Brachyura). *Kirtlandia* 52, 9–62.
- Scasso, R.A., McArthur, J.M., del Río, C.J., Martínez, S., Thirlwall, M.F., 2001. $^{87}\text{Sr}/^{86}\text{Sr}$ Late Miocene age of fossil mollusks in the "Entrerriense" of the Valdes Peninsula (Chubut, Argentina). *Journal of South American Earth Sciences* 14, 319–329.
- Schweitzer, C.E., Feldmann, R.M., 2000. New fossil portunids from Washington, U.S.A., and Argentina and a reevaluation of generic and family relationships within the Portunoidea Rafinesque (Decapoda: Brachyura). *Journal of Paleontology* 74, 636–653.
- Schweitzer, C.E., Salva, E.W., 2000. First recognition of the Chieragonidae Ortmann (Decapoda, Brachyura) in the fossil record and comparison of the family to the Ateleyclidae Ortmann (Decapoda, Brachyura). *Journal of Crustacean Biology* 20, 285–298.
- Sowerby, R., 1846. Descriptions of the Tertiary fossil shells from South America. In: Darwin, C. (Ed.), *Geological Observations on the Volcanic Islands and Parts of South America Visited During the Voyage of H.M.S. "Beagle"*. Appleton, London, pp. 1–548.
- Veizer, J., Buhl, D., Diener, A., Ebner, S., Podlaha, O.G., Bruckschen, P., Jasper, T., Korte, Ch., Schaaf, M., Ala, D., Azmy, K., 1997. Strontium isotope stratigraphy: potential resolution and event correlation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 132, 65–77.
- Veizer, J., Ala, D., Azmy, K., Bruckschen, P., Buhl, D., Bruhn, F., Carden, G.A.F., Diener, A., Ebner, S., Godderis, Y., Jasper, T., Korte, Ch., Pawellek, F., Podlaha, O.G., Strauss, H., 1999. $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ evolution of Phanerozoic seawater. *Chemical Geology* 161, 59–88.
- Zinsmeister, W.J., 1981. Middle to late Eocene invertebrate fauna from the San Julián Formation at Punta Casamayor, Santa Cruz province, Argentina. *Journal of Paleontology* 55, 1083–1103.