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# Holocene sea-level change inferred from palynological data in the Beagle Channel, southern Tierra del Fuego, Argentina

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**Abstract.** An early-middle Holocene section in Bahía Lapataia (54º 50' S, 68º 34' W), Beagle Channel, Tierra del Fuego, Argentina has been examined taking into account its sporomorphs and organic-walled microplankton. The palynological assemblage suggests nearshore environments. Two relatively higher sea levels were identified by the increased abundance of organic-walled dinoflagellate cysts (*Brigantedinium* spp., *Selenopemphix* sp., *Operculodinium centrocarpum sensu* Wall and Dale, *Spiniferites* spp.), the acritarch *Halodinium* sp. and zoomorph remains (test linings of foraminifera and copepod egg-envelopes). The littoral vegetation at the time of the marine incursion was mainly arboreal, as can be seen in the pollen records by significant increase in *Nothofagus dombeyi* type frequencies, while a forest-steppe vegetational pattern developed regionally. After comparison with another nearby fossil marine terrace, the palynological analysis has demonstrated that these terraces represent the same transgressive-regressive event. The relative altitudinal differences between these terraces in the area may be the result of seismotectonic activity during the Holocene.

**Resumen.** CAMBIOS DEL NIVEL DEL MAR HOLOCENOS INFERIDOS A PARTIR DE DATOS PALINOLÓGICOS EN EL CANAL BEAGLE, SUR DE TIERRA DEL FUEGO, ARGENTINA. Se estudia una sección del Holoceno temprano-medio en Bahía Lapataia (54º 50' S, 68º 34' O), Canal Beagle, Tierra del Fuego teniendo en cuenta los esporomorfos y el microplancton. La asociación de microplancton sugiere ambientes cercanos a la costa. Son identificados dos niveles relativos de mar alto con las mayores abundancias de quistes de dinoflagelados (*Brigantedinium* spp., *Selenopemphix* sp., *Operculodinium centrocarpum sensu* Wall y Dale, *Spiniferites* spp.), del acritarco *Halodinium* sp. y restos de zoomorfos (caparazón de foraminíferos y huevos de copépodos). La vegetación del litoral durante la incursión marina fue principalmente arbórea, como puede observarse en los registros polínicos con un incremento significante de *Nothofagus* tipo *dombeyi*, mientras patrones vegetacionales de bosque-estepa se extendían regionalmente. Por comparación con una terraza marina cercana, el análisis palinológico ha demostrado que las dos terrazas representan el mismo evento transgresivo-regresivo. Las diferencias relativas altitudinales entre las terrazas podrían ser el resultado de la actividad sismotectónica durante el Holoceno.

**Key words.** Palynology. Paleoenvironment. Holocene transgression. Bahía Lapataia. Beagle Channel. Tierra del Fuego. Argentina.

**Palabras clave.** Palinología. Paleoambiente. Transgresión holocena. Bahía Lapataia. Canal Beagle. Tierra del Fuego. Argentina.

## Introduction

The Beagle Channel (54º 53' S, 67º-68º W) links the Atlantic and Pacific oceans, thus separating Isla Grande de Tierra del Fuego from the southern islands of the Fuegian archipelago (figure 1). It is a drowned glacial valley 5 km wide and 180 km long in a W-E trend located in the seismotectonically active area of the Fuegian Andes that was ice-covered during the Last Maximum Glaciation. Several Holocene raised beach deposits have been recognized along the northern coast of the Beagle Channel. These deposits are mostly sandy and gravelly, although clay-like sediments are found mainly in the westernmost sector of the Beagle Channel. The marine deposits are divided on the basis of their elevation above the present sea level and by radiocarbon dating, and at least three levels have been established at 8-10, 4-6 and 1.5-3 m above mean sea level (a.m.s.l.) (Gordillo *et al*., 1992). Several authors have debated the processes concerning the deposition of this marine sequence and the timing of sea-level changes along the coast of the Beagle Channel (Porter *et al*., 1984; Rabassa *et al*., 1986, 1989; Mörner,

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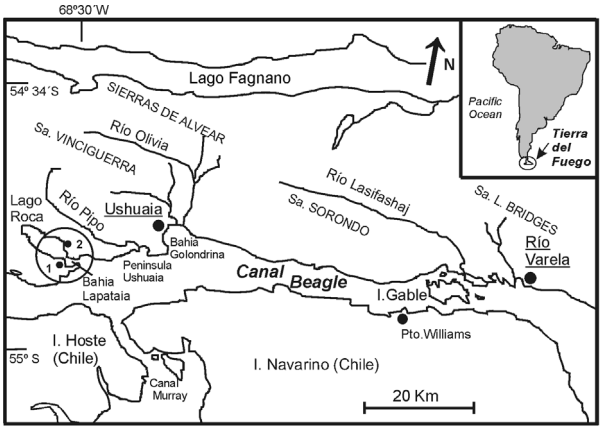


**Figure 1.** Location map of the area / *mapa de ubicación del área.*

1991; Gordillo *et al*., 1992). Taking into account the local glacial history, the oldest holocene coastal deposits may be partially the result of isostatic recovery and the younger levels have been caused by recent tectonic uplift (Rabassa *et al*., 2000).

The present climate is determined by a belt of prevailing humid and cold southern westerlies. Daily temperature in summer (January) at Ushuaia city averages 9.2° C and in winter (July) 1.6° C . Annual average temperature is 3.9° C and mean annual precipitation is 574 mm (Prohaska, 1976). The studied area is placed within the Subantarctic Deciduous Beech Forest formation (Pisano, 1977 ; Moore, 1983) characterized by three species of southern beech, *Nothofagus pumilio* (lenga) (Poepp. and Endl.) Krasser, *Nothofagus betuloides* (guindo) (Mirb.) Oerst. and *Nothofagus antarctica* (ñire) (Forst.) Oerst., which grows from the sea shore to an average altitudinal limit of 550-600 m a.s.l. and predominates where precipitation is between 400 and 800 mm/year.

The aim of this paper is to determine the depositional environment, vegetational changes, climatic conditions and eustatic fluctuations during the Holocene transgressive-regressive cycle at the Bahía Lapataia 2 site (54º 50′ S, 68º 34′ W, figure 1) using palynological analysis. Correlation with a studied section (Borromei and Quattrocchio, 2001) serves to assess the existence of tectonic activity in the Bahía Lapataia area.

Palynological studies of holocene marine sediments in the Beagle Channel region are few (e.g. Borromei *et al*., 1997; Borromei and Quattrocchio, 2001; Grill *et al*., 2002). The present study contributes to the understanding of the environmental conditions which took place during the Holocene transgression of the Beagle Channel area, Tierra del Fuego.

## Bahía Lapataia locality

Bahía Lapataia is a fjord-like embayment located about 20 km west of Ushuaia city, on the north coast in the westernmost end of the Beagle Channel, in the National Park of Tierra del Fuego. It is a typical glacial landscape that was submerged during the Holocene transgression resulting in deep and narrow fjords and intricate archipelagos. The regressive-transgressive cycle has generated several levels of marine deposits. These deposits are scattered along Bahía Lapataia up to the eastern shore of Lago Roca, including the Archipiélago Cormoranes area and both margins of Río Ovando and Río Lapataia (Gordillo *et al*., 1992) (figure 1).

At Bahía Lapataia two marine deposits separated by horizontal distance of 20 m, Bahía Lapataia 1 (Borromei and Quattrocchio, 2001) and Bahía Lapataia 2, can be observed. Their conventional (= uncorrected) radiocarbon ages and altitudes are summarized in table 1. A reservoir effect somewhere between 630 ± 70 yr (Albero *et al*., 1987; Beagle Channel) and 380 ± 100 yr (Angiolini and Fernández, 1984; Estrecho de Magallanes) should be taken into consideration for those radiometric analyses performed on marine shells. The dates of 8240 ± 60 $^{14}$C yr B.P. (1.65 m a.s.l.) from Bahía Lapataia 1 and 7518 ± 58 $^{14}$C yr B.P. (3.95 m a.s.l.) from the nearby Lago Roca (Gordillo *et al*., 1993) (figure 1) correspond to the oldest Holocene dates for the Beagle Channel, so the marine environment was fully established along the channel at this time. The transgressive episode may have peaked around 6000 $^{14}$C yr B.P. (Rabassa *et al*., 1986).

The holocene sequence at Bahía Lapataia 1 (Borromei and Quattrocchio, 2001) (1.04 m depth) unconformably overlies Paleozoic-Lower Mesozoic sediments belonging to the Lapataia Formation (Borrello, 1969). Five informal lithological units, separated by unconformities, have been identified (from base to top, Lithological Unit A to Lithological Unit E) (figure 2):

Lithological Unit A (104 - 100 cm). Ferruginous sandy clay with a radiocarbon date of 8580 ± 120 $^{14}$C yr B.P. (Rabassa *et al*., 1989).

Lithological Unit B (100 - 71 cm). Peat with fossil wood dated 7700 + 130 $^{14}$C yr B.P. and 7530 ± 398 $^{14}$C yr B.P., respectively (Rabassa *et al*., 1989).

Lithological Unit C (71 - 24 cm). Greenish sandy clay with marine shells dated 8240 ± 60 $^{14}$C yr B.P. (1.65 m a.s.l.) and 7260 ± 70 $^{14}$C yr B.P. (1.80 m a.s.l.) (Rabassa *et al*., 1986).

Lithological Unit D (24 - 12 cm). Ferruginous gravels and sandy gravels.

Lithological Unit E (12 - 0 cm). Peat and soil.

**Table 1.** Summary of published radiocarbon dates from marine terraces, Beagle Channel (conventional ages, localities, altitudes as reported by authors) / *resumen de los fechados radiocarbónicos publicados de las terrazas marinas, Canal Beagle (edades convencionales, localidades y altitudes según reporte de los autores).*

| Locality | Age ($^{14}$C yr B.P.) | Altitude (m a.s.l.) | Laboratory N° | Source |
|---|---|---|---|---|
| Lago Roca | 5920 + 90 | 8.40 | AC-1060 | Rabassa *et al*., 1986 |
| Lago Roca | 7518 + 58 | 3.95 | NZ-7730 | Gordillo *et al*., 1993 |
| Bahía Lapataia 1 | 7260 + 70 | 1.80 | SI-6738 | Rabassa *et al*., 1986 |
| | 8240 + 60 | 1.65 | SI-6737 | Rabassa *et al*., 1986 |
| Bahía Lapataia 2 | 5800 + 65 | 1.95 | SI-6739 | Rabassa *et al*., 1986 |
| Ushuaia | 5160 + 130 | 8 | AECV-876Cc | Gordillo *et al*., 1993 |
| Bahía Golondrina | 5460 + 110 | 10 | AECV-877Cc | Gordillo *et al*., 1993 |
| Punta Pingüinos | 5430 + 270 | 8.5 | L-1016C | Urien, 1966 |

At Bahía Lapataia 2 section (1.02 m depth) (this paper), four informal lithological units, separated by unconformities, are recognized (from base to top, Lithological Unit B to Lithological Unit E) (figure 3):

Lithological Unit B (> 92 cm). Black peat. Palynological sample: 17. Base not observed because it is below water level.

Lithological Unit C (92 - 45 cm). Greenish sandy clay with marine shells of *Mytilus* sp. dated 5800 ± 65 $^{14}$C yr B.P. (1.95 m a.s.l.) (Rabassa *et al*., 1986). Palynological samples: 16 to 2.

Lithological Unit D (45 - 10 cm). Ferruginous gravels and sandy gravels. Palynological sample: 1 (at 43 cm depth).

Lithological Unit E (10 - 0 cm). Peat and soil.

## Materials and methods

A total of 17 samples were collected, from the base at 1.02 m depth to the surface. All samples were processed for palynological analysis according to Heusser and Stock's techniques (1984). Following the procedure advocated by Dale (1976), the marine samples were treated with cold acids (HCl, HF) to preserve the organic-walled dinoflagellate cysts, and no oxidation and no acetolysis was applied in order to prevent the loss of more fragile protoperidiniacean cysts. All samples were stained with Safranin O, in accord with the Stanley's technique (Stanley, 1966). Exotic *Lycopodium* spores were added to allow calculation of palynomorph concentration per gram of dry weight of sediment (Stockmarr, 1971). The residue was sieved through a 10µm mesh to concentrate the palynomorphs.

To evaluate the biosphere components, the frequencies (%) of trees, shrubs and herbs were based upon counts between 200 and 350 grains; aquatic and cryptogam frequencies were from counts of total pollen and spores. To evaluate the terrestrial/marine environmental relationships and the sea level changes, the palynomorph (organic-walled dinoflagellate cysts, acritarchs, copepod egg-envelopes, test linings of foraminifera and tintinnomorphs) frequencies (%) were based on counts of total pollen and organic-walled microplankton.

Following Heusser (1998), *N. betuloides*, *N. pumilio* and *N. antarctica* are shown collectively as *Nothofagus dombeyi* type due to the impossibility of specific level differentiation. Another special case is *Empetrum rubrum* Vahl and *Gaultheria/Pernettya* (Ericaceae) which are morphologically similar. The later may sometimes have been included with *Empetrum* when its sculpture is not distinct.

Cluster analysis using Edwards & Cavalli-Sforza distance (Program TILIA, E. Grimm, 1991) was applied to the fossil assemblages. Taxa with percentages below 2% are excluded from the pollen sum.

The pollen/spore frequency (%) and total palynomorph frequency (%) at Bahía Lapataia 2 section are represented, respectively, in figures 3 and 4. From Unit C, the raw data, resulting from the organic-walled microplankton analysis, is given in Table 2, which shows the original counts and the numbers of dinoflagellate cysts, acritarchs and zoomorphs per gram of sediment recovered throughout the unit.

Microphotographies of the main marine palynomorphs from Unit C are showed in Borromei and Quattrocchio (2001).

## Results

Based on cluster analysis, four palynological assemblage subzones spanning the full sequence are distinguished at Bahía Lapataia 2 (figure 3). The identified pollen assemblages are correlated with Pollen Zone 2 (10,000 - 5000 yr B.P) of Heusser (1989). In order from the lower to the upper part of the sequence, the palynological subzone LP2-2b corresponds to Unit B and the palynological subzones LP2-2e to LP2-2g correspond to Units C and D.

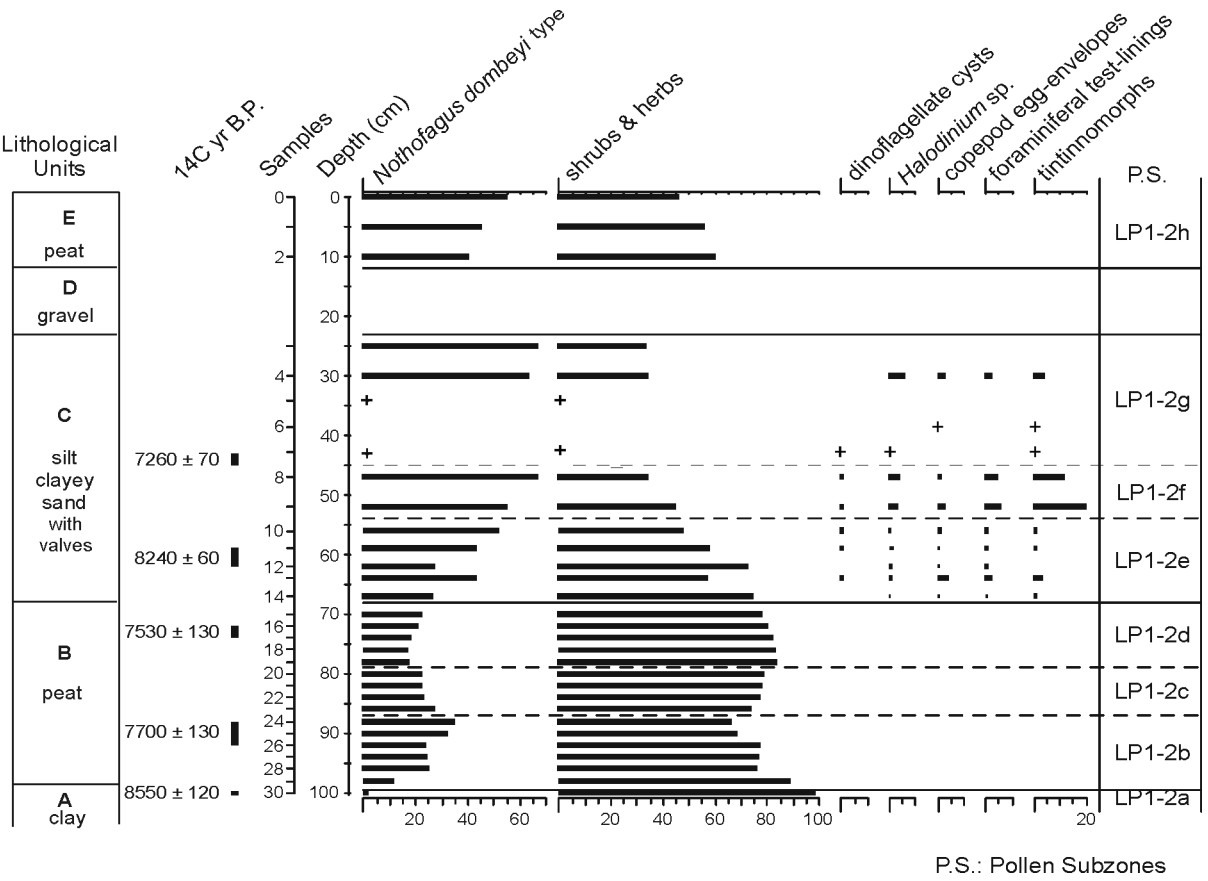


**Figure 2.** Palynomorph total frequency (%) at Bahía Lapataia 1 section (modified from Borromei and Quattrocchio, 2001) / *frecuencia total de palinomorfos (%) en la sección de Bahía Lapataia 1 (modificado de Borromei y Quattrocchio, 2001).*

Palynological Subzone LP2-2b is dominated by Polypodiaceae (58%), *Nothofagus dombeyi* type (33%), Asteroideae (26%) and Poaceae (14%). *Acaena* (9%), *Valeriana* (5%), *Empetrum*/Ericaceae (4%) and Cyperaceae (4%) are also present.

The total pollen concentration is 13412 grains/gram, with herb and shrub concentration values of 10371 grains/gram and tree concentration values of 4452 grains/gram.

At this subzone no organic-walled microplankton are recorded.

Palynological Subzone LP2-2e is characterized by increase of *Nothofagus dombeyi* type (62-73%), Poaceae (10-20%) and *Empetrum*/Ericaceae (4-11%), while Polypodiaceae (16-25%), although predominant in the pollen spectrum, decreases together with Asteroideae (3-10%).

The total pollen concentration decreases (1830-10696 grains/gram) with tree concentrations higher (1134-6379 grains/gram) than herb and shrub concentrations (662-4316 grains/gram).

The frequencies (<5%, figure 4) and concentration values (45-69 palynomorphs/gram, table 2) of organic-walled microplankton are low. In samples 14 and 13, the foraminiferal test-lining concentration values increase slightly (49 foraminifera/gram) indicating a marine environment.

Palynological Subzone LP2-2f dominated by *Nothofagus dombeyi* type (75-88%). There is a decreases in Poaceae (1-12%), Polypodiaceae (2-8%) and *Empetrum*/Ericaceae (3-5%).

The total pollen concentration is lower (654-1679 grains/gram) than for the previous subzone. Tree concentration values reach 560-1480 grains/gram, and herb and shrub concentration values, 94-348 grains/gram.

Marine palynomorph frequencies (figure 4) increase to maximum values in samples 9 and 8, and are characterized by *Halodinium* sp. (4-8%) and test linings of foraminifera (18-20%), respectively. At these levels, copepod egg-envelopes (4-1%) and dinoflagellate cysts (1-4%) are also recorded.

The greatest abundance and diversity of marine palynomorphs is also registered in samples 8 and 9 (table 2). Dinoflagellate cyst concentrations is 14 specimens/gram in sample 9 and 51 specimens/gram in sample 8. Species are represented by *Brigantedinium* spp., *Selenopemphix* sp. and *Spiniferites* spp. *Halodinium* sp. (94 specimens/gram) in sample 8, and zoomorphs (298-387 zoomorphs/gram), main-

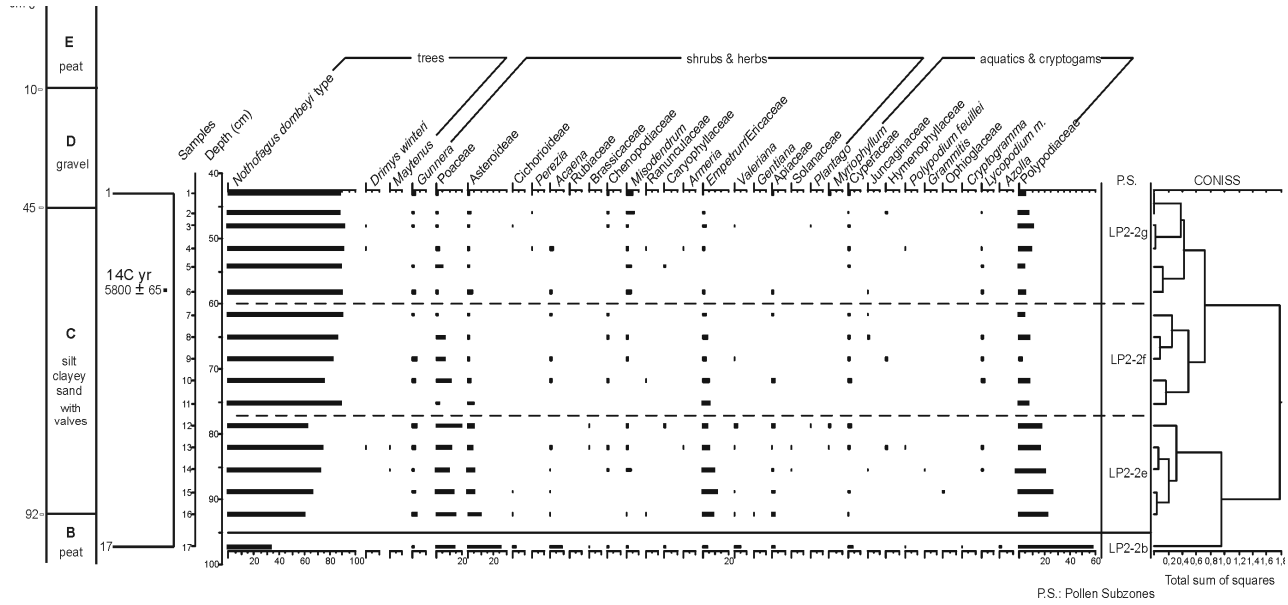


**Figure 3.** Pollen/spore frequency (%) at Bahía Lapataia 2 section / *frecuencia de polen/esporas (%) en la sección de Bahía Lapataia 2.*

ly test linings of foraminifera (232-262 foraminifera/gram) are accompanied by copepod egg-envelopes (52 copepods/gram) in sample 9.

Palynological Subzone LP2-2g is characterized by the predominance of *Nothofagus dombeyi* type (87-91%) accompanied by Polypodiaceae (3-10%). *Misodendrum* and Poaceae are found with percentage values of at least 5%.

The total pollen concentrations are still low (880-5190 grains/gram). Tree concentration values (786-4728 grains/gram) are higher than herb and shrub concentration values (93-443 grains/gram).

Beginning at the base of the subzone, marine palynomorph percentages are low (<5%) (figure 4). Higher up, they increase to a maximum in samples 5 and 4. *Halodinium* sp. (6-4%), copepod egg-envelopes (3-8%) and test linings of foraminifera (1-6%), are dominant. Dinoflagellate cysts are present in low percentages (1%). Marine palynomorph frequencies then decrease upwards in the subzone.

The greatest abundance and diversity of marine palynomorphs is recorded in sample 4 (table 2). Dinoflagellate cysts, 37 dinocysts/gram, belonging to *Spiniferites* spp. and *Operculodinium centrocarpum sensu* Wall and Dale. *Halodinium* sp. is represented by 295 specimens/gram and zoomorphs (1311 zoomorphs/gram) are represented by copepod egg-envelopes (628 copepods/gram) and test linings of foraminifera (443 foraminifera/gram).

## Discussion

### *Terrestrial and marine environmental reconstruction*

Palynological analysis of the Bahía Lapataia 2 section shows a predominance of terrestrial palynomorphs (pollen and spores) over marine palynomorphs (dinoflagellate cysts, acritarchs and zoomorphs) (figure 4). In general, pollen and spores in coastal marine records reflect the regional vegetation at the time of deposition, although their records are often overprinted with a coastal signal. The abundance (relative and absolute) and diversity of dinoflagellate cysts are considered to indicate coastline fluctuations, temperature, salinity of the sea water and, nutrient availability. Palynomorphs originating from zoobenthos (foraminifera) and zooplankton (copepod egg envelopes) may provide supplementary information for marine productivity (Boessenkool, 2001).

The identified pollen assemblages (figure 3), correlated with Pollen Zone 2 (10,000 - 5000 yr B.P) of Heusser (1989), resemble the modern forest-steppe ecotone of the central part of the Isla Grande de Tierra del Fuego, with 400-500 mm annual precipitation and summer temperatures averaging 10-11º C. Fluctuations in the floristic composition represent variation in the plant paleocommunities of the forest-steppe ecotone. The principal arboreal component is

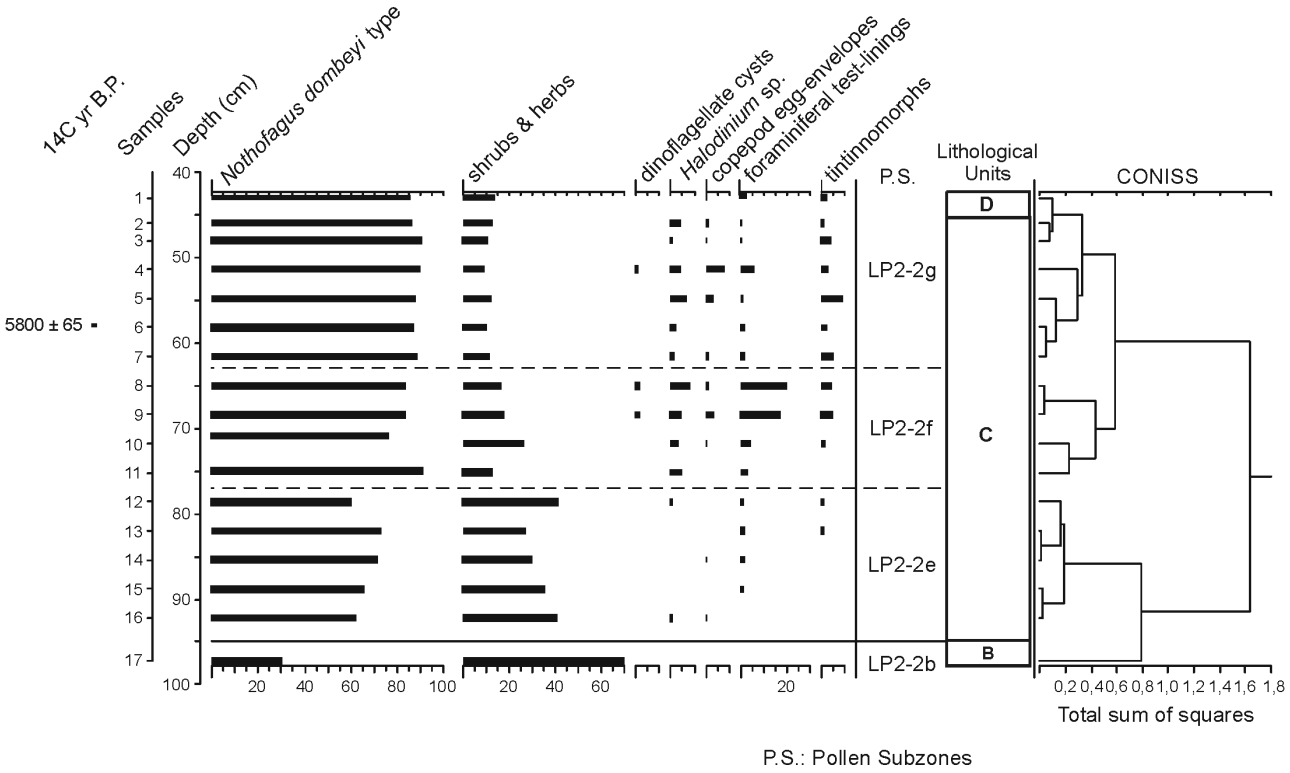


**Figure 4.** Palynomorph total frequency (%) at Bahía Lapataia 2 section / *frecuencia total de palinomorfos (%) en la sección de Bahía Lapatia 2.*

*Nothofagus dombeyi* type. Poaceae and Asteroideae characterize the principal shrub and herb elements. Cyperaceae and Polypodiaceae represent the major aquatics and cryptogam taxa.

The marine palynomorphs recovered from Unit C and D are *Spiniferites* spp., *Operculodinium centrocarpum*, *Brigantedinium* spp. and *Selenopemphix* sp. among the dinoflagellate cysts. *Halodinium* sp. characterizes the acritarchs. Other palynological remains are copepod egg-envelopes, test linings of foraminifera and tintinnomorphs. Among the non-marine palynomorphs, *Botryococcus*, *Zygnema*-type, Type 128 (Pals *et al*., 1980) are also found.

Lithological Unit B lacks organic-walled microplankton and corresponds to a low sea level. The pollen subzone LP2-2b represents the open-growing communities of beech woodland. *Nothofagus dombeyi* type is accompanied by significant values of Asteroideae and Poaceae with other non-arboreal components such as *Acaena*, *Empetrum*/Ericaceae, *Valeriana*, Cichorioideae and Apiaceae. The vegetal paleocommunities suggest lower precipitation and a slightly higher temperature than today in the Ushuaia region. Cyperaceae, an aquatic family, is probably locally derived. The light-demanding Polypodiaceae prospers initially but later declines when the openness of the vegetation disminishes and the closed forest spreads.

In Lithological Unit C, a relative rise in sea level is registered by the presence of marine palynomorphs. The pollen subzones LP2-2e, LP2-2f and LP2-2g show a predominance of *Nothofagus dombeyi* type accompanied by Poaceae together with a decrease in Asteroideae and Polypodiaceae. *Nothofagus dombeyi* type frequencies increase upwards in each pollen subzone in opposition to herb and shrub communities. These intervals suggest periods of more suitable environmental conditions that favoured the expansion of the beech forest communities in the littoral environment while a forest-steppe vegetational pattern spreads at regional level (Heusser, 1998). The forest expansion is associated with more humid and variable environmental conditions than in Lithological Unit B and related to the marine incursion.

Two relatively higher sea levels are registered in this unit. The oldest, before 5800 ± 65 $^{14}$C yr B.P. (Pollen Zubzone LP2-2f), exhibits the greatest abundance of dinoflagellate cysts (*Brigantedinium* spp., *Selenopemphix* sp. and *Spiniferites* spp.), the acritarch *Halodinium* sp., and zoomorphs, mainly test linings of foraminifera accompanied by copepod egg-envelopes (figure 4, table 2).

At present, foraminifera linings are abundant probably because of high organic carbon fluxes and possible dissolution of calcium carbonate (de Vernal,

**Table 2.** Marine palynomorph raw counts and concentrations of marine palynomorph per gram of sediments at Bahía Lapataia 2 section / *recuentos y concentraciones por gramo de sedimento de palinomorfos marinos en la sección de Bahía Lapataia 2.*

| Bahía Lapataia 2 | Lithological Units | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | D | | | | | | | C | | | | | | | | |
| Samples | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Dinocysts | | | | | | | | | | | | | | | | |
| *Spiniferites* spp. | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *O.centrocarpum* | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Brigantedinium* spp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Selenopemphix* sp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total Dinocysts | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 7 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dinocysts/gram | 0 | 0 | 0 | 37 | 0 | 0 | 0 | 51 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Acritarchs | | | | | | | | | | | | | | | | |
| *Halodinium* sp. | 0 | 15 | 2 | 16 | 17 | 4 | 3 | 13 | 12 | 5 | 4 | 1 | 0 | 0 | 0 | 1 |
| Acritarchs/gram | 0 | 13.0 | 25 | 295 | 30.6 | 17 | 21 | 94 | 57 | 54 | 88 | 15 | 0 | 0 | 0 | 32 |
| Zoomorphs | | | | | | | | | | | | | | | | |
| Copepod egg-env. | 1 | 3 | 1 | 34 | 8 | 0 | 2 | 2 | 11 | 1 | 0 | 0 | 0 | 2 | 0 | 1 |
| Foraminiferal test-l. | 4 | 2 | 1 | 24 | 3 | 4 | 4 | 32 | 55 | 8 | 3 | 1 | 13 | 8 | 4 | 0 |
| Tintinnomorphs | 6 | 2 | 13 | 13 | 25 | 6 | 15 | 7 | 15 | 2 | 0 | 1 | 5 | 0 | 0 | 0 |
| Total Zoomorphs | 11 | 7 | 15 | 71 | 36 | 10 | 21 | 41 | 81 | 11 | 3 | 2 | 18 | 10 | 4 | 1 |
| Zoomorphs/gram | 95 | 61 | 18.8 | 131.1 | 64.9 | 42 | 14.6 | 29.8 | 38.7 | 120 | 66 | 30 | 69 | 69 | 56 | 32 |

pers. comm., 2005). Their abundance also indicate benthic production (de Vernal and Giroux, 1991) and they are related to variable salinity estuarine marshes environments (Batten, 1996).

The distribution of copepod egg-envelopes, in general, may be related to the combined effects of high productivity and high sedimentation rates (van Waveren, 1994). Copepod eggs are present everywhere and they are particularly abundant in Antarctic environments (Marret, pers. comm, 2005).

The increased nutrient availability may also be caused by the simultaneously rising sea level and river discharge from meltwater. Strong fluvial influence is suggested by the record of *Halodinium* sp., a common Quaternary acritarch that typically occurs in large number in Arctic estuaries (Mudie, 1992; Mudie and Harland, 1996) and, is related to low salinity environments associated with seasonal sea-ice cover where it is deposited from the melting ice in spring/summer (Matthiessen, 1995).

In sample 4, another relatively higher sea level is registered, after 5800 ± 65 $^{14}$C yr B.P. (Pollen subzone LP2-2g), with a maximum abundance of dinoflagellate cysts (*Spiniferites* spp. and *Operculodinium centrocarpum*), *Halodinium* sp., and zoomorphs, mainly copepod egg-envelopes accompanied by test linings of foraminifera (figure 4, table 2).

The fossil dinoflagellate cyst assemblages show low species diversity and occur in very low numbers. During major sea-level changes, the steady state of microplankton associations in surface waters and associated sediments is exposed to disturbances from various dynamic processes like erosion, winnowing of sediments, intrusion and mixing of different water masses, which affect the regional microplankton associations within the water column and associated sediments respectively (Prauss, 2000). The low dinoflagellate production suggested by the sparse dinocyst occurences may be related to low and variable salinities and/or turbulence, which inhibits dinoflagellate production (de Vernal and Giroux, 1991). In areas with strong bottom water activity accumulation of clay-silt particles is often curtailed. Dinocysts typically range in size between 20 and 100 µm, and behave like sediment particles of the silt fraction. Copepod egg-envelopes and foraminifera are generally larger and their accumulation will be less affected by bottom currents (Boessenkool, 2001).

The microplankton association in the fossil record, although with low species diversity, is dominated by Peridiniales taxa suggesting inner neritic environments (de Vernal and Giroux, 1991).

*Brigantedinium* spp., among the peridinialean cysts, is a cosmopolitan taxon especially in epicontinental environments. Its distribution does not show any preference with regard to temperature or salinity nor with nutrient availability or productivity. It probably is an opportunistic genus (de Vernal *et al*., 2001). This taxon tolerates a broad range of temperatures, salinities and nutrient concentrations (Marret

**Table 3.** Marine palynomorph raw counts and numbers of marine palynomorph per gram of sediments at Bahía Lapataia 1 section / *recuentos y concentraciones por gramo de sedimento de palinomorfos marinos en la sección de Bahía Lapataia 1.*

| Bahía Lapataia 1 | Lithological Unit C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Samples | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Dinocysts | | | | | | | | | | | | |
| *Spiniferites* spp. | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| *O. centrocarpum* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| *Pyxidinopsis* sp. | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Total Dinocysts | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 |
| Dinocysts/gram | 0 | 0 | 0 | 0 | 16 | 17 | 17 | 42 | 37 | 0 | 19 | 0 |
| Acritarchs | | | | | | | | | | | | |
| *Halodinium* sp. | 0 | 14 | 0 | 0 | 1 | 9 | 8 | 1 | 7 | 4 | 2 | 1 |
| Acritarchs/gram | 0 | 64 | 0 | 0 | 16 | 155 | 134 | 42 | 262 | 155 | 38 | 19 |
| Zoomorphs | | | | | | | | | | | | |
| Copepod egg-e. | 0 | 5 | 0 | 1 | 0 | 2 | 6 | 4 | 2 | 2 | 7 | 1 |
| Foraminiferal test-l. | 0 | 4 | 0 | 0 | 0 | 10 | 14 | 1 | 1 | 3 | 4 | 1 |
| Tintinnomorphs | 0 | 9 | 0 | 5 | 10 | 27 | 52 | 5 | 2 | 0 | 5 | 3 |
| Total Zoomorphs | 0 | 18 | 0 | 6 | 10 | 39 | 72 | 10 | 5 | 5 | 16 | 5 |
| Zoomorphs/gram | 0 | 82 | 0 | 54 | 157 | 671 | 1211 | 417 | 188 | 194 | 308 | 96 |
| Reworked dinocysts | | | | | | | | | | | | |
| *Dingodinium* sp. | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| *Escharisphaeridia* sp. | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| *Kalyptea* sp. | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 0 |
| *Tanyosphaeridium* sp. | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |

and Zonneveld, 2003). It often dominates in low-salinity environments and reflects high concentration of nutrients in the surface waters owing to freshwater input from glaciers meltwater (Grøsfjeld *et al*., 1999).

Other taxa include *Selenopemphix* sp. that resembles the *Selenopemphix nephroides* (Benedek) Benedek and Sarjeant as recorded at Río Varela locality about 100 km (Grill *et al*., 2002) (figure 1). *Selenopemphix nephroides* is a temperate to tropical heterotrophic species characteristically present in coastal environments reflecting the variance of food availability. This species is distributed within a broad range of temperatures and occurs in mesotrophic/eutrophic environments (Marret and Zonneveld, 2003). Its record in the western Arctic marine region (eastern Bering Sea and Chukchi Sea) suggests that temperature probably is not the most determinant parameter for the distribution of this taxa (Mudie and Rochon, 2001; Radi *et al*., 2001).

The gonyaulacalean cysts include cosmopolitan taxa such as *Spiniferites* spp. which is usually found in neritic environments from tropical to polar regions, and *Operculodinium centrocarpum* recorded in coastal and deep-sea environments and tolerant of large fluctuations in temperature and salinity (Matthiessen, 1995; de Vernal *et al*., 2001).

Zoomorphs represented by tintinnomorphs (palynomorphs resembling tintinnids or cysts of other protozoans) are present throughout Lithological Unit C. According to van Waveren (1994), as with to the preservation of microscopic crustacean remains (copepod egg-envelopes), their occurrence may be related to the combined effects of high productivity and high sedimentation rates, associated with nutrient enrichment during upwelling period.

Lithological Unit D corresponds to gravel beach deposits associated with a relatively low sea level. The studied palynological sample contains some test lininigs of foraminifera and copepod egg-envelopes. The coarser lithology of this unit may explain the scarcity of marine palynomorphs.

## *Correlation with other dated marine deposits in the Bahía Lapataia area, Beagle Channel*

A comparison between Bahía Lapataia 1 (LP1) and Bahía Lapataia 2 (LP2) sites is made in order to

discuss their possible relationship. The marine deposit at the LP2 section is correlated according to its lithology, thickness and palynological assemblages (sporomorphs and marine palynomorphs) with marine deposits at the LP1 site (Borromei and Quattrocchio, 2001) (figure 2).

Lithological Unit A is not recorded in LP2 site but Unit B is represented at both localities together with Pollen Subzone LP-2b representing open-grown communities of beech woodland associated with a relatively low sea level. The spread of *Nothofagus* forest with a decline of grass and shrub vegetation at times of the marine incursion (Lithological Unit C: Pollen Subzones LP-2e, LP-2f and LP-2g) is registered in both marine deposits. The sediments consist of 47 cm of greenish sandy clay with marine shells of *Mytilus* sp. The palynological assemblages reveal nearshore environments, where the great abundance of pollen and spores indicates large fluvial and/or atmospheric inputs. The marine environment is characterized by sparse assemblages of dinoflagellate cysts dominated by Peridiniales taxa (*Brigantedinium* spp. and *Selenopemphix* sp.) in addition to Gonyaulacales taxa (*Spiniferites* spp. and *Operculodinium centrocarpum*). The occurrence of *Halodinium* sp. together with copepod egg-envelopes and test linings of foraminifera is abundant. The overall palynological assemblages reflect inner estuarine environments related to low and variable salinities and/or turbulence, cool-temperate sea water temperature and abundant dissolved nutrients associated with significant dilution of surface waters from freshwater runoff.

Two relatively higher sea levels are identified by abundance of dinoflagellate cysts, the acritarch *Halodinium* sp. and zoomorphs, mainly test linings of foraminifera accompanied by copepod egg-envelopes (tables 2 and 3). In both localities the marine sediments are overlain by gravel beach deposits (Lithological Unit D) associated with a relatively low sea-level.

The lithology, thickness and palynological analyses provide evidence that LP2 and LP1 sites correspond to the same marine deposit and represent the same transgressive-regressive phase into the Beagle Channel. Palynological analysis corroborates the existence of two phases of relatively higher sea-level, one of them between 8240 ± 60 $^{14}$C yr B.P. and 7260 ± 70 $^{14}$C yr B.P. (Pollen Subzone LP-2f) and the other at ca. 6000 $^{14}$C yr B.P. (Pollen Subzone LP-2g, 5800 ± 65 $^{14}$C yr B.P.).

Marine deposits at the LP1 site, with marine levels dated 8240 ± 60 $^{14}$C yr B.P. at 1.65 m a.s.l. and 7260 ± 70 $^{14}$C yr B.P. at 1.80 m a.s.l., can be correlated by their apparent age and elevation, with the radiocarbon-dated and altitude-equivalent marine deposits around Lago Roca (figure 1, table 1). This seems to correspond to the >7000 $^{14}$C yr B.P. remnants of a shoreline around 1.5-3 m a.s.l. (Gordillo *et al*., 1992). The marine level dated 5800 ± 65 $^{14}$C yr B.P. at 1.95 m a.s.l. at LP2 site cannot be correlated by its apparent elevation with to the marine deposits in Lago Roca, Ushuaia Peninsula (Bahía Golondrina and Punta Pingüinos) or those in the city of Ushuaia dated 5100-5900 $^{14}$C yr B.P. at 8-10 m a.s.l. (figure 1, table 1) (Gordillo *et al*., 1992). Coronato *et al*. (in press) propose that the differential seismotectonic movements since the middle Holocene would have forced the ascent of the western portion of the Argentine sector of the Beagle Channel and the lowering of its eastern section. The transcurrent fault systems with NW-SE and NE-SW orientations bound sectors in which the marine deposits and landforms do not present a clear chronological-altitudinal correlation. Gordillo *et al*. (1992) suggested that the younger radiocarbon age of LP2 section could result from geochemical rejuvenation phenomena in older deposits.

## Conclusions

The two marine deposits observed at tha Bahía Lapataia locality have previously been studied in relation to their relative altitude, sediment type, faunal composition and radiocarbon dates (Rabassa *et al*., 1986; Gordillo *et al*., 1992). It was established that two different marine deposits existed, and that one of them (LP2 section) was not correlatable to altitude-equivalent marine deposits using radiocarbon dating. The palynological analyses from both sections have demonstrated that they correspond to the same marine deposit embracing the 8000-?6000 $^{14}$C yr B.P. marine record at Beagle Channel, and the existence of two relatively higher sea-levels is corroborated.

Although palynological assemblages provide a partial picture of the organic matter inputs and fluxes to marine systems, they enable the characterization of marine environments. The high pollen frequencies at the LP1 and LP2 sites reveals very high terrestrial organic matter inputs to the area which is consistent with a marginal marine environment. The pollen assemblages represent the adjacent terrestrial vegetation and allow direct correlation with the terrestrial palynostratigraphy. Vegetational paleocommunities in the coastal areas during low sea levels, were those of the forest-steppe ecotone. However, during transgressive phases, the vegetation was mainly arboreal suggesting high levels of humidity, while the forest-steppe vegetation expanded at regional levels. A similar vegetational pattern was also observed in the Río Varela locality at marine levels dated 6240 ± 70 $^{14}$C yr B.P. and 6060 ± 70 $^{14}$C yr B.P. (Grill *et al*., 2002) (figure 1).

The palynomorph assemblages at the LP1 and LP2 sites are characteristic of inner neritic environments having a great abundance of terrestrial palynomorph content, low species diversity of dinocysts, cool-temperate sea water temperature, low and variable salinity and/or turbulence, and abundant dissolved nutrients associated with significant dilution of surface waters from meltwater discharge.

Several raised Holocene marine terraces were found all along the Argentinian Patagonia coast representing sea-level highstands at 7 to 2 m a.s.l. with ages of 8000, 7000, 5000, 4000, 3000 and 1000 $^{14}$C yr B.P. respectively. They reflect spasmodic Holocene regressive phases of Patagonian sea-level (Rostami *et al*., 2000). According to these authors, the 7000-8000 $^{14}$C yr B.P. terraces would mark the peak of the Holocene highstand. Isla (1989) recognized in Tierra del Fuego that the maximum transgressive episode ocurred between 9000 and 7000 $^{14}$C yr. B.P. Those sites younger in age would represent regressive coastline phases.

Additional palynological information based on other fossil marine records and from surface sediments of the Beagle Channel will be necessary to refine our paleoenvironmental reconstruction of the Holocene marine transgression into the Beagle Channel and its inter-oceanic relationships.

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