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PALEONTOLOGY

Palaeoenvironmental changes based on foraminifera during the late Holocene at the Beagle Channel, Argentina

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Abstract: A foraminiferal faunal study was carried out in a Holocene marine section from Arroyo Baliza, located on the northwest coast of the Beagle Channel, to contribute to the knowledge of the palaeoenvironmental conditions during the marine Holocene event. Foraminiferal assemblage was represented by 32 species distributed among 21 genera. The assemblage was dominated by *Elphidium macellum* (Fichtel & Moll) *Elphidium alvarezianum* (d'Orbigny), *Cribroelphidium excavatum* (Terquem) and *Buccella peruviana* (d'Orbigny), accompanied by *Cibicides fletcheri* Galloway & Wissler and *Cibicidoides dispars* (d'Orbigny) in low proportion. The predominance of Peridiniales dinocysts in the marine palynomorphs assemblage, suggested inner neritic conditions with cooler and more nutrient-rich waters. The distribution of the foraminiferal species was variable throughout the section indicating palaeoenvironmental changes in Arroyo Baliza between 3499–2595 cal yr BP. A gradual passage from high energy, cold and well-oxygenated marine waters towards a shallower environment with low energy and low to moderate salinity of the waters were linked to the regressive phase. This study complements and supports the previous palynological data from this section, which reflects an increase in number and diversity of dinocyst species indicating marine environmental conditions during the late Holocene as it exists today in the Beagle Channel.

Key words: Holocene, foraminifers, palynomorphs, sea level, south smerican.

INTRODUCTION

The Beagle Channel is located at 54º 53´ S between 66º 30´ and 70º 00´ W and connects the Pacific and Atlantic Oceans in the southernmost part of South America. This depression of glacial origin was flooded during the Holocene marine transgression after about 8600 cal yr BP (Candel et al. 2018, McCulloch et al. 2019). Several Holocene marine deposits, mostly raised beaches, distributed along both northern and southern Beagle Channel coasts testify this marine incursion (Gordillo et al. 1993). The Holocene sea-level variations in the Isla Grande de Tierra del Fuego, were analyzed mostly from a geological and geomorphological focus (Codignotto 1984, Porter et al. 1984, Rabassa et al. 1986, 1992, 2000, Rutter et al. 1989, Mörner 1990, Bujalesky et al. 2004, Bujalesky 2007) and palaeoecological studies (Gordillo et al. 1992, 1993, 2005, 2008, 2013, 2015, Isla et al. 1999). Also, palynological studies of Holocene marine sediments in the Fuegian Archipelago (Tierra del Fuego and Isla de los Estados) and their palaeoenvironmental aspect were made by different authors (Borromei & Quattrocchio 2001, 2007, Grill et al. 2002, Candel et al. 2009, 2011, 2012, 2013, 2017, 2018, Rabassa et al. 2009, Candel 2010, Candel & Borromei 2013, 2016, Fernández et al. 2014).

Integrated studies of mollusks, foraminifera and ostracods from Patagonian and Beagle

Channel were conducted by Cusminsky & Whatley (2008), Gordillo et al. (2010), and Gordillo et al. (2013). The first researches based on recent foraminifera fauna have been carried out along the Patagonian coast and the Malvinas/Falkland Islands by d'Orbigny (1839) and Brady (1884). Later, Herb (1971) and Boltovskoy (1976) described foraminifera from the Drake Passage. The modern foraminifera from the Straits of Magellan were also studied by Zapata & Alarcón (1988), Hromic & Águila (1993), Hromic (1996, 1999, 2002, 2009), and Hromic et al. (2006). Hromic & Zúñiga-Rival (2003, 2005), and Figueroa et al. (2005) determined the modern association present in southern Chile. The modern foraminifera from Tierra del Fuego were analyzed by Boltovskoy & Watanabe (1980), Boltovskoy et al. (1980) and Zúñiga-Rival (2006). However, little is known about the fossil foraminifers from Beagle Channel region, being able to mention the work carried out by Gordillo et al. (2010), who described Pleistocene foraminifers from sediments of the Navarino Island, Chile. Also, Gordillo et al. (2013) reported Holocene foraminifera from several sites located in the Lago Roca-Lapataia area, close to the study site.

The aim of this research is to contribute to the knowledge of the palaeoenvironmental conditions and palaeoclimatic changes during the late Holocene in the Beagle Channel using foraminifera fauna as a proxy data. In this context, the foraminiferological study of a marine section from Arroyo Baliza (AB) at Bahía Lapataia, complements the palynological results documented for this site by Candel et al. (2017). The integration of these studies provides new data to adjust the palaeoenvironmental reconstruction during the transgressive-regressive marine Holocene event in the Beagle Channel, southernmost Patagonia.

STUDY AREA

The Beagle Channel (Fig. 1) has been described as an estuarine system controlled by repeated important fluvial input and by tidal currents from both the east (Atlantic) and the west (Pacific) sides (Isla et al. 1999). Present-day seawater conditions are characterized by a strongly thermohaline stratified water column with water mixing at 12 m depth mainly during the summer season. The sea-surface temperature average 6.5 °C, and sea-surface salinity varies between 27 and 33.5 PSU (Isla et al. 1999). The Beagle Channel has ice-free conditions throughout the whole year (Iturraspe et al. 1989, Isla et al. 1999).

Bahía Lapataia (Fig. 1), where is located the study site Arroyo Baliza, is a fjord-like embayment distant about 20 km west of the Ushuaia city, on the north coast in the westernmost end of the Beagle Channel, in the National Park of Tierra del Fuego. It is placed within the deciduous forest represented by two species of southern beech, *Nothofagus pumilio* and *N. antarctica*, which grow from sea-level to the tree line at 550-600 m a.s.l. and become dominant where precipitation surpass 450 mm yr^{-1}. Sheltered inland areas are mainly covered by enclaves of evergreen forest dominated by *Nothofagus betuloides* associated with *Drimys winteri* when annual precipitation exceeds 700 mm (Tuhkanen 1992).

Bahía Lapataia belongs to a glacial landscape featured by a series of low, rounded bedrock hills, a typical ice-scoured terrain, surrounded by interconnected depressions filled with freshwater lakes and ponds, peat bogs, or both. During the post-glacial marine transgression, the former deglaciated valley became into deep and narrow fjords and complex archipelagos. At present, the oldest marine radiocarbon dates to this sector of the Beagle Channel were recorded at Bahía Lapataia and Aserradero-Lapataia 2 (Fig. 1) marine outcrops, dated at ca. 8478 and

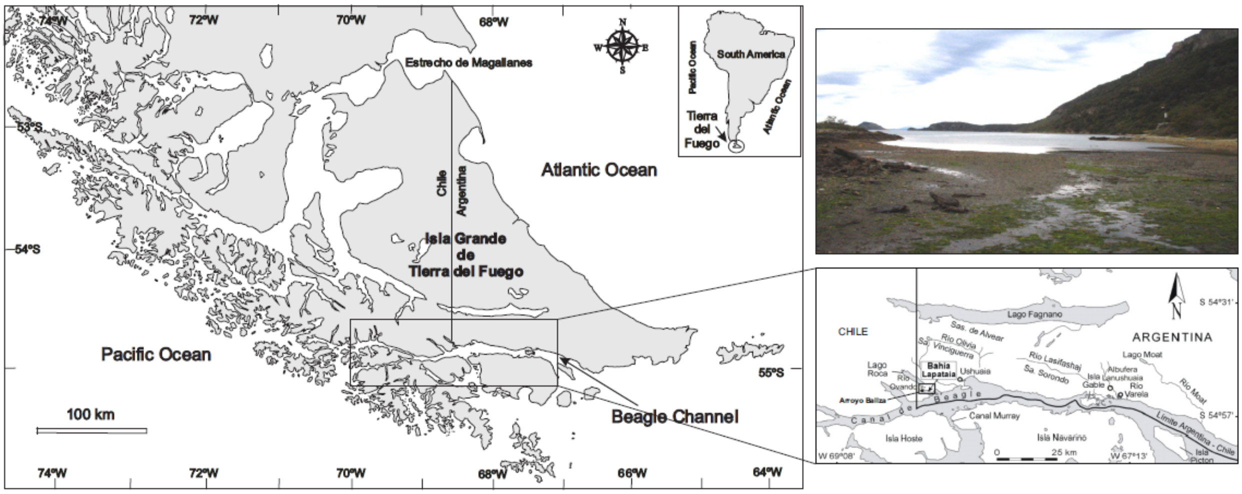

Figure 1. Location map of the study area and sampling section of Arroyo Baliza.

8278 cal yr BP, respectively (Candel & Borromei 2016, Candel et al. 2018).

The studied site at Arroyo Baliza (54° 51' S, 68° 33' W; Fig. 1) comprises a 70 cm-deep of sedimentary section. It is mainly composed of dark olive-grey muddy silt with shells of the mollusks *Venus antiqua*, *Aulacomya atra* and *Mytilus chilensis*. Candel et al. (2017) identified three informal lithological units based on granulometric and sedimentological visual descriptions. From base to top, they are: Unit 1 (70-24 cm), Unit 2 (24-20 cm), and Unit 3 (20-0 cm). Lithological details are fully described in Candel et al. (2017).

MATERIALS AND METHODS

A Holocene marine section was obtained from Arroyo Baliza (54º 51´S and 68º 33´W). A total of twenty-five sediment samples were collected from Unit 1 and Unit 2 with a high-resolution interval of 2 cm depth. The upper 20 cm (Unit 3) were not sampled because of their coarse lithology (Candel et al. 2017). Only twenty-three samples of all of them were analyzed for foraminiferal study given that the two uppermost samples (samples 1 and 2) were totally used for palynological analysis and radiocarbon dating.

All samples were water washed through a 63 μm mesh screen (Tyler Screen System № 230) and dried at room temperature. From the residue, the entire available tests were picked. Also, mesh screens >2 mm, <2 to >0.063 mm and <0.063 mm were used to separate the different fractions gravel, sand and mud, respectively.

The foraminifera genera were identified following Loeblich & Tappan (1992), and Sen Gupta (1999), and the species were determined according to Boltovskoy et al. (1980), Kahn & Watanabe (1980), Hromic (1996, 2002), Hromic & Águila (1993), Figueroa et al. (2005) and Hromic et al. (2006).

In order to calculate the total abundance, the number of individuals in 10 grams of bulk sediment per sample was counted. Regarding diversity, species richness (S) and Shannon-Wienner (H) index were calculated. According to Buzas & Gibson (1969), the H values higher than 3 would indicate normal marine conditions, while low values suggest a highly unstable environment. On the other hand, Murray (1991) mentioned that values lower than 0.6 would reflect hyposaline lagoon environments and those values higher than 2.5–3 would indicate normal marine conditions.

The most represented specimens were photographed using a scanning electron microscope (FEI–Inspect S50) at the Characterization of Materials Department, Centro Atómico Bariloche (CAB), Bariloche, Argentina. The main foraminifera microfossils are shown in Fig. 2. The specimens were stored at the repository of Universidad Nacional del Comahue, Río Negro province, Argentina, under numbers UNC-PMIC 221–236.

The diagram of relative frequencies of foraminiferal and section zoning was carried out applying Coniss software, TILIA 2.0.4 statistic package (Grimm 2004). The analysis considered only those species whose relative abundance was ≥2 %. Standardized Euclidian distance was applied as the distance coefficient, and data transformation by standardization to mean 0, and 1 typical deviation. Clusters formed according to the sum of squared error hierarchical clustering method (Grimm 2004) (Fig. 3).

Subsequently, the main foraminifera species and marine microplankton data were integrated through a cluster analysis to allow the palaeoenvironmental reconstruction in the Arroyo Baliza area during the late Holocene (Fig. 4).

Conventional radiocarbon ages and latitude from the study section are shown in Table I (Candel et al. 2017). The dating was converted to calendar years BP using the Calib 7.1 software (Stuiver et al. 2015) and the Marine13 calibration data set (Reimer et al. 2013). A local ^{14}C marine reservoir effect (DR) value for the Beagle Channel region of 221 ± 40 years should be taken into consideration (Candel et al. 2018).

RESULTS

A total abundance of 40,368 individuals was found throughout the section represented by 32 species of foraminifera, five of them correspond to nomenclature aperta. These

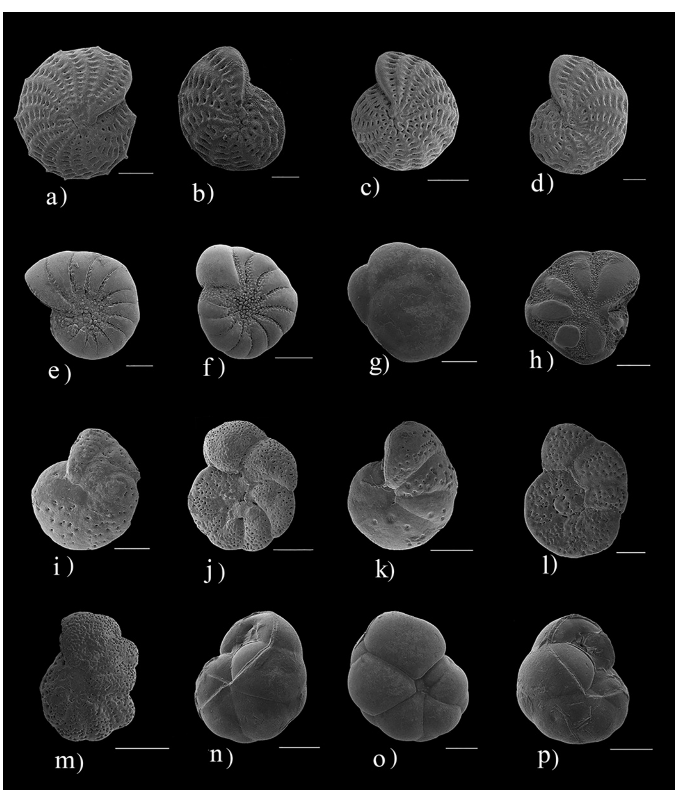

Figure 2. Photomicrographs of the most important foraminiferal species from Arroyo Baliza site; a) ***Elphidium macellum*** **(Fitchel & Moll), UCN-PMIC-221; b)** ***Elphidium macellum*** **(Fitchel & Moll), UCN-PMIC-222; c)** ***Elphidium alvarezianum*** **(d'Orbigny), UCN-PMIC-223; d)** ***Elphidium alvarezianum*** **(d'Orbigny), UCN-PMIC-224; e)** ***Cribroelphidium excavatum*** **(Terquem), UCN-PMIC-225; f)** ***Cribroelphidium excavatum*** **(Terquem), UCN-PMIC-226; g)** ***Buccella peruviana*** **(d´Orbigny), dorsal view; UCN-PMIC-227; h)** ***Buccella peruviana*** **(d´Orbigny), umbilical view; UCN-PMIC-228; i)** ***Cibicides fletcheri*** **Galloway & Wissler, dorsal view; UCN-PMIC-229; j)** ***Cibicides fletcheri*** **Galloway & Wissler, umbilical view; UCN-PMIC-230; k)** ***Cibicides aknerianus*** **(d´Orbigny), dorsal view; UCN-PMIC-231; l)** ***Cibicides aknerianus*** **(d´Orbigny), umbilical view; UCN-PMIC-232; m)** ***Cibicidoides variabilis*** **(d'Orbigny), dorsal view; UCN-PMIC-233; n)** ***Globocassidulina subglobosa*** **(Brady), apertural view; UCN-PMIC-234; o)** ***Globocassidulina rossensis*** **(Kennett), dorsal view; UCN-PMIC-235; p)** ***Globocassidulina rossensis*** **(Kennett), apertural view; UCN-PMIC-236. Scale 300 µm (1 and 13), 200 µm (3, 6, 10) and 100 µm (2, 4, 5, 7, 8, 9, 11, 12, 14, 15, and 15).**

species were distributed among 21 genera (see list of systematic classification). The individuals were predominantly calcareous form belonging to four Orders: Rotaliina (99.3 %), Lagenina (0.6 %), Buliminida (0.05 %), and Miliolina (0.03 %). The agglutinated individuals were absent. The foraminiferal assemblage along the entire sequence was mainly constituted by three species belonging to the genus *Elphidium*: *Elphidium macellum* (Fichtel & Moll), *Elphidium alvarezianum* (d´Orbigny), and *Cribroelphidium excavatum* (Terquem), accompanied by *Buccella peruviana* (Boltovskoy), *Cibicides fletcheri* (Galloway & Wissler), and *Cibicidoides dispars* (d' Orbigny) (Fig. 2). Species richness (S) ranged from 5 to 18 and the H values varied between 1.2 and 2.1.

In general, sedimentological analysis showed variations in the lithological composition. It was constituted by proportions of mud that varied between 15.9-80.6 %, sand between 10.2-53.7 %, and gravel content varied between 4.1-30.5 %.

Based on foraminiferal cluster analysis, two zones AB-FI and AB-FII were distinguished at the Arroyo Baliza sequence. The zone AB-FII was also divided into two subzones (AB-FIIA and AB-FIIB) (Fig. 3).

Zone AB-FI (70–60 cm; samples 25 to 21) is mainly characterized by *E. macellum* (22.0–32.0 %), *E. alvarezianum* (17.7–33.2 %), *C. excavatum* (8.7–15.6 %), *B. peruviana* (8.0–17.7 %), *Astrononion* sp. (2.0-11 %), *C. fletcheri* (3.4 – 6.6 %), *C. dispars* (0.5-8.5 %), *C. aknerianus* (d'Orbigny) (1.9-7.7 %), *C. variabilis* (d´Orbigny) (0.5-2.3 %), *Globocassidulina rossensis* Kennet (1.0-4.3 %) and *G. subglobosa* (Brady) (1.0-2.0 %). Total abundance ranged from 606 to 11,300 individuals. Values for S and H ranged from 10 to 18 and 1.9 to 2.1, respectively.

Zone AB-FII (60–26 cm; samples 20 to 3) is divided in two subzones. Subzone AB-FIIA (60–46 cm; samples 20 to 13) is constituted mostly by *E. macellum* (20.7–39.4 %), *E. alvarezianum* (10.1–29.6 %), *C. excavatum* (12.4–35.6 %), *B. peruviana* (1.6–5.4 %), *C. fletcheri* (0.7-13.9 %), *C. dispars* (0.5-7.0

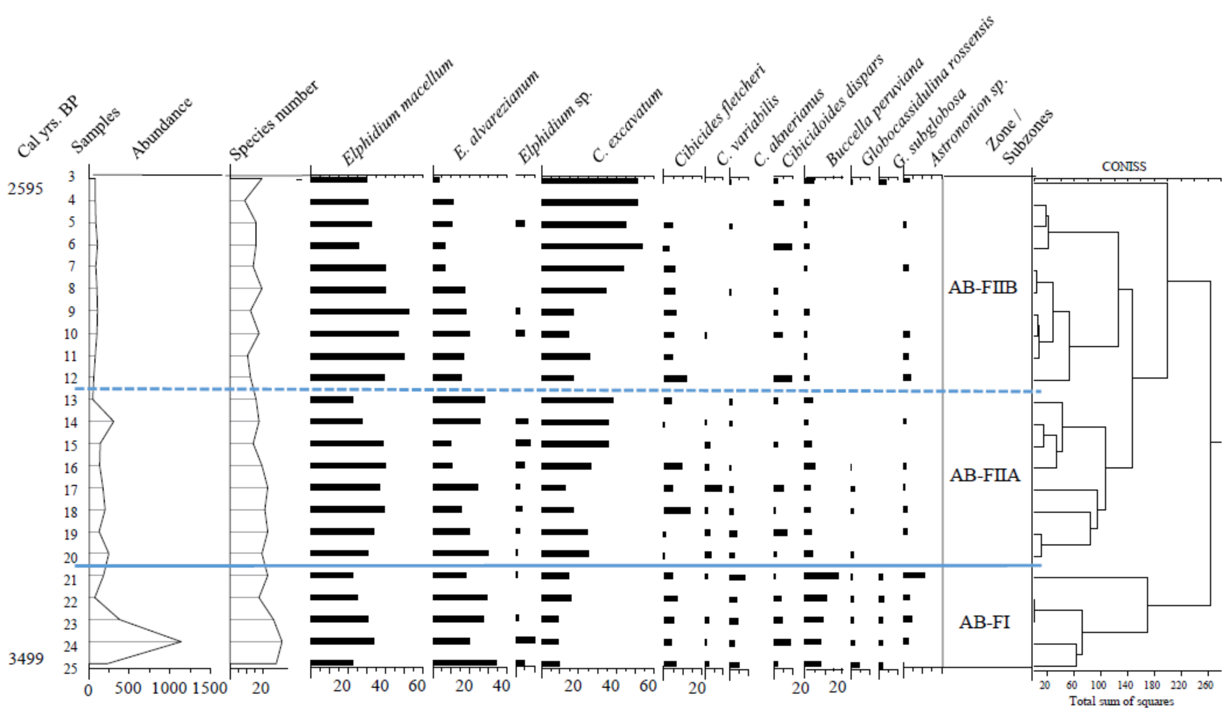

Figure 3. Distribution of foraminiferal species in Arroyo Baliza with ≥2 % of relative abundance at least in 2 levels.

%), *C. aknerianus* (0.6-3.5 %), *C. variabilis* (0.6–8.8 %), *Globocassidulina rossensis* (0.3-1.8 %) and, *G. subglobosa* (1.0 -1.4 %). Total abundance varied between 365 and 2943 individuals. Values for S and H ranged from 8 to 13 and 1.5 to 1.9, respectively.

Subzone AB-FIIB (44–26 cm; samples 12 to 3). It is represented mainly by *E. macellum* (24.5–52.5 %), *C. excavatum* (14.5–51.7 %), *E. alvarezianum* (3.7-20.0 %), *B. peruviana* (0.9–4.9 %), *C. fletcheri* (2.7 – 11.8 %), *C. dispars* (1.5-9.5 %). Total abundance ranged from 517 to 983 individuals. Values for S varied between 5 and 11, and H between 1.2 and 1.6, respectively.

Ann integrated analysis between the main foraminifera species and marine microplankton data allowed us to distinguish two zones at the Arroyo Baliza sequence (AB-FPI and AB-FPII). The first zone includes the lower samples (25 to 21) and the second one extends from samples 20 to 1. Also, the latter zone is subdivided into two subzones (AB-FPIIA and AB-FIIPB) (Fig. 4).

DISCUSSION

Ecological features related to the foraminiferal taxa composition

The foraminiferal assemblage identified at Arroyo Baliza (AB) section was mainly constituted by *E. macellum, E. alvarezianum*, and *Cribroelphidium excavatum*, accompanied by *B. peruviana*, *Cibicidoides dispars* and *Cibicides fletcheri* in low proportions. These dominant foraminifera species are typical of cold waters of the Magellan region. The identified foraminifera assemblage was characterized by species typical of the Malvinas current zone (Boltovskoy 1976, Boltovskoy et al. 1980, Khan & Watanabe 1980).

Modern individuals of *Elphidium* were recorded along the entire section; it is a typical genus of the inner shelf and is founded between 0_50 m in shallow waters of the Argentine coast (Boltovskoy 1966, Boltovskoy et al. 1980) and also, in Chilean waters from Bahía Zenteno in the Magellan Straits, fjords and Patagonian channels in shallow waters between 5 and 9 m-depth (Hromic & Águila 1993, Hromic &

Figure 4. Summary of integrated analysis (main foraminifera species and marine microplankton data) from Arroyo Baliza section.

Zúñiga-Rival 2005, Zúñiga-Rival 2006). Also, *Buccella* is registered in inner shelf between 0 to 100 m and cold temperate waters (Murray 1991). *B. peruviana* is the most common species that inhabits the coast of Argentina (Boltovskoy et al. 1980). Besides, the genera *Cibicides* and *Cibicidoides* were described by Murray (1991) as epifaunal from cold to temperate waters and distributed from 0 to 2000 m of the bathyal shelf. The species *C. dispars* recorded throughout the AB section, occur along the Argentine continental shelf between 35º and 56º S, and are typical for the Malvinas current zone (Boltovskoy et al. 1980). It has been cited as eubathyal species and its abundance increases with depth; it is found in shallow to deep waters up to 4000 m, in Patagonian channels and fjords, and the Magellan Straits (Boltovskoy & Watanabe 1980, Hromic 1996, 2002, Hromic & Zúñiga-Rival 2005).

The association constituted by *E. macellum*, *C. dispars*, and *B. peruviana* is found in southern Chile, the Austral zone, in the Magellan Straits and Tierra del Fuego (Hromic 1999, Zúñiga-Rival 2006). This association is in coincidence with the main species founded in the Chilean channels, except for the absence of *Ammonia beccarii* and non-calcareous forms. The absent of *Ammonia becarii* in the sediments from Arroyo Baliza is most likely due to its inability to live in the cold temperatures of this austral region, since this species is usually recorded in further north areas (Hromic 2011). Although non-calcareous forms have been mentioned for other places in this region (Violanti et al. 2000, Zúñiga-Rival 2006), their absence in the study area could indicated determined local parameters which impeded their development. Other genus recorded at Arroyo Baliza section was *Globocassidulina* that has a free lifestyle; is infaunal, detritivore and live in muddy-sandy substrates in cold waters (Murray 2006). The presence of species belonging to the genus *Globocassidulina* would be suggesting an environment of cold marine waters with high oxygen levels (Murray 2006). They were documented in the open shelf area between 100-200 m, and bathyal zone (Arellano et al. 2011).

In general, the identified assemblage at Arroyo Baliza section was constituted by individuals that inhabit in muddy–sandy sediments in shallow waters from inner shelf. However, the predominance of rotalid individuals and absence of non-calcareous forms reflected a highly-oxygenated and cold seawater temperature in an open sea area between 100-200 m. In addition, the presence of species that adhere to the substrate suggested a high-energy environment (Ishman & Martínez 1995) that is also evidenced by the presence of gravel sediments.

Palaeoenvironmental reconstruction based on foraminiferal assemblages

The distribution and abundance of the foraminifera fauna recorded at Arroyo Baliza section was variable along the entire section indicating palaeoenvironmental changes (Fig. 3). The abundance and diversity of individuals

Table I. Radiocarbon and calibrated ages from Arroyo Baliza section (from Candel et al. 2017).

Locality	Latitude (S)	Longitude (W)	Depth (cm)	Laboratory code	^{14}C yr BP	Cal age (BP median probability
Arroyo Baliza	54º 51’	68º 33’	24-26	AA105987	3062 ± 40	2595
			68-70	AA105987	3823 ± 40	3499

showed their highest values in the lowermost levels of the section. In particular, the diversity values such as species richness (S) and H index determinated in this work were consistent with the data published by Gordillo et al. (2013) in sediments from Archipelago Cormoranes. In that context, taken together the foraminifera and marine microplankton data allowed an integrated palaeoenvironmental reconstruction in the Arroyo Baliza area during the late Holocene (Figs. 4 and 5).

The zone AB-FI (70–60 cm), at 3499 cal yr BP, was characterized by the highest values of abundance and diversity (Fig. 3). *E. macellum* and *E. alvarezianum* were well represented reflecting shallow waters of the inner shelf. Both species are characteristic of the South Patagonian Subprovince and are very abundant in the Malvinas Subprovince, and also considerably more abundant on the Patagonian coasts (Boltovskoy 1976, Boltovksoy et al. 1980). *E. macellum* and *E. alvarezianum* were both founded in recent sediments from the Southern Chile (Zapata & Moyano 1997) and Pleistocene sediments from Navarino Island (Gordillo et al. 2010). Also, these species were cited by Gordillo et al. (2013), in Holocene sediments from the Beagle Channel. Also, *E. macellum* was founded in the inner shelf at 37 m depth by Bernasconi et al. (2018) to the southeast of Buenos Aires province. The presence of species of the genus *Cibicides*, which adhere to the substrate, indicates well-oxygenated, sandy sediments and relatively high-energy conditions, possibly reflecting the strength of the bottom currents (Kaiho 1994, 1999, Ishman & Martínez 1995, Hromic

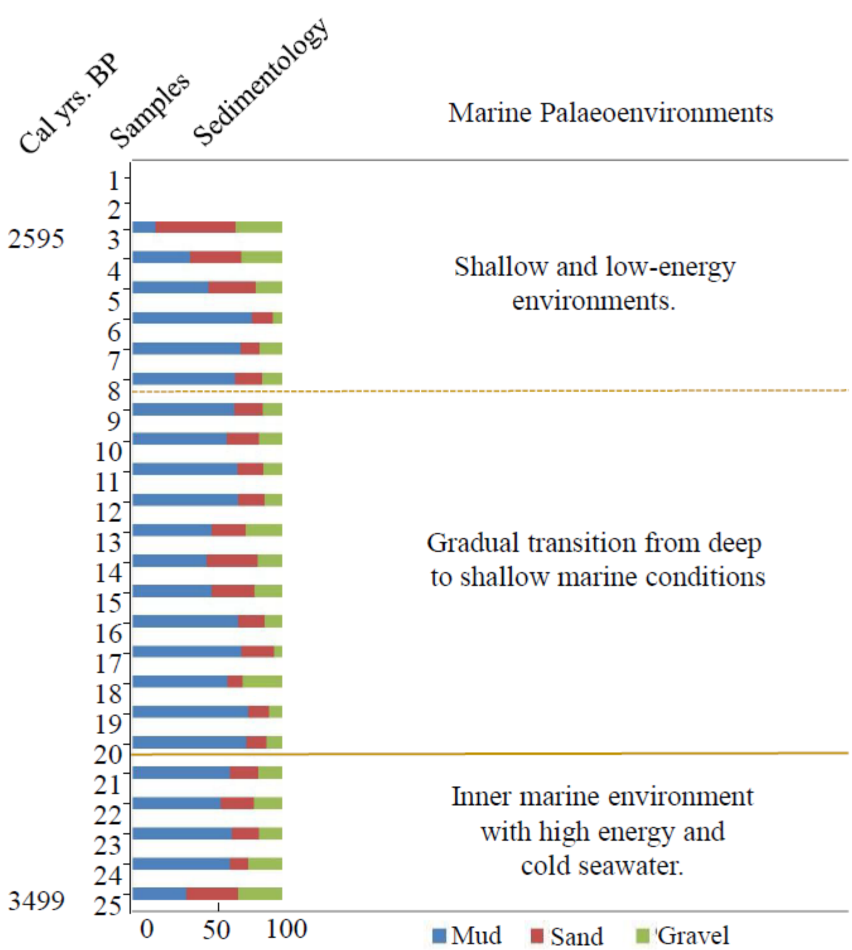

Figure 5. Sedimentological distribution and palaeoenvironmental reconstruction based on the integrated analysis of micropaleontological data from Arroyo Baliza.

2002, Figueroa et al. 2005, Schönfeld et al. 2011, Bernasconi et al. 2018). The relative proportion of both species *C. dispars* and *E. macellum* is related to depth because of *E. macellum* is especially found in shallow waters, while *C. dispars* can live not only in shallow waters but also in deep zones (Boltovskoy 1966, Hromic 1996, 1999). Also, individuals of *G. rossensis* and *G. subglobosa* were recorded, the latter in low proportion, in this zone. *G. subglobosa* was found in the Horn Cape at 120 m-depth (Heron Allen & Earland 1932), Magellanic Straits (Hromic 1996), and in the austral zone of Chile (Zapata & Moyano 1997). Also, it is frequent in the Malvinas zone (Boltovskoy & Totah 1985). *G. rossensis* was found in channels and chilean fjords by Ishman & Martínez (1995) with a great abundance between 42° and 55º S. It was also recorded in Buenos Aires province coast, Tierra del Fuego and Beagle Channel (Boltovskoy et al. 1980, Zúñiga-Rival 2006). This species is an important component in the oceanic biofacies and intermediate channels (Hromic et al. 2006). On the other hand, *B. peruviana* was also recognized in great proportion in this zone. It was found in modern sediments from the marginal environments such as coastal lagoons, estuaries and inner shelf of the Buenos Aires province (Boltovskoy 1957, Wright 1968, Cusminsky et al. 2006) and is also registered in the outer shelf and in the Malvinas current zone (Boltovskoy & Watanabe 1980, Boltovskoy et al. 1980, Kahn & Watanabe 1980). It was found in Holocene sediments in the Bahía Blanca estuary by Cusminsky et al. (2009) and in shelf environments by Bernasconi & Cusminsky (2007, 2015). This species was also recorded in low proportions in Holocene marine sediments in the western sector of the Beagle Channel (Gordillo et al. 2013). The presence of the genera *Cibicides*, *Globocassidulina* and *Buccella* together would indicate a coastal, cold water and high-energy biofacies (Hromic 2009). These characteristics would reflect a cold water marine environment with coarse sediments and high oxygen levels. The palynological record during this interval (zone AB-1, Candel et al. 2017) was characterized by a relatively high dinocyst species diversity (16 taxa) mainly Protoperidiniaceae. From the integrated analysis (Fig. 4), the aquatic palynomorphs assemblage showed high dinocyst species diversity along with acritarchs and copepod eggs (AB-FPI), suggesting the proximity of a terrestrial source with a high input of organic matter in the marginal marine environment under restricted circulation conditions (Candel et al. 2013).

The zone AB-FII (60–26 cm; Fig. 3) showed a drastic decrease in the total abundance while the diversity decreases gradually towards the end of the sequence. *E. macellum* and *E. alvarezianum* were well represented along with an increase in the proportion of *C. excavatum*. Instead, a decrease of individuals of *B. peruviana*, *Cibicides* spp., and *G. rossensis* was observed while *G. subglobosa* was absent. This change in the taxa composition would be reflecting a gradual transition from a marine environment of greater depth, cold waters with a wide availability of oxygen to a shallow environment with a less marine influence. Also, this change is observed in the microplankton assemblage (AB-FPII). This transition was carried out in two stages. In the first one, during the subzone AB-FIIA (60–46 cm; Fig. 3), in which was observed the drops in the number of individuals and species along with the increase in the relative abundance of some species such as *C. excavatum*. These facts would reflect a shift towards a shallower environment related to the previous zone (AB-FI). During this interval, (zone AB-2; Candel et al. 2017) a decrease in the dinocyst species diversity (9 taxa) was registered, probably indicating stressed and restricted conditions with often unstable salinities (Gorin & Steffen

1991). According to de Vernal & Giroux (1991) the low dinoflagellate production may be related to low and variable salinities and/or turbulence, which inhibits the dinoflagellate production. Also, according to Mudie & Harland (1996), the low diversity and abundance dinocysts could be related to changing the conditions in the surface waters. The second stage occurred during the subzone AB-FIIB (44–26 cm), in which the total foraminifera abundance drops to its minimum values. *C. excavatum* reached higher proportions towards the end of the sequence while *E. alvarezianum* and *C. fletcheri* tend to decrease. *Criboelphidium excavatum* was found in shallow waters from marginal environments of Río Quequén and Dos Patos and Mar Chiquita lagoons in recent (Boltovskoy et al. 1980) and Holocene sediments (Márquez et al. 2016). Species of the genus *Globocassidulina* were absent. These variations would be suggesting a shallow and low-energy environment, and the low diversity could reflect non-normal marine conditions. The palynological zone (AB-3; Candel et al. 2017) showed an increase in the dinocyst species diversity to 16 species, and the heterotrophic cysts were dominant over the autotrophic cysts, probably related to increased nutrient availability in the upper water column of coastal environments that would have favored the dinoflagellate production (Godhe et al. 2001, Susek et al. 2005, Dale 2009).

The integrated analysis showed differences in the subdivision of the zone AB-FII (Fig. 3) and AB-FPII (Fig. 4), possibly suggesting a longer transition time from a deep and high-energy environment (AB-FPI) to a shallower environment with lower energy (Fig. 4 and 5).

Regional inferences

The Holocene littoral deposits and landforms are distributed along the northern coast of the Beagle Channel. In particular, the Bahía Lapataia-Lago Roca valley (Fig. 1), in the northwestern sector of the channel, is a palaeofjord that was flooded by the sea during the postglacial marine transgression (Gordillo 1993). The palynological data from both Bahía Lapataia and Aserradero-Lapataia 2 sites (Fig. 1), allowed to feature the marine environment in the Beagle Channel during the transgressional phase between ca. 8478 and 6082 cal yr BP (Borromei & Quattrocchio 2007, Candel et al. 2018). During the beginning of the marine transgression, the aquatic assemblage was characterized by freshwater to brackish algae taxa along with a scarce occurrence of marine components, especially dinoflagellate cysts such as *Brigantedinium* spp., *Echinidinium granulatum* and *Selenopemphix quanta*, suggesting the development of low-energy estuarine environments with low-salinities caused by glacier meltwater discharge. The increasing salinity was accompanied by an increase in the number of dinocysts species with dominance of Peridiniales taxa, indicating the change from transitional to fully marine environment with low to moderate salinities and high nutrient levels during the mid-Holocene in the Beagle Channel.

Towards 4000 cal yr BP, the Río Ovando (RO, Archipelago Cormoranes) and Arroyo Baliza (AB, Bahía Lapataia) sites (Fig. 1) reflected the marine regressive phase dated between before 3929 and 2595 cal yr BP (Candel & Borromei 2016). During this regressive interval, was observed in RO a short-term environmental variability between 3929 and 3797 cal yr BP, when the dinocyst assemblage was dominated by *Islandinium-Echinidinium* complex. It was in coincidence with the mollusk shell data reported by Gordillo et al. (2015) that infer warmer conditions linked to changes in the position of the westerly wind belt, increasing precipitation and higher productivity in the seawater of the channel.

Probably the climatic amelioration would have favored the discharge of cold freshwater from neighboring glaciers into the channel, increasing the terrestrial input and resulting in the occurrence of 'opportunistic species' given the restricted geographical setting. Meanwhile, as the sea was receding, RO located in an inner position, recorded a scarce occurrence of marine palynomorphs between after 3797 and 3164 cal yr BP (subzone RO-2a) (Candel et al. 2009, 2017), and AB in a more open geographical setting, recorded a decrease in the abundance and species diversity during the zone AB-2 (Candel et al. 2017). On the other hand, the new data from foraminifera record along with the dinocysts at AB section (this paper), provided a more accurate information about short-term environmental changes during the regressive phase. In this sense, the regressive event would have carried out between 3499 and 2595 cal yr BP, through a transition from deep, and relative high-energy marine environments under restricted circulation conditions to a shallow, low-energy environments under stressed conditions and unstable salinities. The entire dinocysts assemblages recorded at AB section showed similarities with those modern records from the Beagle Channel (Candel et al. 2012) indicating that the mostly identified marine microplankton species were able to tolerate any minor changes in the environmental and climatic conditions.

CONCLUSIONS

The integration of foraminiferal and palynological data from Arroyo Baliza section provides new information allowing us to adjust the palaeoenvironmental reconstruction proposed for the Holocene transgressive-regressive marine event in the Beagle Channel, Tierra del Fuego. In this sense, the terrace system that featured the marine incursion into the channel brings us different time windows that contribute to the understanding of palaeoenvironmental changes during the transgressive-regressive marine event. In particular, the present study showed that the regressive phase would have occurred through two progressive stages, from high-energy environment reflected by the species of *Cibicides* spp. that adhere to the substrate with cold and well-oxygenated seawater as is indicated by the presence of species such as *Globocassidulina* spp. to a low-energy and shallow environment with a variable salinity and increasing seawater productivity. The Arroyo Baliza section, with a relative opener geographic setting under the influence of the open seawaters of the Beagle Channel, showed a gradual installation of the present marine conditions during the late Holocene in the Beagle Channel, southern Tierra del Fuego.

List of species

Ammonia parkinsoniana (d'Orbigny 1839)
Ammonia tepida (Cushman 1926)
Astrononion echolsi Kennett 1967
Astrononion sp.
Buccella peruviana (d'Orbigny 1839)
Bulimina gibba Fornasini 1902
Cassidulinoides parkeriana (Brady 1881)
Cibicides aknerianus (d'Orbigny 1846)
Cibicides fletcheri Galloway & Wissler 1927
Cibicides sp.
Cibicidoides dispars (d'Orbigny 1839)
Cibicidoides variabilis (d'Orbigny 1826)
Cornuspira involvens (Reuss 1850)
Criboelphidium excavatum (Terquem 1875)
Cribroelphidium gunteri (Cole 1931)
Discorbis malovensis Heron-Allen & Earland 19 32
Discorbis peruvianus (d'Orbigny 1839)
Elphidium alvarezianum (d'Orbigny 1839)
Elphidium macellum (Fichtel & Moll 1798)

Elphidium poeyanum (d'Orbigny 1839)
Elphidium sp.
Epistominella exigua (Brady 1884)
Globocassidulina rossensis Kennett 1967
Globocassidulina subglobosa (Brady 1881)
Lenticulina rotulata (Lamarck 1804)
Nonion sp.
Nonionella sp.
Oolina vilardeboana
Paracassidulina minuta (Cushman 1933)
Pullenia subcarinata (d'Orbigny 1839)
Quinqueloculina angulata (Williamson 1858)
Rosalina williamsoni (Chapman & Parr 1932)

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Author contributions

MSC and AMB collected and sampled from section-AB; they led the writing of the Study Area and everything related to palynological information. MSC did the integrated analysis. EB processed the samples for foraminifera analysis and wrote everything related to foraminifera fauna. All authors contributed critically to the integration of micropaleontological data, drafts, and figures; and gave final approval for publication.