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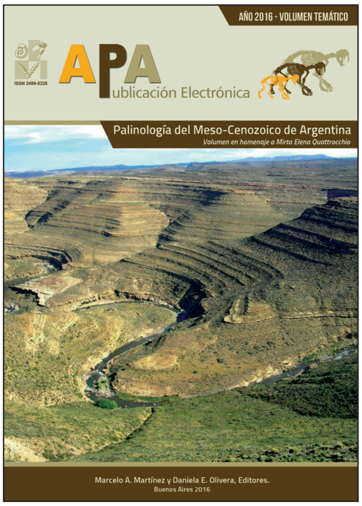


# REVIEW OF THE PALAEOENVIRONMENTAL RECONSTRUCTION OF LATE QUATERNARY MARINE SEQUENCES, TIERRA DEL FUEGO (ARGENTINA)

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# REVIEW OF THE PALAEOENVIRONMENTAL RECONSTRUCTION OF LATE QUATERNARY MARINE SEQUENCES, TIERRA DEL FUEGO (ARGENTINA)

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**Abstract.** This work is an updated review of the knowledge on the evolution and development of palaeoenvironments during the Holocene marine ingression and posterior regressive event in Tierra del Fuego. During the beginning of the marine transgression, *ca.* 8,000 cal yr BP, the vegetation in the southern coastal areas along the Beagle Channel was mainly arboreal with dominance of *Nothofagus* forest and scarcity of shrub and herbaceous communities, while in the northeastern Atlantic coast, the treeless steppe was replaced by a relatively open *Nothofagus* forest. The Early–Middle Holocene aquatic assemblages were characterized by a scarce occurrence of marine components, especially dinoflagellate cysts, suggesting the development of low energy estuarine environments with low-salinities caused by glacier meltwater discharge. After 6,000 cal yr BP, an increase in the number of aquatic species was observed with dominance of Peridiniales dinoflagellate cysts, indicating the establishment of marginal marine environments with low to moderate salinities and high nutrient levels. During the last 1,000 cal yr BP, the littoral vegetation along the Beagle Channel showed an open *Nothofagus* forest and the development of peatlands, while in the northeastern Atlantic coast the steppe vegetation developed under less humid environmental conditions related to the marine regressive event. These assemblages have a similar composition to those observed in modern sediments of the Beagle Channel and suggest palaeoenvironmental conditions comparable to today.

**Key words.** Palaeoenvironments. Marine sequences. Late Quaternary. Tierra del Fuego.

**Resumen.** REVISIÓN DE LA RECONSTRUCCIÓN PALEOAMBIENTAL DE SECUENCIAS MARINAS DEL CUATERNARIO TARDÍO, TIERRA DEL FUEGO (ARGENTINA). Este trabajo es una revisión actualizada del conocimiento sobre la evolución y desarrollo de los paleoambientes durante la ingresión marina del Holoceno y su posterior regresión en Tierra del Fuego. Durante la incursión marina *ca.* 8.000 años cal AP, la vegetación en las zonas costeras a lo largo del Canal Beagle estuvo dominada por el bosque de *Nothofagus* con escasos arbustos y hierbas, mientras que en la costa atlántica la estepa fue sustituida por un bosque de *Nothofagus* relativamente abierto. Las asociaciones acuáticas desarrolladas durante el Holoceno Temprano–Medio se caracterizaron por una escasa ocurrencia de componentes marinos, especialmente quistes de dinoflagelados, sugiriendo el desarrollo de ambientes estuarinos de baja energía y salinidad, afectados por la descarga de agua de los glaciares. Después de los 6.000 años cal AP, se observó un aumento en el número de especies acuáticas con dominancia de quistes de dinoflagelados Peridiniales, lo que sugiere el desarrollo de ambientes marinos marginales con baja a moderada salinidad y alto contenido de nutrientes. Durante los últimos 1.000 años cal AP, la vegetación litoral a lo largo del Canal Beagle mostró el predominio de un bosque abierto de *Nothofagus* y turberas, mientras que en el noreste de la costa atlántica se desarrolló una vegetación de estepa bajo condiciones ambientales menos húmedas y relacionadas al evento marino regresivo. Estas asociaciones tienen una composición similar a las observadas en los sedimentos modernos del Canal Beagle y sugiere que las condiciones paleoambientales fueron comparables a las actuales.

**Palabras clave.** Paleoambientes. Secuencias marinas. Cuaternario Tardío. Tierra del Fuego.

THE LATE Quaternary palynological studies, particularly of the Late Pleistocene–Holocene, represent a research line of growing interest in Argentina since they provide important information about the variability of past environments. About 15,000 years ago, the climate of the southernmost region of South America underwent irreversible transformations that determined profound changes in the geomorphology, position of the shoreline, terrestrial and coastal ecosystems of the region. The study of palaeoclimatic conditions during the last 15,000 years provides the elements to understand the history and evolution of terrestrial and marine ecosystems, their dynamics and ability to react to the climate change. The analysis of palynological organic matter preserved in the sedimentary records has special interest given its importance and potential for the palaeoenvironmental and palaeoclimatic assessment (Candel *et al.*, 2013). The palynofacies analysis comprises the study of the total palynological organic matter (palynomorphs plus other organic matter) and contributes to the understanding of marine transgressive-regressive sedimentary cycles. The relationship between the source material (continental or marine), and the size and diversity provides information on the hydrodynamics and ecology of the depositional environment (Candel *et al.*, 2013). The conventional palynological analysis considers the content of palynomorphs (pollen, spores, and organic-walled microplankton) present in a palynological preparation. The study of fossil pollen records provides evidence for the reconstruction of vegetation com-

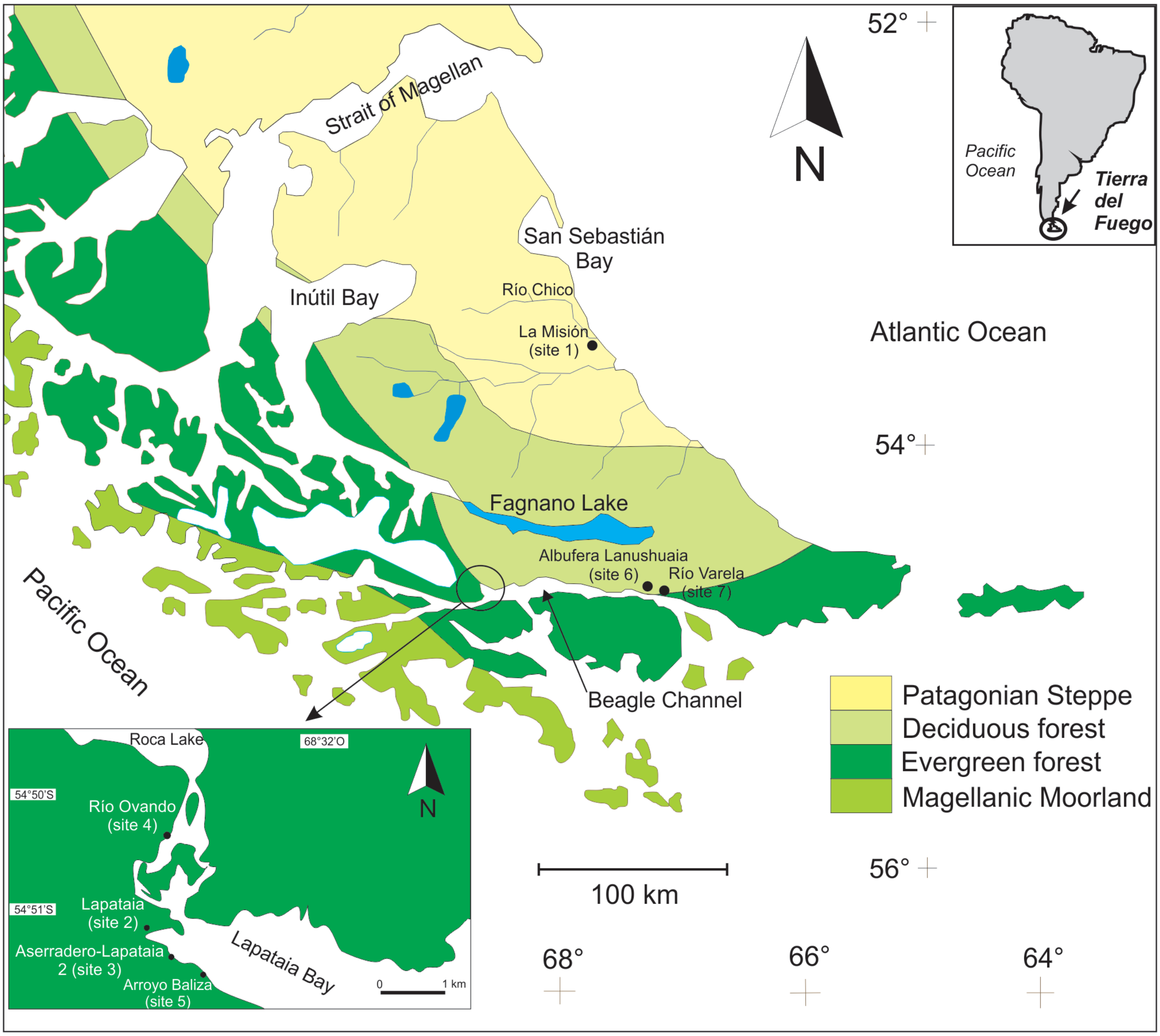



**Figure 1.** Vegetation map of Isla Grande de Tierra del Fuego showing the localities mentioned in the text, the vegetational units and mean annual precipitation (mm) (modified after Tuhkanen, 1992). **1,** La Misión; **2,** Lapataia; **3,** Aserradero-Lapataia 2; **4,** Río Ovando; **5,** Arroyo Baliza; **6,** Albufera Lanushuaia; **7,** Río Varela.

munities and infers the changes that occurred in these communities at spatial and temporal scales in response to environmental and climatic variations. Also, the study of marine organic-walled palaeomicroplankton (mainly dinoflagellate cysts and acritarchs) has a special interest for palaeoenvironmental assessment and palaeoclimatic inferences. Numerous studies have shown the existence of a close relationship between the distribution of dinoflagellate cyst (dinocyst) assemblages and the physico-chemical conditions of seawater such as sea-surface temperature, sea-surface salinity, nutrient availability, primary productivity and seasonality and extent of the sea ice cover (de Vernal *et al.*, 2001, 2013; Radi and de Vernal, 2008). The variations in their records are interpreted in terms of oceanographic and atmospheric changes.

Many studies of Late Quaternary palaeoecological conditions from Isla Grande de Tierra del Fuego, southernmost Patagonia, were largely based on palynological records from terrestrial sediments (Heusser and Rabassa, 1987, 1995; Heusser, 1989, 1998, 2003; Markgraf, 1993; Borromei, 1995; Quattrocchio and Borromei, 1998; Mauquoy *et al.*, 2004; Borromei *et al.*, 2007, 2010, 2014; Borromei and Quattrocchio, 2008; Markgraf and Huber, 2010; Musotto, 2013; Waldmann *et al.*, 2014; Musotto *et al.*, 2016a, in press; among others works). Studies on dinocyst assemblages and palynofacies from Late Quaternary deposits of the southern South America are still limited to a few contributions (Borromei and Quattrocchio, 2001, 2007; Grill *et al.*, 2002; Candel *et al.*, 2009, 2011, 2012, 2013, in press; Rabassa *et al.*, 2009; Candel, 2010; Candel and Borromei, 2013; Fernández *et al.*, 2014).

The present contribution is a compilation of pollen, microplankton, and palynofacies datasets from Holocene radiocarbon-dated marine deposits located in Tierra del Fuego (Tab. 1). Palaeocommunities and palaeoenvironments during the Holocene marine ingression into the Beagle Channel were interpreted from the palynological and palynofacies analyses of material mostly recovered from sites located on the northern coast of the channel. The terrace system that characterise this marine incursion into the Beagle Channel

**TABLE 1. Selected Late Quaternary marine deposits from Isla Grande de Tierra del Fuego (53–55° S). The palynological sites are listed according to their location on the Atlantic coast and the northern coast of the Beagle Channel, from west to east sectors.**

| *Site No.* | *Site name* | *Latitude (S)* | *Longitude (W)* | *References* |
|---|---|---|---|---|
| *Atlantic coast* | | | | |
| *1* | *La Misión* | *53° 30′* | *67° 50′* | *Markgraf (1980, 1993)* |
| *North coast of Beagle Channel* | | | | |
| *2* | *Bahía Lapataia* | *54° 50′* | *68° 34′* | *Borromei and Quattrocchio (2001, 2007)* |
| *3* | *Aserradero-Lapataia2* | *54° 51′* | *68° 34′* | *Rabassa* et al. *(2009); Candel and Louwye (2015)* |
| *4* | *Río Ovando* | *54° 51′* | *68° 35′* | *Candel* et al. *(2009)* |
| *5* | *Arroyo Baliza* | *54° 51′* | *68° 33′* | *Candel* et al. *in press* |
| *6* | *Albufera Lanushuaia* | *54° 52′* | *67° 60′* | *Candel* et al. *(2011)* |
| *7* | *Río Varela* | *54° 52′* | *67° 11′* | *Grill* et al. *(2002)* |

provides evidence for different temporal windows contributing significantly to the understanding of the palaeoenvironmental response to Holocene climate variability. Conventional radiocarbon ages of marine sediments belonging to own studies were converted to calibrated $^{14}C$ ages by the program Calib 7.1 (Stuiver *et al.*, 2015) using the Marine13 calibration data set (Reimer *et al.*, 2013). A local $^{14}C$ marine reservoir effect ($\Delta R$) value for the study region of 221±40 years should be taken into consideration (Gordillo *et al.*, 2015). The published radiocarbon dates corresponding to marine environments and carried out by different authors have been maintained as $^{14}C$ ages.

## GEOGRAPHICAL SETTING

Isla Grande de Tierra del Fuego is the largest island of the Fuegian Archipelago and is located at the southernmost end of South America between latitude 53–55° S and longitude 66–74° W (Fig. 1). It is the highest latitude landmass in the Southern Hemisphere outside Antarctica and is strongly influenced by the climatic conditions of the Southern Ocean and the Antarctic Peninsula. Its separation from continental South America was a result of marine flooding of deep glacial valleys during the Holocene (Rabassa *et al.*, 2011). The Beagle Channel forms a connection between the Atlantic Ocean and the Pacific Ocean in the southernmost Argentinian coast of Tierra del Fuego. It is a former tectonic valley that extends over 220 km from west to east and was completely covered by ice during the Last Glacial Maximum (LGM) *ca*. 25 ka ago (Rabassa, 2008). Following deglaciation, the depressed areas were occupied by proglacial lakes and glaciofluvial and glaciolacustrine environments until the valley was flooding by seawater (Rabassa *et al.*, 1986). The Beagle Channel opened before 8,200 $^{14}C$ yr BP and the lake water was replaced by seawater. The Holocene transgression is recorded at several sites along the Patagonian coast reaching a maximum sea-level between 6,500 and 4,000 yr BP (Codignotto *et al.*, 1992). According Flemming *et al.* (1998), during the period 9,500 to 7,000 yr BP the postglacial sea-level suffered a sharp rise from -24 m to -3 m indicating an uplift rate of 0.084 m/yr. The global scale of sea level rise would have accelerated around 0.428 m/yr from 7,000 BP until reach the current level.

The channel was submerged by the sea and the entire area turned into a fjord by 7,900 $^{14}C$ yr BP (Rabassa *et al.*, 1986) leaving marine deposits, mostly raised beaches, distributed along both the northern and southern Beagle Channel coasts (Gordillo, 1993). These deposits are mostly sandy and gravely in grain-size, although clay-like sediments are recorded mainly in the westernmost sector of the Beagle Channel. The origin of these raised beaches appears related to tectonic uplift and/or isostatic recovery following deglaciation (Rabassa *et al.*, 2000; Bujalesky *et al.*, 2004).

Conversely, the Atlantic coast was ice-free during the LGM (Rabassa *et al.*, 2000). The distinctive characteristic of the Holocene littoral deposits at the northern Atlantic coast (Bahía San Sebastián and Río Chico area) is the presence of regressive-like sequences at protected areas, while transgressive-like beach facies have developed at exposed areas (Rabassa *et al.*, 2000, p. 227). The dissimilarities in geomorphological and evolutionary trends of these littoral deposits of the northeastern Atlantic coast occurred as a consequence of the underlying palaeorelief that was dipping northwards and carved during the Pleistocene glaciations (Rabassa *et al.*, 2000). The comparison of the Holocene raised beaches between the northern Atlantic coast of Tierra del Fuego (La Misión, Río Chico, Bahía San Sebastián) (Fig. 1) and the northwestern coast of Beagle Channel (Punta Pingüinos, Bahía Golondrina, Playa Larga) (Fig. 2), indicate that these dissimilarities may partially be the result of differential tectonic uplifting rates (Rabassa *et al.*, 2000). The tectonic uplift during the last 8,000 yr was greatest at the western Beagle Channel (approximately 1.2+0.2 mm/yr), diminishing northward and eastward. It seems to be negligible toward the northern coast of Isla Grande. The glacioisostatic rebound at the Beagle Channel seems to have operated only during deglaciation or in 1–2 millennia after the final ice recession (Isla and Bujalesky, 2008).

## MODERN CLIMATE AND VEGETATION

The climate of Tierra del Fuego is cold-temperate and is influenced predominantly by the seasonal shifts of the Polar Front and the cyclonic activity related to the southern westerlies (Pisano, 1977). It is highly oceanic in the western and southern parts of the archipelago and increasingly continental towards the east and north. Mean summer isotherms increase northeastward from 9 to 12 °C. The precipitation decreases to the north and east. The mean annual rainfall in Ushuaia is 570 mm and less than 300 mm in Río Grande to the north (Prohaska, 1976). The modern vegetation corresponds to the Fuego-Patagonian Steppe in the north, followed southward successively by the Subantarctic Deciduous Beech Forest and the Evergreen Beech Forest (Fig. 1). They are characterized by three species of southern beech, *Nothofagus pumilio* (Poeppig and Endl.) Krasser 1896 (lenga), *N. antarctica* (Forster f.) Oersted 1871 (ñire), and *N. betuloides* (Mirbel) Oersted 1871 (guindo), which grow to an average altitudinal limit of 550–600 m a.s.l. (meters above sea level) and predominate where precipitation exceeds 400 mm yr$^{-1}$. Magellanic Moorland occurs beyond the forest along the exposed outermost coast under conditions of increased precipitation, wind and poor drainage. High Andean Desert vegetation develops above the treeline (600 m a.s.l.) in the Fuegian Andes until the snowline is reached (Tuhkanen, 1992).

## SURFACE SEDIMENTS SAMPLES AS MODERN ANALOGUES

Palynological and palynofacies analyses of surface sediments from the Beagle Channel (Fig. 2) were carried out to establish modern analogues for comparison with other Holocene marine records in southern Tierra del Fuego. The results showed the predominance of *Nothofagus dombeyi*-type pollen indicating the presence of forest communities in the coastal area (Candel *et al.*, 2013). The aquatic palynomorph assemblages, mainly dinoflagellate cysts, are dominated by Peridiniales over Gonyaulacales taxa (Candel *et al.*, 2012, 2013). The assemblages (Tab. 2) were mostly composed by Protoperidiniaceae such as *Brigantedinium* spp., *Echinidinium* spp., and *Selenopemphix quanta* (Bradford 1975) Matsuoka 1985, typical of a marginal marine and surface waters characterized by low to moderate salinity, and high nutrient input by rivers. These assemblages were thus compatible with the occurrence of freshwater to brackish water taxa (*Botryococcus braunii* Kützing 1849, *Botryococcus* sp., *Polyasterias* sp., *Halodinium* sp., and *Radiosperma corbiferum* Meunier 1910). The assemblages from the Beagle Channel showed similarities with those of high latitude regions of the Northern Hemisphere (Candel *et al.*, 2012).

The palynofacies showed the dominance of highly degraded translucent phytoclasts associated with amorphous organic matter (AOM) and palynomorphs, while opaque phytoclasts were poorly represented. The organic constituents indicated the proximity of a continental source area to the marine environment, with distances and/or times of relatively short transport. The predominance of translucent phytoclasts associated with pyrite suggested reducing conditions, probably associated with marginal-marine environments. The high terrestrial organic matter input into the depositional area was consistent with these coastal environments. A comparison with the sections of Holocene age (Río Varela, Aserradero-Lapataia, Arroyo Baliza, Río Ovando, and Albufera Lanushuaia) (Fig. 1) showed similar distribution of the total palynological matter (Grill *et al.*, 2002; Rabassa *et al.*, 2009; Candel *et al.*, 2011, 2013).

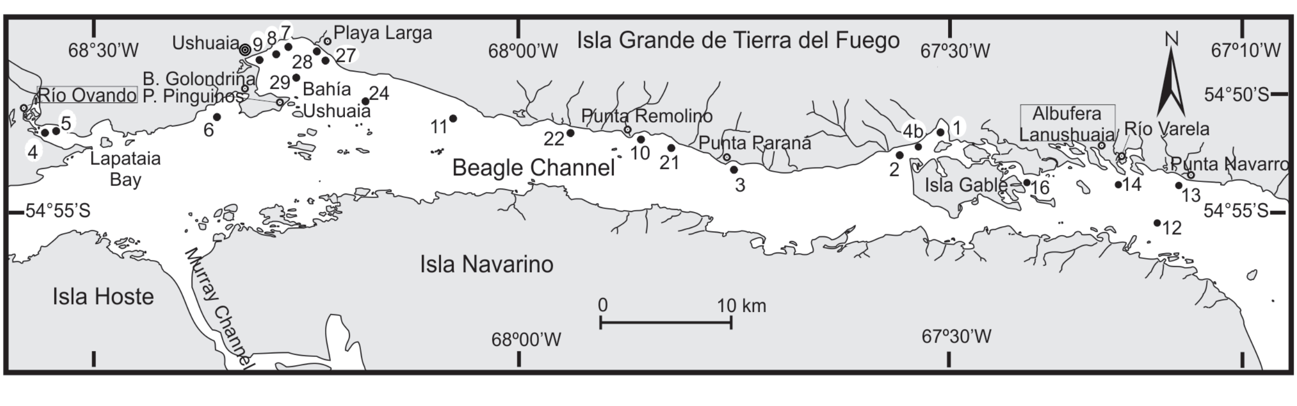



**Figure 2**. Detailed map of the Beagle Channel region and location of the surface sediment samples.

TABLE 2. **Aquatic palynomorphs identified in surface sediments from the Beagle Channel area (modified after Candel *et al.*, 2012). BL,** Bahía Lapataia; **BG,** Bahía Golondrina; **BU,** Bahía Ushuaia; **PR,** Punta Remolino; **PP,** Punta Paraná; **IG,** Isla Gable; **EIG,** External Isla Gable.

| *Sector* | *WESTERN* | *CENTRAL* | *EASTERN* |
|---|---|---|---|
| *Sampling sites* | *BL, BG, BU* | *PR, PP* | *IG, EIG* |
| *Dinocysts* | | | |
| **Brigantedinium cariacoense** *(Wall 1967) Lentin and Williams 1993* | | x | x |
| **Brigantedinium simplex** *Wall 1965 ex Lentin and Williams 1993* | x | x | x |
| **Brigantedinium** *spp.* | x | x | x |
| *Dinocyst sp. 1* | x | x | x |
| **Dubridinium** *cf.* **D.** *sp. Reid 1977* | x | | x |
| **Echinidinium** *cf.* **E. delicatum** *Zonneveld 1997* | x | x | x |
| **Echinidinium granulatum** *Zonneveld 1997* | x | x | x |
| **Echinidinium** *cf.* **E. granulatum** *Zonneveld 1997* | x | x | x |
| **Echinidinium** *spp.* | x | x | x |
| **Islandinium? cezare** *(de Vernal* et al. *1989 ex de Vernal in Rochon* et al. *1999) Head* et al. *2001* | x | x | x |
| **Islandinium minutum** *(Harland and Reid in Harland* et al. *1980) Head* et al. *2001* | x | x | x |
| **Pentapharsodinium dalei** *Indelicato and Loeblich III 1986* | x | x | x |
| **Polykrikos kofoidii** *Chatton 1914* | x | x | x |
| **Polykrikos schwartzii** *Bütschli 1873* | x | x | x |
| *Protoperidinioids* | x | x | x |
| **Quinquecuspis concreta** *(Reid 1977) Harland 1977* | x | x | x |
| **Selenopemphix nephroides** *(Benedek 1972) Benedek and Sarjeant 1981* | x | x | x |
| **Selenopemphix quanta** *(Bradford 1975) Matsuoka 1985* | x | x | x |
| **Selenopemphix** *cf.* **S. quanta** *(Bradford 1975) Matsuoka 1985* | x | x | x |
| **Spiniferites lazus** *Reid 1974* | x | | |
| **Spiniferites ramosus** *(Ehrenberg 1838) Mantell 1854 sensu lato* | x | x | x |
| **Spiniferites** *cf.* **S. mirabilis** *(Rossignol 1964) Sarjeant 1970* | | | x |
| **Spiniferites** *sp.* | x | | |
| **Spiniferites** *spp.* | x | x | x |
| **Trinovantedinium** *cf.* **T. applanatum** *(Bradford 1977) Bujak and Davies 1983* | x | x | |
| **Votadinium calvum** *Reid 1977* | x | x | x |
| **Votadinium spinosum** *Reid 1977* | x | x | x |
| *Dinocyst species diversity* | *17* | *16* | *17* |
| *Acritarchs* | | | |
| *Acritarch sp. 1* | | x | x |
| *Acritarch sp. 2* | | x | |
| *?***Cyclopsiella** *sp.* | | x | |
| **Halodinium** *sp.* | x | x | x |
| *Zoomorphs* | | | |
| *Copepod eggs* | x | x | x |
| *Foraminiferal linings* | x | x | x |
| *Other algae* | | | |
| **Botryococcus braunii** *Kützing 1849* | x | | |
| **Botryococcus** *sp.* | x | x | x |
| *Zygnemataceae* | x | | x |
| **Spirogyra** *sp.* | | x | |
| *Tasmanaceae* | x | | |
| **Radiosperma corbiferum** *Meunier 1910* | x | x | x |
| **Polyasterias** *sp.* | x | x | x |
| *Other aquatic palynomorphs diversity* | *8* | *10* | *8* |

## PALAEOENVIRONMENTS AND PALAEOCLIMATIC RECONSTRUCTION DURING THE HOLOCENE TRANSGRESSION IN TIERRA DEL FUEGO

### *Holocene times*

The Early Holocene after 11,500 cal yr BP was characterized by a significant increase in temperature coinciding with the onset of the Antarctic Climate Optimum (Bentley *et al.*, 2009). The increasing temperature and lower levels of effective moisture than today would have favored the establishment of an open *Nothofagus* woodland in southern Tierra del Fuego (Beagle Channel area), with high fire frequency (Heusser, 1998; Markgraf and Huber, 2010); while steppe environments remained in central Tierra del Fuego (Fagnano Lake area) until *ca.* 9,500 cal yr BP (Musotto *et al.*, 2016a). Nowadays, a similar pattern of vegetation belonging to the steppe/forest ecotone and steppe is observed in the central and north sector of the island, respectively, with precipitations less than 500 mm $yr^{-1}$ and summer temperature between 11–12 °C (Tuhkanen, 1992). This climatic scenario could have been induced by the migration of the westerlies winds toward higher latitudes, reduced Antarctic ice sheet and decrease of the thermal gradient between the poles and Ecuador (Markgraf and Huber, 2010).

This warm period was coincident with a transgressive event in Tierra del Fuego. The oldest marine levels identified into the Beagle Channel are located in the western sector: Bahía Lapataia (site 2, Fig. 1) at 8,478 cal yr BP (Rabassa *et al.*, 1986), Aserradero-Lapataia 2 (site 3, Fig. 1) at 8,408 cal yr BP (Rabassa *et al.*, 2009), and Lago Roca (Fig. 1) at 7,760 cal yr BP (Gordillo *et al.*, 1993). The ingression of marine waters generated deep and narrow fjords with complex archipelagos (Gordillo *et al.*, 1993). The Lago Roca-Lapataia area was a low energy, freshwater estuarine environment. The recorded mollusk association is represented by epibenthic taxa (mytilids and cirripeds) tolerant of estuarine conditions (Gordillo *et al.*, 1993; Gordillo, 1999). According with the mollusk assemblages, around 7,500 $^{14}C$ yr BP, the whole area turned into a fjord and Río Ovando (site 4, Fig. 1) and Lago Roca sites became in shallow-marine environments (Gordillo *et al.*, 2005). The mollusk assemblages indicate that the northern coast of the Beagle Channel was occupied by shallow benthic palaeocommunities during the Holocene (Gordillo, 1999; Gordillo *et al.*, 2005). Postglacial mollusk assemblages from the Beagle Channel are similar to current mollusk associations living in the region. Therefore, it was inferred that the climatic conditions remained stable enough to allow the development of these marine faunal associations with a wide ecological range (Gordillo, 1999).

In the northeastern Atlantic coast at the La Misión locality (site 1, Figs. 1 and 7), a sediment core located circa 3.5 km from the present shore, holds marine sediments dated between 8,720 $^{14}C$ yr BP and 270 $^{14}C$ yr BP (Markgraf, 1983, 1993). Changes in Chenopodiaceae pollen, diatoms and ostracodes provided a history of the sea-level variation. The marine sediments are clays with high percentages of Chenopodiaceae pollen and an abundance of diatom and ostracode taxa with brackish to coastal marine affinities (Markgraf, 1980, 1993). During the marine transgression, the vegetation was represented by a relatively open *Nothofagus* forest at *ca.* 8,000 $^{14}C$ yr BP. This forest environment continued with only minor changes until after 1,000 $^{14}C$ yr ago, when the steppe expanded again (Markgraf, 1993).

### *Early to Mid-Holocene marine palynomorph assemblages*

Between *ca.* 8,200 and 5,500 cal yr BP the palynological analysis showed for the Bahía Lapataia locality in western the Beagle Channel (site 2, Figs. 3 and 7) the presence of marginal-marine environments with a predominance of terrestrial palynomorphs over marine palynomorphs indicating an important freshwater input. Two relatively higher sea levels were identified by the increased abundance of marine palynomorphs; the first was observed between 8,478 cal yr BP and the second after 5,978 cal yr BP (Borromei and Quattrocchio, 2007). The marine palynomorphs were characterized by a poor dinoflagellate cyst assemblage dominated by Peridiniales taxa (*Brigantedinium* spp. and *Selenopemphix* sp.) over Gonyaulacales taxa (*Spiniferites* spp. and *Operculodinium centrocarpum* Deflandre and Cookson 1955 *sensu* Wall 1967) (Fig. 6). The acritarch *Halodinium* sp. and zoomorphs, such as foraminiferal linings and copepod eggs, were abundant. This marine palynomorph assemblage reflects an inner estuarine environment with low and variable salinities and/or turbulence, cool-temperate sea water temperature and abundance of dissolved nutrients caused by freshwater runoff (Borromei and Quattrocchio, 2001, 2007). Likewise, the palynological record from Aserradero-Lapataia 2 (site 3) showed at 8,408 cal yr BP a dominance of arboreal *Nothofagus* pollen associated with shrubs and herbs. The aquatic palynomorph assemblage consisted of dinoflagellate cysts (mainly *Brigantedinium simplex* Wall 1965 ex Lentin and Williams 1993, *Echinidinium granulatum* Zonneveld 1997, *Selenopemphix quanta*, *Polykrikos schwartzii* Bütschli 1873, among others) which showed an increasing diversification from the middle to upper part of the section, acritarchs (*Halodinium* sp., *Palaeostomocystis fritilla* Bujak 1984, and *P. subtilitheca* Roncaglia 2004), foraminiferal linings, copepod eggs and freshwater to brackish-marine algae (Candel and Louwye, 2015). The low dinoflagellate cyst species diversity could indicate the development of low-salinity environments affected by glacier meltwater discharge. These environments persisted at least several years, as the influence of seawater was expanding by global eustatic rise (Candel and Louwye, 2015).

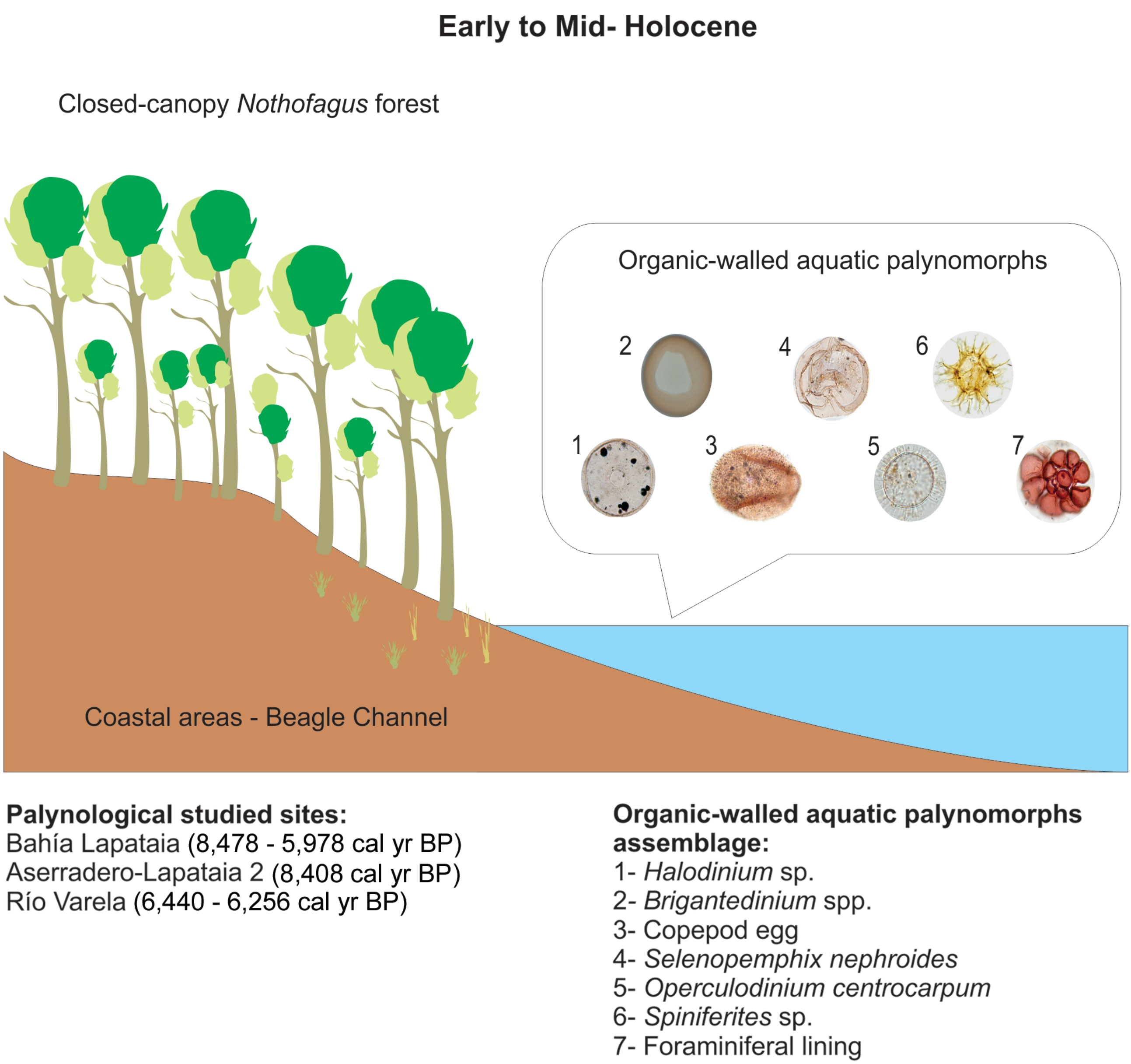



**Figure 3**. Evolutionary coastal model during the Early and Mid-Holocene of the Beagle Channel.

East of Beagle Channel, more precisely at Río Varela locality (site 7, Figs. 1, 3 and 7) 100 km to the east of Bahía Lapataia site, two marine levels were identified. The first level was recorded at the base of the sequence at 6,440 cal yr BP (Units 1-2: 1.60 m depth), and the other marine level at 6,256 cal yr BP (Unit 4: 1.27 m depth) (Grill *et al*., 2002). Unit 1 holds a microplankton assemblage constituted by Protoperidiniaceae dinocysts (*Brigantedinium* spp. and *Selenopemphix nephroides* (Benedek 1972) Benedek and Sarjeant, 1981), the acritarch *Halodinium* sp., copepod eggs and foraminiferal linings. These palynomorphs indicated a nearshore and low-energy environment with high nutrients supply, low salinity and cooler sea water temperature. In Unit 2 the record of Gonyaulacales dinocysts (*Spiniferites* sp. and *Operculodinium centrocarpum;* Fig. 6), accompanied with a decrease in *Halodinium* sp. and zoomorphs, suggested external neritic-marine conditions. Towards 6,256 cal yr BP (Unit 4) the presence of heterotrophic dinocysts (*Brigantedinium* spp. and *Selenopemphix nephroides*), *Halodinium* sp., and foraminiferal linings indicating a marine environment with nutrient-rich waters, variable salinity and high fluvial input (Grill *et al*., 2002). The organic matter content in sediments from Río Varela was mainly characterized by amorphous organic matter (AOM) related to degraded plankton and associated with pyrite, indicating anoxic marine conditions (Grill *et al*., 2002).

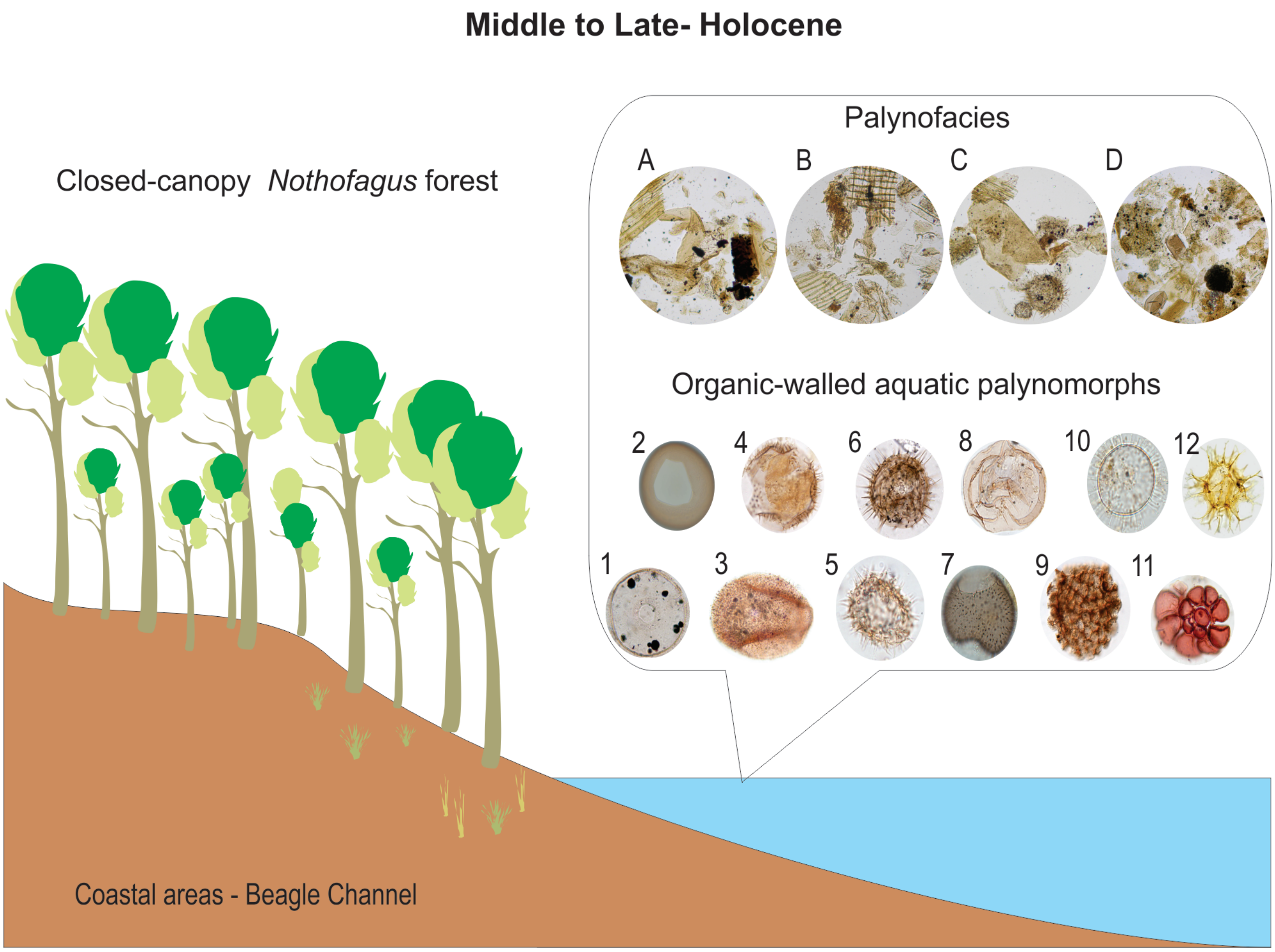
The pollen records revealed in coastal areas, prior to the transgressive event, the development of the forest-steppe ecotone in concordance with the regional vegetational pattern (Borromei and Quattrocchio, 2008). However, at the time of the marine incursion the coastal vegetation in the Beagle Channel area was mainly arboreal characterised by a significant increase in *Nothofagus* pollen, suggesting high effective moisture due to the moderating action of the sea (Grill *et al*., 2002; Borromei and Quattrocchio, 2007, 2008).

### *Middle to Late Holocene marine palynomorph assemblages*

The climate changed towards colder and wetter conditions after *ca*. 6,000 cal yr BP, and favored the regional expansion of a closed-canopy *Nothofagus* forest, the replacement of minerotrophic fens to ombrotrophic *Sphagnum* bogs, and the decrease in fire activity (Heusser, 2003; Markgraf and Huber, 2010; Musotto *et al*., 2016a, in press). In coastal areas, significant percentages of *Nothofagus* pollen recorded throughout the profiles suggested the presence of a closed-canopy forest, confirming the existence of a cool and wet climate (Candel *et al*., 2009, in press). These climatic conditions could be related with the increased strength and enhanced seasonal cycle of the westerlies (Markgraf and Huber, 2010).

Low concentration and diversity of dinocysts (9 identified taxa) were recorded in the eastern sector of Beagle Channel, at Albufera Lanushuaia (site 6, Figs. 1, 4 and 7). Between 5,916 cal yr BP and 5,713 cal yr BP, the dinocysts assemblage showed low diversity species (*Brigantedinium* spp., *Echinidinium* spp., *Islandinium minutum* (Harland and Reid in Harland *et al*., 1998) Head *et al*. 2001, *Dubridinium* sp. Reid 1977, *Selenopemphix nephroides*, round brown cysts, and indeterminate proximochorate dinocysts) suggested a marginal-marine environment with low to moderate salinity and high nutrients concentration in the surface waters, probably due to the contribution of freshwater runoff. After 5,713 cal yr BP, a slight increase in species diversity and a decrease in the concentration of the dinocysts were observed. The assemblage included *Brigantedinium* spp., *Echinidinium* spp., *Selenopemphix quanta, Selenopemphix* cf. *S. quanta*, *Votadinium spinosum* Reid 1977, *Polykrikos kofoidii* Chatton 1914, *Polykrikos schwartzii*, round brown cysts, and indeterminate proximochorate dinocysts (Fig. 6). The assemblage suggested environmental conditions similar to the beginning of this sedimentary sequence. However, the presence of species such as *P. kofoidii*, *P. schwartzii,* and *V. spinosum* could indicate a marine environment with normal salinity above 30 psu (Candel, 2010; Candel *et al*., 2011). The palynofacies analysis showed a dominance of translucent phytoclasts accompanied by amorphous organic matter and palynomorphs. Thus, the organic constituents indicated the proximity of a continental source to the marine environment, with relatively short distances and/or times of transport. The predominance of translucent phytoclasts associated with pyrite suggested reducing conditions, probably related to marginal-marine environments (Candel *et al*., 2011).

At the western sector of the Beagle Channel, the palynological analysis of Río Ovando (site 4, Figs. 4, 7) showed the dominance of terrestrial (pollen grains and spores) over aquatic palynomorphs (dinocysts, acritarchs, foraminiferal linings, copepod eggs and other algae) during the Middle Holocene. Towards 3,929 cal yr BP, a relatively high species diversity of 10 identified taxa and a low concentration of dinocysts were recorded. The identified dinocysts assem-



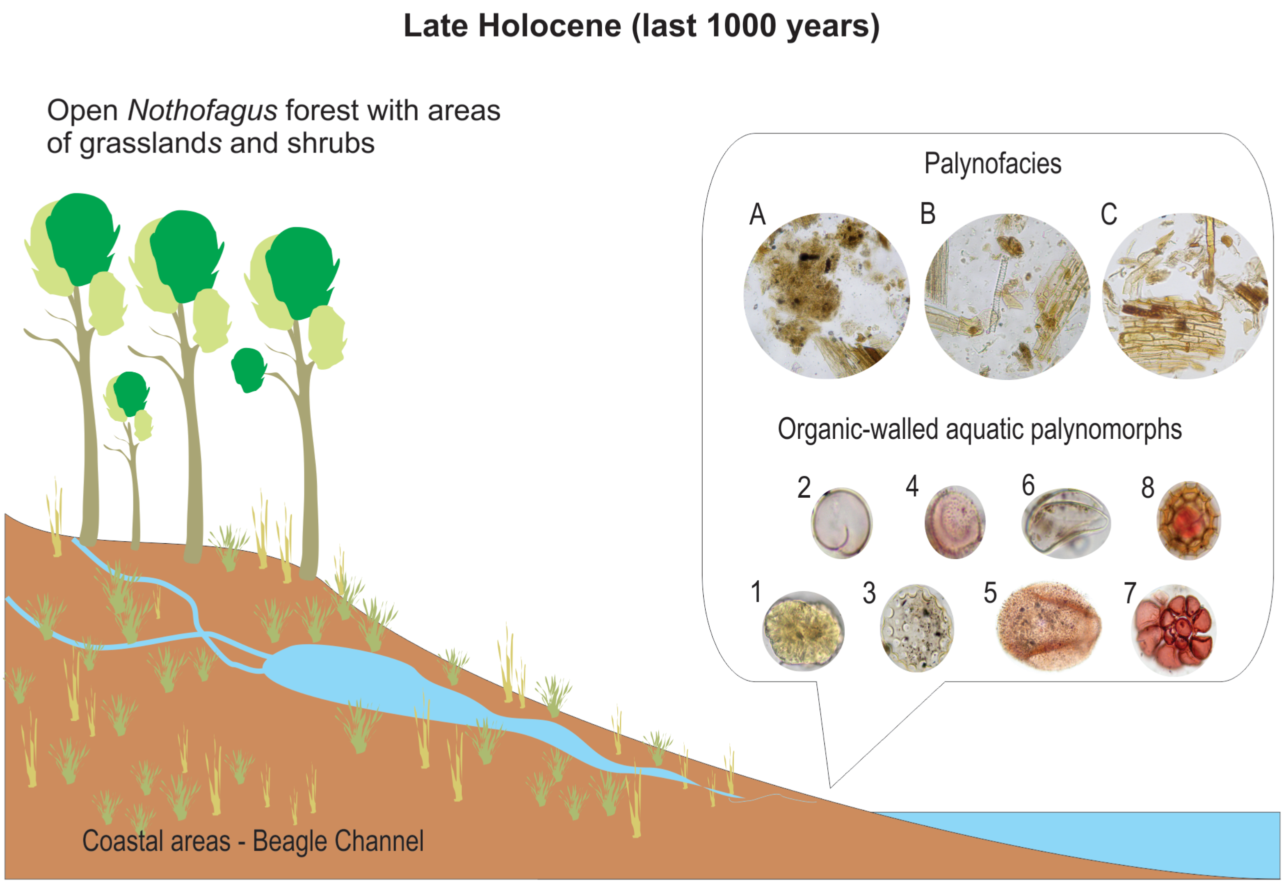

**Palynological studied sites:**
Albufera Lanushuaia: 6,000 - 5,713 cal yr BP
Río Ovando: 3,929 - 3,797 cal yr BP
Arroyo Baliza: 3,499 - 2,595 cal yr BP

**Particulate organic matter constituents:**
A-B. Palynofacies with detail of biostructure translucent phytoclasts (BPh) and non-biostructure translucent phytoclasts (nBPh), palynomorphs (Pollen) and pyrite (Py).
C-D. Palynofacies with detail of non-biostructure translucent phytoclasts (nBPh), amorphous organic matter (AOM) and dinocysts (D).

**Organic-walled aquatic palynomorphs assemblage:**
1- *Halodinium* sp.
2- *Brigantedinium* spp.
3- Copepod egg
4- *Islandinium minutum*
5- *Echinidinium granulatum*
6- *Selenopemphix quanta*
7- *Votadinium spinosum*
8- *Selenopemphix nephroides*
9- *Polykrikos schwartzii*
10- *Operculodinium* cf. *O. centrocarpum*
11- Foraminiferal lining
12- *Spiniferites* sp.

**Figure 4**. Evolutionary coastal model during the Middle and Late Holocene of the Beagle Channel.

blage (*Islandinium minutum*, *Islandinium* cf. *I. minutum*, *Echinidinium* spp., accompanied by *Brigantedinium* spp., *Polykrikos kofoidii*, *Polykrikos schwartzii*, *Operculodinium* cf. *O. centrocarpum*, and *Selenopemphix quanta*) (Fig. 6) suggested a marginal-marine environment with low to moderate salinity and high concentrations of nutrients in the sea surface waters,

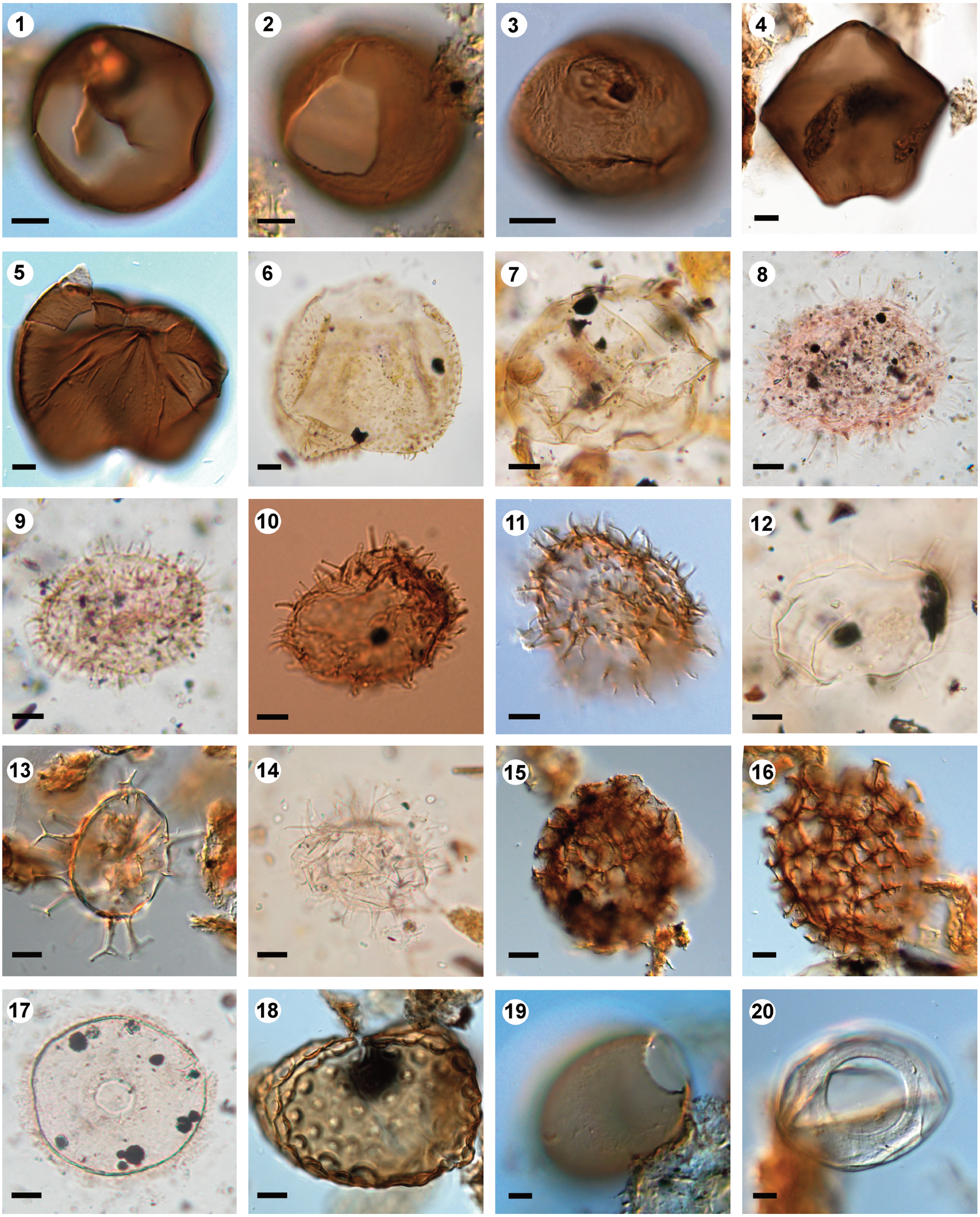



**Palynological studied sites:**
Río Ovando: after 3,797 cal yr BP (Palynological Zone RO-1, Candel *et al.*, 2009)
Albufera Lanushuaia: after 1,958 cal yr AD (Palynological Zone AL-1, Candel *et al.*, 2011)

**Organic-walled aquatic palynomorphs assemblage:**
1. *Botryococcus* sp.
2. *Sigmopollis* sp.
3. *Zygnema* sp.
4. 181 type (van Geel)
5. Copepod egg
6. *Spirogyra* sp.
7. Foraminiferal lining
8. *Cymatiosphaera* sp.

**Particulate organic matter constituents:**
A. Palynofacies with detail of biostructure translucent phytoclasts (Bph) and non-biostructure translucent phytoclasts (nBPh), together with amorphous organic matter (AOM).
B. Palynofacies detail (FtB) of biostructure translucent phytoclasts (Bph) and non-biostructure translucent phytoclasts (nBPh).
C. Palynofacies biostructure translucent phytoclasts (Bph).

**Figure 5**. Evolutionary coastal model during the last 1,000 years of the Beagle Channel.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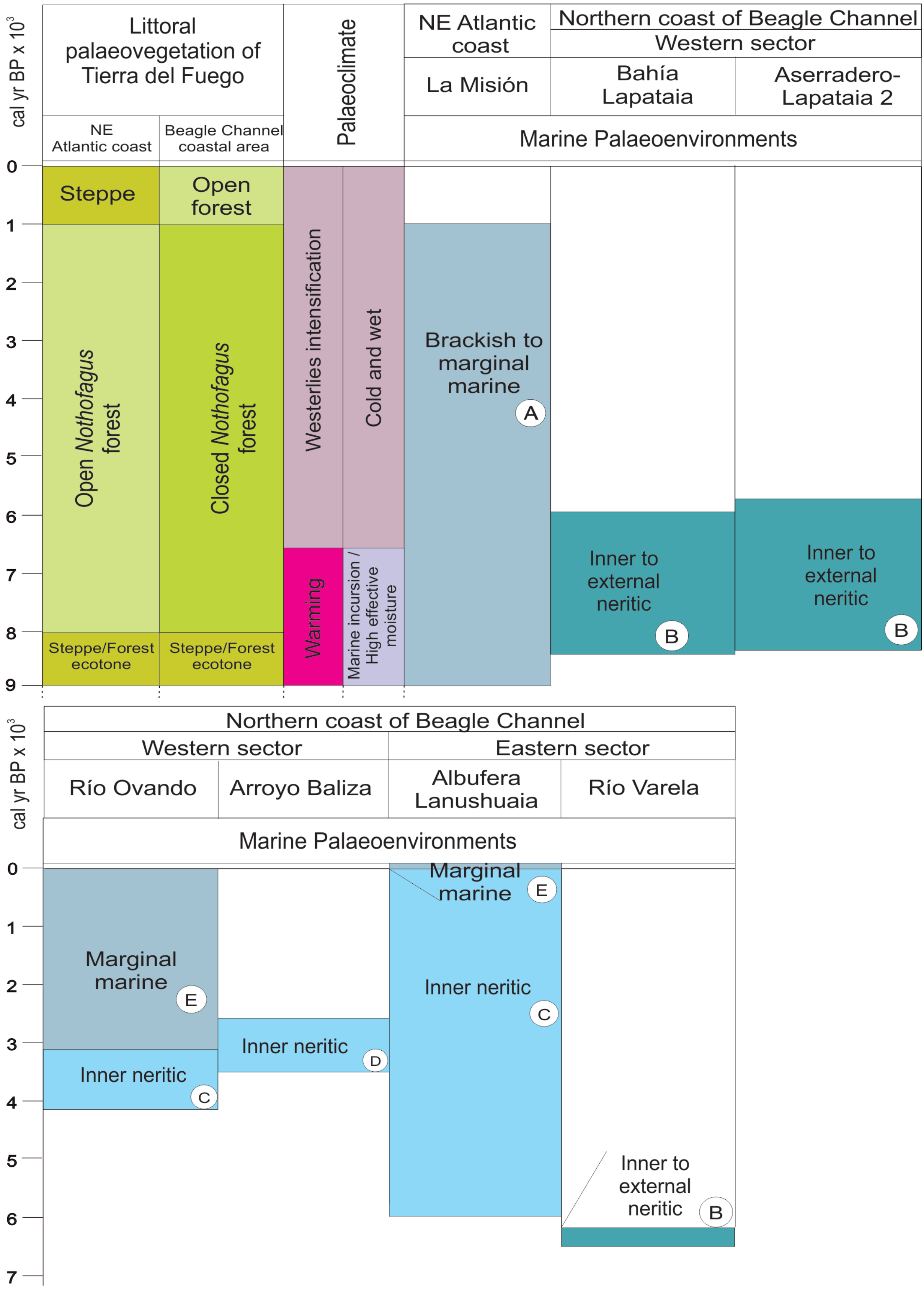
probably due to the contribution of freshwater by runoff (Candel, 2010). This diversification of species was also supported by data from mollusks confirming that during this period a major expansion took place of the fauna through a diversification of mollusk assemblages characterized by *Tawera gayi*, *Venus antiqua*, *Hiatella solida*, *Trophon geversianus*, *Xymenopsis muriciformis*, *Pareuthria plumbea*, *Laevilitorina*, *Neolepton*, *Carditella naviformis*, and *Cyclocardia compresa*. This indicates a change to present-day conditions. Most of these species could have survived the neoglacial episodes (Gordillo *et al.*, 2005). A dinocysts assemblage dominated exclusively by *Islandinium-Echinidinium* complex was recorded between 3,929 and 3,797 cal yr BP, showing the greatest abundance but lower diversity of dinocysts. This assemblage might indicate the occurrence of 'opportunistic species' suggesting a high input of freshwater by surface runoff. The low diversity of microplankton associations may be indicative of stressed, restricted conditions with often unstable salinities (Gorin and Steffen, 1991). According to Sluijs (2006), the sediments deposited under low-oxygen conditions show reduced cyst diversities and high abundance of a single species. The low dinoflagellate production suggested by the sparse dinocyst occurrences may be related to low and variable salinities and/or turbulence which inhibits dinoflagellate production (de Vernal and Giroux, 1991). At the same time, the replacement of a varied mollusk assemblage, characterized by venerids and other bivalves including mollusks, gastropods and chitons, by an almost monospecific assemblage (*Mytilus* Hupé in Gay 1854 and *Hiatella* Sowerby 1834) tolerant to low or variables salinities suggested a high seasonal freshwater input by river discharge and/or glacial meltwater (Candel *et al.*, 2009). The interval between 3,797 and 3,164 cal yr BP was characterized by an increase of the species diversity and a decrease of the dinocysts concentration. The assemblage composed by *Echinidinium granulatum, Echinidinium delicatum* Zonneveld 1997*, Echinidinium* spp., *Islandinium minutum*, accompanied by *Selenopemphix* spp., *Brigantedinium simplex,* cf. *Pentapharsodinium dalei*, and *Spiniferites* spp., suggested environmental conditions comparable with those at the beginning of the sequence (Candel *et al.*, 2009; Candel, 2010). The palynofacies analysis of Río Ovando showed high frequencies of mostly translucent phytoclasts associated with sporomorphs and freshwater algae, suggesting high fluvial input into the marine environment with relatively short distances and/or times of transport, related to the proximity of a terrestrial source. Also, these samples showed low percentages of AOM content suggesting oxic to dysoxic conditions in the depositional environment with good to moderate bottom water ventilation (Roncaglia, 2004; Candel, 2010; Candel *et al.*, 2013).

In the same sector of the channel, the Arroyo Baliza section (site 5, Figs. 1, 4 and 7) (3,499–2,595 cal yr BP) is located closer to the previous locality (site 4), although with a more open geographic setting influenced by the open seawaters of the Beagle Channel. Consequently, the record from this section show that aquatic palynomorphs are represented by 18 dinoflagellate cyst taxa (mainly *Brigantedinium simplex*, *Brigantedinium* spp., *Polykrikos schwartzii*, *Echinidinium granulatum*, *Dubridinium* sp., *Polykrikos kofoidii*, *Selenopemphix nephroides*, *S. quanta* and *Islandinium cezare* (de Vernal *et al*. 1989 ex de Vernal in Rochon *et al*. 1999) Head *et al*., 2001. The acritarchs *Halodinium* sp., *Palaeostomocystis fritilla, P. subtilitheca* and *P.* sp1 (Fig. 6) are also

**Figure 6.** Photomicrographs of the main aquatic palynomorphs identified in fossil marine sediments from the Beagle Channel. Scale bar is 10 μm. Sample number followed by England Finder coordinates. **1,** ***Brigantedinium cariacoense*****, LGC AB25-B25/2** (in Candel *et al.*, in press); **2,** ***Brigantedinium simplex*****, LGC AB9-A33/2**; **3**, ***Dubridinium*** sp., **LGC AB22-S20/3** (in Candel *et al.*, in press); **4,** ***Quinquecuspis concreta*****, LGC AB5-P35/4** (in Candel *et al.*, in press); **5,** ***Votadinium calvum*****, LGC AB21-V25** (in Candel *et al.*, in press); **6,** ***Votadinium spinosum*****, UNSP AL2638-Q47/4** (in Candel and Borromei, 2013); **7,** ***Selenopemphix nephroides,*** **UNSP BL1631a-C22/2** (in Candel and Borromei, 2013), **8,** ***Selenopemphix quanta,*** **UNSP RO1972b-M38/2** (in Candel *et al.*, 2009); **9,** ***Islandinium minutum,*** **UNSP RO1968-S14/2** (in Candel and Borromei, 2013); **10,** ***Islandinium cezare*****, LGC AB18-U20/1** (in Candel *et al.*, in press); **11,** ***Echinidinium granulatum*****, LGC AB11-W41** (in Candel *et al.*, in press); **12,** ***Operculodinium centrocarpum*****, UNSP RV1532a-F23/3** (in Candel and Borromei, 2013); **13,** ***Spiniferites ramosus*****, LGC AB1-Q24/4** (in Candel *et al.*, in press); **14,** ***Spiniferites*** sp., **UNSP BL843a-K53** (in Candel and Borromei, 2013); **15,** ***Polykrikos kofoidii*****, LGC AB4-M34/4** (in Candel *et al.*, in press); **16,** ***Polykrikos schwartzii*****, LGC AB4-O13** (in Candel *et al.*, in press); **17,** ***Halodinium*** sp., **UNSP RO1972c-R13** (in Candel *et al.*, 2009); **18,** ***Zygnema*** sp., **LGC AS19-H15/3**; **19,** ***Palaeostomocystis fritilla,*** **LGC AB12-J25/2**; **20,** ***Palaeostomocystis subtilitheca*****, LGC AB10-H11/1** (in Candel *et al.*, in press).


cal yr BP x 10³
Littoral palaeovegetation of Tierra del Fuego
NE Atlantic coast
Beagle Channel coastal area
Palaeoclimate
NE Atlantic coast
La Misión
Northern coast of Beagle Channel
Western sector
Bahía Lapataia
Aserradero-Lapataia 2
Marine Palaeoenvironments
Steppe
Open forest
Open Nothofagus forest
Closed Nothofagus forest
Steppe/Forest ecotone
Steppe/Forest ecotone
Westerlies intensification
Cold and wet
Warming
Marine incursion / High effective moisture
Brackish to marginal marine
A
Inner to external neritic
B
Inner to external neritic
B
cal yr BP x 10³
Northern coast of Beagle Channel
Western sector
Eastern sector
Río Ovando
Arroyo Baliza
Albufera Lanushuaia
Río Varela
Marine Palaeoenvironments
Marginal marine
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Inner neritic
C
Inner neritic
D
Marginal marine
E
Inner neritic
C
Inner to external neritic
B

present together with foraminiferal linings, copepod eggs and freshwater to brackish-marine algae (*Zygnema* sp., *Spirogyra* sp., *Cymatiosphaera* sp., *Tasmanites* sp.). The palynological records from the Arroyo Baliza site have a similar composition to those observed in surface samples from the Beagle Channel (Candel *et al*., 2012), with a higher diversity of dinoflagellate cyst species, suggesting that the environmental conditions during the late Holocene are comparable to today. It indicates that most of the marine species were able to persist in the area even during neoglacial climatic deterioration (Candel *et al*., in press). A preliminary palynofacies analysis of Arroyo Baliza showed a dominance of translucent phytoclasts, mainly non-structured, degraded and pale in colour, with some of them in transition to amorphous organic matter (Rabassa *et al*., 2009). The high numbers of translucent phytoclasts indicate the proximity of a continental source to the marine depositional environment and thus a relatively short transportation time.

### *Late Holocene marine palynomorph assemblages*

Palaeoclimatic records from southern South America during the last 1,000 cal yr BP, indicate a general trend of decreasing temperature (reduced insolation) and an increase in the westerly winds intensity, culminating with the Little Ice Age event (*ca.* 600–100 yr BP) (Moy *et al*., 2009). Marine records from the Chilean continental shelf (41°S) show cooling surface seawater temperature about ~1.5° C (Lamy *et al*., 2001) and ~1° C (Mohtadi *et al*., 2007) from 2,000 cal yr BP culminating in the last 100 years, probably due to the northward shift in the Antarctic Circumpolar Current and the westerly winds (Moy *et al*., 2009).

The uppermost section in Río Ovando (site 4, Figs. 5 and 7) recorded a decrease in the *Nothofagus* and an increase in grass and shrub associated with an increase of Prasinophyceae (*Cymatiosphaera* (Wetzel) Deflandre 1954) and Zygnemataceae (*Spirogyra* Link 1820) algae. This palynomorph assemblage suggested the development of an open *Nothofagus* forest with areas of grassland and shrubs, with river discharge to the marine environment indicated by the occurrence of freshwater to brackish aquatic palynomorphs related to a sea-level regressive event (Candel, 2010).

On the other hand, eastwards in Beagle Channel, at Albufera Lanushuaia (site 6, Figs. 5 and 7) showed similar conditions after 1958 cal yr AD to those observed in the uppermost section of Río Ovando. The development of an open forest of *Nothofagus* is accompanied with an increase in herb-shrub vegetation and by an increase in copepod eggs and foraminiferal linings reflecting the proximity of marine environments (Candel *et al*., 2011).

## FINAL REMARKS

The Early Holocene climatic amelioration, following by a deglaciation, was accompanied by a marine transgression in Tierra del Fuego. During the marine incursion the vegetation in the coastal areas along the Beagle Channel was mainly arboreal with a dominance of a *Nothofagus* forest and scarcity of shrub and herbaceous communities indicative of high effective moisture conditions caused by the moderating action of the sea. Also, in the northeastern Atlantic coast the treeless steppe was replaced by a relatively open *Nothofagus* forest at times of the Holocene marine transgression. The cold and wet conditions during the Middle to Late Holocene favored the regional expansion of a closed-canopy *Nothofagus* forest. During the last 1,000 years BP, the littoral vegetation along the Beagle Channel

**Figure 7.** Palaeoenvironmental correlation of the Holocene marine deposits from Tierra del Fuego. **A,** Diatoms: ***Melosira sulcata***, ***Actinoptychus undulatus***, ***Hyalodiscus***. Ostracodes: ***Loxoreticulatum fallax, Loxocythere*** sp., ***Cytherura***, ***Cytheromorpha***, ***Perissocytheridea***. **B,** Organic-walled dinocyst assemblage: ***Brigantedinium*** spp., ***Selenopemphix nephroides***, ***S. quanta***, ***Polykrikos schwartzii***, ***Spiniferites*** sp., ***Operculodinium centrocrapum.*** **C,** Organic-walled dinocyst assemblage: ***Brigantedinium*** spp., ***Islandinium minutum***, ***Echinidinium*** spp., ***Selenopemphix nephroides***, ***S. quanta***, ***Votadinium spinosum***, ***Polykrikos kofoidii***, ***P. schwartzii***, cf. ***Pentapharsodinium dalei***, cf. ***Dubridinium*** sp. **D,** Organic-walled dinocyst assemblage: ***Brigantedinium cariacoense***, ***B. simplex***, ***Dubridinium caperatum***, ***Echinidinium delicatum***, ***E. granulatum***, ***Islandinium cezare***, ***I. minutum***, cyst of ***Pentapharsodinium dalei***, ***Polykrikos schwartzii***, ***P. kofoidii***, ***Quinquecuspis concreta***, ***Selenopemphix nephroides***, ***S. quanta***, ***Trinovantedinium applanatum***, ***Votadinium calvum***, ***V. spinosum***, ***Operculodinium centrocarpum***, ***Spiniferites ramosus***. **E,** Aquatic palynomorphs assemblage: foraminiferal linings, copepod eggs, Prasinophyceae and Zygnemataceae.

coast was characterised by an open *Nothofagus* forest and the development of peatlands, while in the northeastern Atlantic coast the steppe vegetation developed under less humid environmental conditions related to a regressive event.

The Holocene marine sediments were characterized by marine palynomorph assemblages dominated by Peridiniales taxa that suggested the development of low energy estuarine environments with low-salinities due to glacier meltwater discharge. These environments would have persisted as the influence of seawater was expanding by global eustatic rise. The increasing salinity was accompanied by an increase in biodiversity in both dinoflagellate cysts and mollusks assemblages.

The marine assemblages recorded in the Middle and Late Holocene sediments (Albufera Lanushuaia, Río Ovando, and Arroyo Baliza sites) showed greater species diversity of dinocysts than those identified in the marine deposits of Early to Mid-Holocene age (Bahía Lapataia and Río Varela sites). This species diversification suggests an increase in marine palaeoproductivity caused by the input of terrigenous nutrients by water runoff probably related to a precipitation increase. Palaeoclimatic evidence from Tierra del Fuego show an increase in precipitation after *ca*. 6,000 yr BP caused by an intensification and/or latitudinal migration of the Westerlies (Markgraf and Huber, 2010).

The Late Holocene marine assemblages have a similar composition to those observed in the surface samples from the Beagle Channel. A higher diversity of dinocyst species was observed in comparison to the Early Holocene assemblages, suggesting palaeoenvironmental conditions comparable to today in the Beagle Channel. Probably, most of the marine species were able to persist in the area even during minor climatic fluctuations.

The palynofacies analysis indicates continental supply to marine environments coming from nearby sectors, and without significant transport. The dominance of translucent phytoclasts associated with pyrite suggests reducing conditions, probably related to marginal-marine environments. Also, high frequencies of AOM indicate the proximity of a terrestrial source with high organic matter input into the aquatic environment combined with favorable conditions for bacterial action.

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This work is dedicated to Prof. Dr. Mirta Elena Quattrocchio, who the authors considered as their "scientific mother". We would like to give a special tribute to Mirta for being a figurehead woman in the field of Argentinian Palynology, a model for generations of young Palynologists in Argentina (and elsewhere), especially in marine and terrestrial studies of Mesozoic and Cenozoic. The authors are also grateful to Marcelo A. Martínez and Lorena L. Musotto (INGEOSUR-CONICET, Universidad Nacional del Sur, Argentina), Juan Federico Ponce and Andrea Coronato (CADIC-CONICET, Ushuaia, Argentina) for field assistance and contributing resources in the field work. We thank Marcelo A. Martínez and Daniela E. Olivera for invited us to contribute to this volume and for their editorial support, and also to two reviewers for their constructive comments that helped to improve our manuscript. This paper was funded by grants PIP 11220100100041 (CONICET) and PGI 24/H126 (Secretaría General de Ciencia y Tecnología, UNS).

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