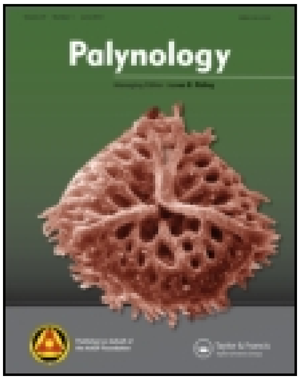

Palynology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tpal20

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Accepted author version posted online: 20 Aug 2012.Published online: 22 Nov 2012.

Palynology, 2013
Vol. 37, No. 1, 62–76, http://dx.doi.org/10.1080/01916122.2012.718994

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Palynofacies analysis of surface sediments from the Beagle Channel, Tierra del Fuego, Argentina, was carried out to establish modern analogues for comparison with other Holocene marine records in southern Isla Grande de Tierra del Fuego. Our results show the dominance of highly degraded translucent phytoclasts, associated with amorphous organic matter (AOM) and palynomorphs, while opaque phytoclasts are poorly represented. The organic constituents indicate the proximity of the continental source area to marine environments, with distances and/or times of relatively short transport. The predominance of translucent phytoclasts associated with pyrite suggests reducing conditions, probably associated with marginal-marine environments. Among the terrestrial palynomorph group, the predominance of *Nothofagus* pollen reveals the presence of forests along the channel. The high terrestrial organic matter input to the depositional area are consistent with a marginal-marine environment. The aquatic palynomorphs, mainly dinoflagellate cyst's show assemblages characterised by low species diversity and low concentration values. The dominance of Peridiniales over Gonyaulacales suggests inner neritic environments. Comparison with two fossil sections of Mid–Late Holocene age (Albufera Lanushuaia and Río Ovando) shows similar distribution of the total palynological matter.

Keywords: palynofacies; surface sediments; modern analogues; Beagle Channel; Argentina

1. Introduction

The Beagle Channel (54°53′S and 66°30′–70°W) connects the Atlantic and Pacific oceans in the southernmost part of South America and is located in the subantarctic environment. During the Last Glacial Maximum (ca. 24,000 years B.P.) this area behaved as a glacial valley that was flooded by the sea at 8000 ^{14}C yr B.P., becoming a deep and narrow fjord. Many studies on Holocene sea-level changes from Isla Grande de Tierra del Fuego have been largely based on geological, geomorphological and palaeoecological records (Codignotto 1984; Porter et al. 1984; Rabassa et al. 1986, 1992, 2000; Rutter et al. 1989; Mörner 1990; Gordillo et al. 1992, 1993, 2005; Isla et al. 1999; Bujalesky et al. 2004; Bujalesky 2007, among others). There are few contributions on palynofacies and microplankton of fossil marine records from Tierra del Fuego (Borromei et al. 1997; Borromei and Quattrocchio 2001, 2007; Grill et al. 2002; Candel et al. 2009, 2011; Rabassa et al. 2009; Candel 2010), but no one has focused on the study of modern marine sediments.

The use of modern analogues for palaeoecological reconstructions is a useful approach to infer past conditions. To detect patterns of biotic change at different spatial and temporal scales, and interpret them, it is necessary to study the modern patterns and processes, since the reconstruction of the ecosystem requires the knowledge of the requirements and tolerances of species, population dynamics and communities involved. One of the main methodological approaches to the reconstruction of past ecosystems is the use of modern analogues derived from known environments and its comparison with fossil assemblages (Birks & Birks 1980).

The analysis of palynological organic matter (or palynofacies analysis) preserved in the sediment records has special interest given the importance and potential of this for the palaeoenvironmental and palaeoclimatic assessment. According to Traverse (1994), the palynomorph/palynodebris-based facies (palyno-biolithofacies) are ‘bi-facial’. That is, they have as goals both the elucidation of the origin of the enclosing rock, and the biosphere association from which the palynomorphs were derived. The analysis of palynofacies provides also information on transgressive-regressive sedimentary cycles. The relationship of the source material (continental or marine), and the

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size and diversity provide information on the hydrodynamics and ecology of the environment of deposition. The palynological assemblages reflect a partial picture of the organic matter inputs and fluxes to marine systems; they enable the characterisation of marine environments. The terrestrial palynomorphs (pollen and spores) in coastal marine records constitute long distance fluvial and/or atmospheric inputs originating from the terrestrial vegetation of adjacent lands (de Vernal et al. 1993) showing the regional vegetation at the time of deposition, although their records are often overprinted with a coastal signal (Borromei & Quattrocchio 2007).

The aim of the present study is to document the distribution of the total palynological organic matter (palynofacies) from surface sediments in the Beagle Channel and its application as modern analogues for comparison with other Holocene marine records in southern Isla Grande de Tierra del Fuego. This analysis will provide information on the hydrodynamics and ecology of the environment of deposition in the Beagle Channel.

2. Physical setting

The Beagle Channel is located between Isla Grande de Tierra del Fuego to the north and Isla Hoste, Isla Navarino and other smaller islands to the south (Figure 1). It is about 200 km long on a W–E trend and connects the Atlantic and Pacific oceans. The Beagle Channel system constitutes an inland passage in a complex web of channels, inlets and surrounding land masses that characterises southern South America (Antezana 1999). It is a drowned glacial valley, which was occupied by a large outlet glacier (the 'Beagle Glacier') from the Cordillera Darwin. The Beagle Channel opened before 8200 ^{14}C yr B.P. and the marine environment was fully established at least by 7900^{14}C yr B.P. (Rabassa et al. 1986). This channel is connected with the Pacific Ocean through Brazo Noroeste and Brazo Sudoeste surrounding the Isla Gordon, with depths around 240–300 m. Despite a major connection to the Pacific Ocean at the mouth, the shallow depth of the eastern end of the channel and the Isla Gable restrict the inflow of subsurface Atlantic Ocean water into the Beagle Channel (Gordillo et al. 2005). However, the Beagle Channel has been described as an estuarine system with thermal stratification at about 12 m depth (Isla et al. 1999). The Isla Gable acts as a sill in estuarine dynamics and the consequent sediment accumulation is influenced by tidal circulation. The estuarine–fjord dynamics are controlled by significant and seasonal freshwater sources, and by tidal flow from both the east (Atlantic) and the west (Pacific) (Isla et al. 1999). The Beagle Channel receives input from numerous rivers that drain the intermontane basins of Isla Grande, Isla Navarino and Isla Hoste. These basins have a nival regime with increasing rains and maximal precipitation between October and December and dry season in March–April (Isla et al. 1999).

3. Material and methods

3.1. Sampling and laboratory treatments

The study was performed on 22 surface sediment samples collected from the bottom of the Beagle Channel, Tierra del Fuego (Figure 1), during two expeditions on the Argentine Coastguard ships (Río Uruguay and Canal Beagle). The sampling was carried out by Dr Gustavo Bujalesky, using a Clamshell Grab-type device. The lithologies consist of fetid dark grey clays and dark brown medium-coarse sands with abundant shells. The samples were grouped into three sectors: western, central and eastern, according to the localities. Seven localities were differentiated and grouped according to the sector that they belonged to: the Western sector includes BL (Bahía Lapataia), BG (Bahía Golondrina) and BU (Bahía Ushuaia); the Central sector includes PR (Punta Remolino) and PP (Punta Paraná), and the Eastern sector includes IG (Isla Gable) and EIG (External Isla Gable). The samples were prepared for palynological analysis according to the standard laboratory procedures of de Vernal et al. (1999). Sediment subsamples (5–10 g) were taken for each sample and two tablets containing a known number of *Lycopodium clavatum* spores were added to each sample prior to treatment for the calculation of palynomorph concentration (Stockmarr 1971). Samples were sieved through 106 and 10 μm mesh screens in order to remove coarse sand, silt and clay particles. The sediment fraction between 106–10 μm was treated repetitively with hydrochloric acid (HCL 10%) and hydrofluoric acid (HF 49%) to remove carbonate and silica material. No oxidation and treatment with heavy liquids were applied in order to prevent the loss of more fragile organic-walled microplankton and the organic content of the palynofacies. According to Tyson (1995), the residual fraction of sediment was sieved again to eliminate particles smaller than 10 μm (to concentrate the particulate material). Then, the residual material was mixed with glycerin jelly and mounted for observation between a glass slide and a cover slide. All the slides are stored in the Palynology Laboratory, Universidad Nacional del Sur, Bahía Blanca, Argentina, under the name UNSP followed by the denomination of the study area (FCB: Fondo Canal Beagle).

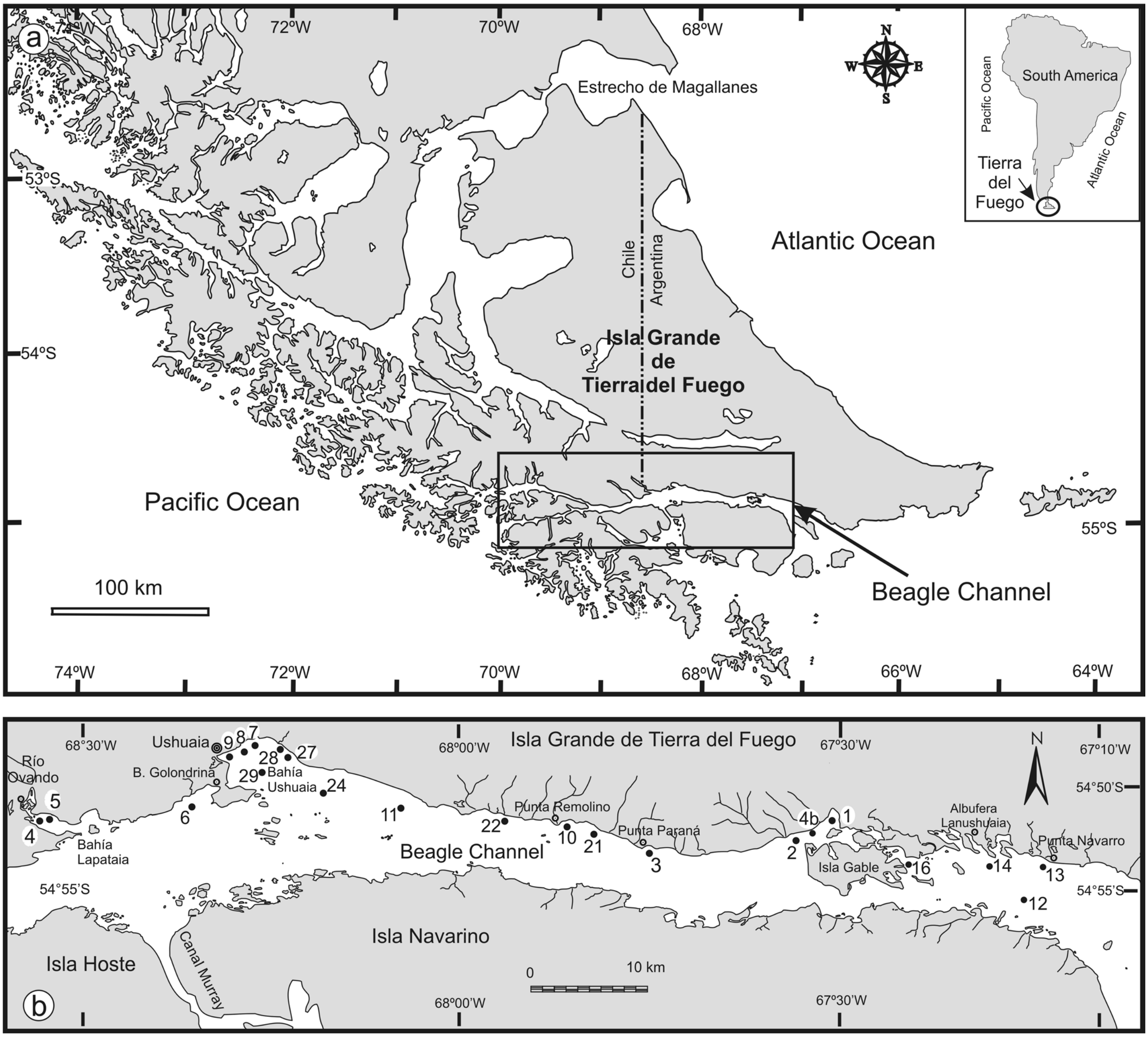

Figure 1. Location map of the study area; (a) Isla Grande de Tierra del Fuego; (b) Beagle Channel region and the sample locations.

3.2. *Palynofacies and palynological analysis*

According to the classification proposed by Tyson (1995), the palynological organic matter is distinguished into four main groups: palynomorphs, phytoclasts (translucent and opaque), AOM and zooclasts. The study of palynological organic matter was performed using transmitted light and blue light fluorescence microscopy on specially mounted slides made for this purpose. In order to quantify the relative amount of particulate organic matter, a minimum of 500 particles larger than 10 µm were counted for each sample (Tyson 1995). The counts were carried out under 400 ×magnification and the systematic determination was made on the basis of morphological and morphometric characteristics of sporomorphs and aquatic palynomorphs with 1000× magnification. Twenty categories were chosen to represent the total particulate organic matter assemblage. The definition, biological sources and constituents of each category are listed in Table 1. The main organic constituents are illustrated in Plate 1.

The present deterioration of palynomorphs and organic matter was determined according to Delcourt and Delcourt (1980), who recognised four types of deterioration: corrosion (produced by biochemical oxidation related to local activity of bacteria and fungi), degradation (chemical oxidation in air and subaerial environments), mechanical damage (for physical transport and/or syn and post-depositional compaction in the sediments) and crystallisation of

Table 1. Categories of total particulate organic matter counted in the samples, with indication of their biological sources and constituents (modified from Tyson 1995). Note: The classification and description of each category follow Tyson (1995).

Group		Source	Category	Constituent
Structured	Palynomorphs	Sporomorphs	Pollen and spores	Trees, shrubs and herbs, aquatic and cryptogams
		Organic-walled phytoplankton	Dinoflagellate cysts	According to Rochon et al. (1999), Zonneveld (1997), Head et al. (2001)
			Acritarchs	*Sensu* Fensome et al. (1990)
			Other freshwater to marine-brackish algae	Clorophyceae, Zygnemataceae, Prasinophyceae
		Zoomorphs	Foraminiferal linings	Planktonic foraminifera
			Copepod eggs	Crustacean remains
	Translucent and opaque phytoclasts	Macrophyte plant debris	Fungi	Hyphae
			Tracheids	
			Cuticles	
			Other structured phytoclasts	Land plant debris
			Equidimensional	
			Blade-shaped	
	Zooclasts	Fragmentary animal-derived organic particles	Spines	Invertebrate remains
			Jaws	
			Wings	
			Hairs	
Unstructured	Amorphous organic matter	Degradation of phytoplankton or bacteria	Granular	Aggregates and cell-filling and extracellular precipitates
		Humic gel	Spongy	
			Membranous	
			Fibrous	

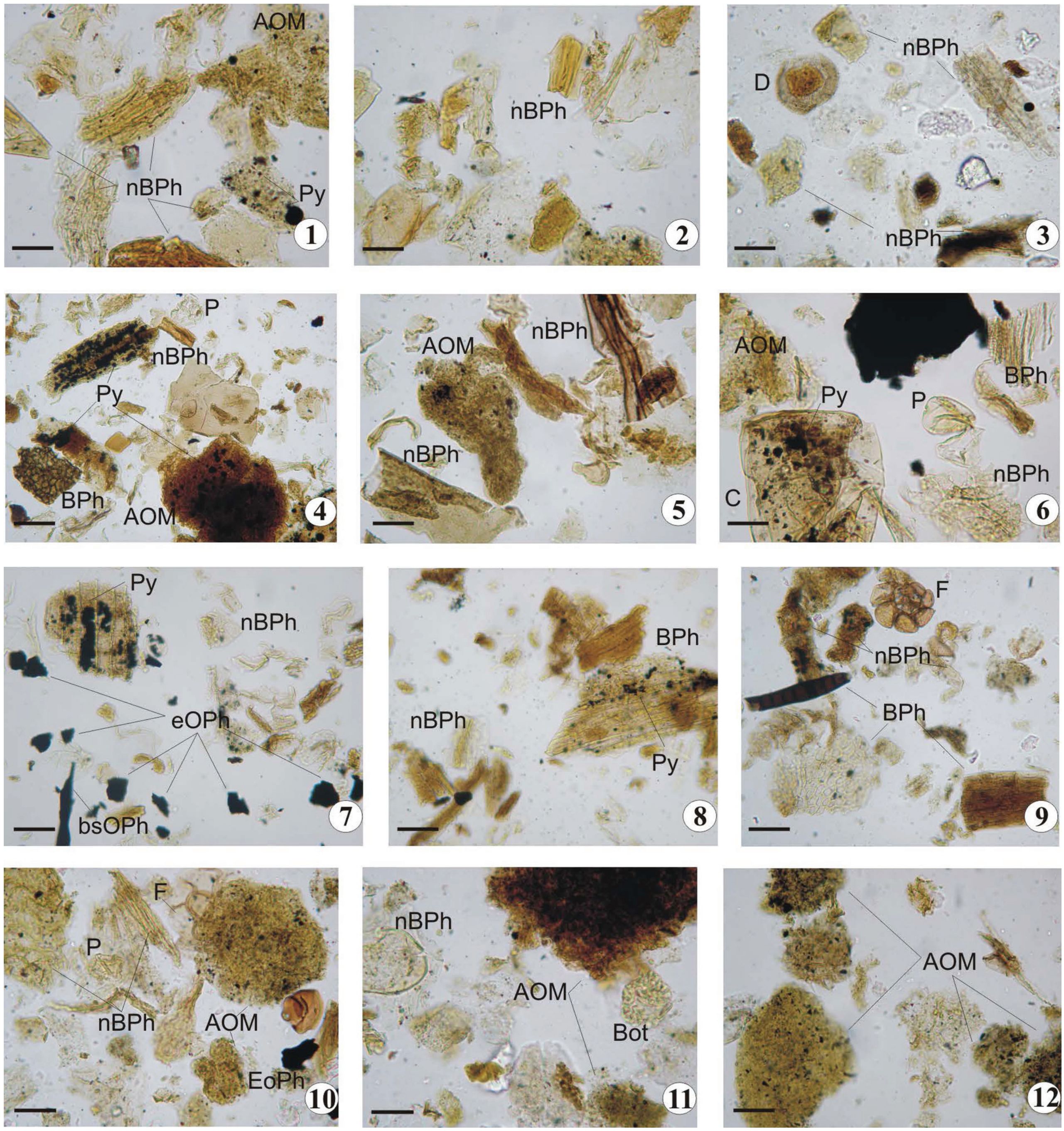

Plate 1. Palynofacies of surface sediments from the Beagle Channel (FCB). Scale bar: 30 μm. Number of sample followed by England Finder coordinates. Figures 1, 2. Palynofacies with detail of non-biostructure translucent phytoclasts (nBPh), amorphous organic matter (AOM) and pyrite (Py). 1: UNSP FCB2347-4, F31/1; 2: UNSP FCB2347-4, G30/2. Figure 3. Non-biostructure translucent phytoclasts (nBPh) and dinoflagellate cyst (D), UNSP FCB2347-5, O20/4. Figures 4, 5, 6. Biostructure translucent phytoclasts (BPh), non-biostructure translucent phytoclasts (nBPh), amorphous organic matter (AOM), palynomorphs (P and C) and pyrite (Py). 4: UNSP FCB2349–1, L32; 5: UNSP FCB2349–1, U14/2; 6: UNSP FCB2349–3, P51/3. Figures 7, 8. Opaque phytoclasts in blade-shaped (bsOPh) and equidimensional form (eOPh), accompanied by biostructure translucent phytoclasts (BPh), non-biostructure translucent phytoclasts (nBPh) and pyrite (Py). 7: UNSP FCB2349–3, R50/4; 8: UNSP FCB2349–3, T34. Figures 9, 10. Biostructure translucent phytoclasts (BPh), non-biostructure translucent phytoclasts (nBPh), opaque equidimensional phytoclasts (eOPh), amorphous organic matter (AOM), palynomorphs (P and F) and pyrite (Py). 9: UNSP FCB3171, L52/4; 10: UNSP FCB3171, B60. Figure 11. Non-biostructure translucent phytoclasts (nBPh), amorphous organic matter (AOM) and palynomorph (Bot: *Botryococcus*), UNSP FCB3170, P34. Figure 12. Detail of amorphous organic matter (AOM), UNSP FCB3166, S18/4.

pyrite (diagenesis with precipitation of authigenic minerals). This tool allows one to make inferences on palaeoenvironmental conditions.

The palynomorph group includes trees, shrubs and herbs, freshwater algae, brackish-marine algae, dinoflagellate cysts, acritarchs, copepod eggs, organic foraminiferal linings and other aquatic palynomorphs. The main aquatic palynomorphs are shown in Plate 2.

Following Heusser (1998), *Nothofagus betuloides*, *N. pumilio* and *N. antarctica* are shown collectively as *Nothofagus dombeyi* type, given the difficulty in species separation. Another special case is *Empetrum rubrum* and *Gaultheria*/*Pernettya* (Ericaceae), which are morphologically similar, so the latter is included together with *Empetrum rubrum*.

The taxonomic nomenclature of dinoflagellate cysts used in this study conforms to Zonneveld (1997), Rochon et al. (1999) and Head et al. (2001). For citations of taxa see Fensome and Williams (2004).

The relative frequencies (%) of palynomorphs, phytoclasts, AOM and zooclasts were calculated on the total particles counted (500 particles). The palynomorph group frequencies (%) were worked out considering the total number of particles counted (500 minimum). The percentages of each one of the constituents of this group (pollen, spores and microplankton) were calculated on the palynological count (200 palynomorphs as minimum). The relative frequencies (%) and concentrations of palynomorphs and organic matter, diagrams and cluster analysis were calculated using TGview 2.0.2 (Grimm 2004). The Shannon index (H) was calculated to determine the dinoflagellate cyst species diversity, using the software PAST (Hammer and Harper 2009). This index takes into account the number of taxa per sample and the proportion of specimens of each taxon (Table 2). For diversity calculation, the number of dinoflagellate cysts counted per sample was 100. The palynofacies and palynological analyses, description and discussion for each sector was carried out on the relative frequencies (%) and concentration diagram of palynofacies and microfloristic associations of the transect (Figure 2).

The present palynofacies analysis data were compared with data obtained from two fossil sections located on the north coast of the Beagle Channel: Río Ovando (54°51′ S–68°35′ W; Candel et al. 2009; Candel 2010) and Albufera Lanushuaia (54°52′ 04.4″ S–67°60′ 44.9″ W; Candel 2010; Candel et al. 2011). In order to provide information about oxygen in the water column and terrestrial influx in the marine sediments, the relative frequencies of the total palynological organic matter from surface samples of the Beagle Channel and the fossil localities (Albufera Lanushuaia and Río Ovando) were plotted in ternary diagrams (Figure 3) modified from Tyson (1993, 1995) and Roncaglia (2004).

4. Results

The palynological organic matter is represented in the three sectors from the Beagle Channel by four main groups: palynomorphs, phytoclasts, AOM and zooclasts (Figure 2). The dinoflagellate cysts and other aquatic palynomorphs identified in the surface samples are listed in Table 2.

4.1. Western sector of Beagle Channel

The western sector comprises Bahía Lapataia, Bahía Golondrina and Bahía Ushuaia. Among the palynological organic matter identified in this sector, the palynomorph group shows percentages varying between 2.6 and 8.4% and it is characterised by the dominance of *Nothofagus* (25.8–89.2%), associated with shrubs and herbs (Poaceae, *Misodendrum*, Asteraceae sub. Asteroideae, Asteraceae sub. Cichorioideae, *Empetrum* /Ericaceae, *Gunnera*, *Acaena*, Apiaceae and Chenopodiaceae) that reach up to 16.8%. The aquatic constituents are represented by marine dinoflagellate cysts with values ranging between 1.5 and 14.4%, accompanied by *Halodinium* sp. (up to 49%). Other marine palynomorphs such as foraminiferal linings and copepod eggs are present with low values (8% and 4.9%, respectively). The *Nothofagus* pollen concentration values vary between 355 and 20,757 grains/g and, the shrub and herb concentrations between 25 and 4938 grains/g. On the other hand, aquatic palynomorphs show high concentration values (95–20,929 palynomorphs/g).

Among the remaining components of palynological organic matter, the phytoclast group shows high concentrations of translucent phytoclasts (93.2%), mainly non-biostructured phytoclasts with pseudoamorphous form, degraded and pale yellow to brown in colour. Some of them show traces of banded or fibrous structure. Low proportions of biostructured phytoclasts like cuticles, tracheids, fungal hyphae and other phytoclasts. The opaque phytoclasts reach values up to 9.7%, mainly equidimensional with sharp to subrounded edges. The highest abundance of opaque phytoclasts in blade-shaped form without biostructure, and small to medium in size, is recorded in this sector.

The AOM (24.5%) is mainly spongy and granular, accompanied by amorphous membranous and fibrous phytoclasts. The zooclasts are present in very low proportion (1.8%) as invertebrate skeletal pieces. Pyrite is present forming agglutinated masses or disseminated on translucent phytoclasts.

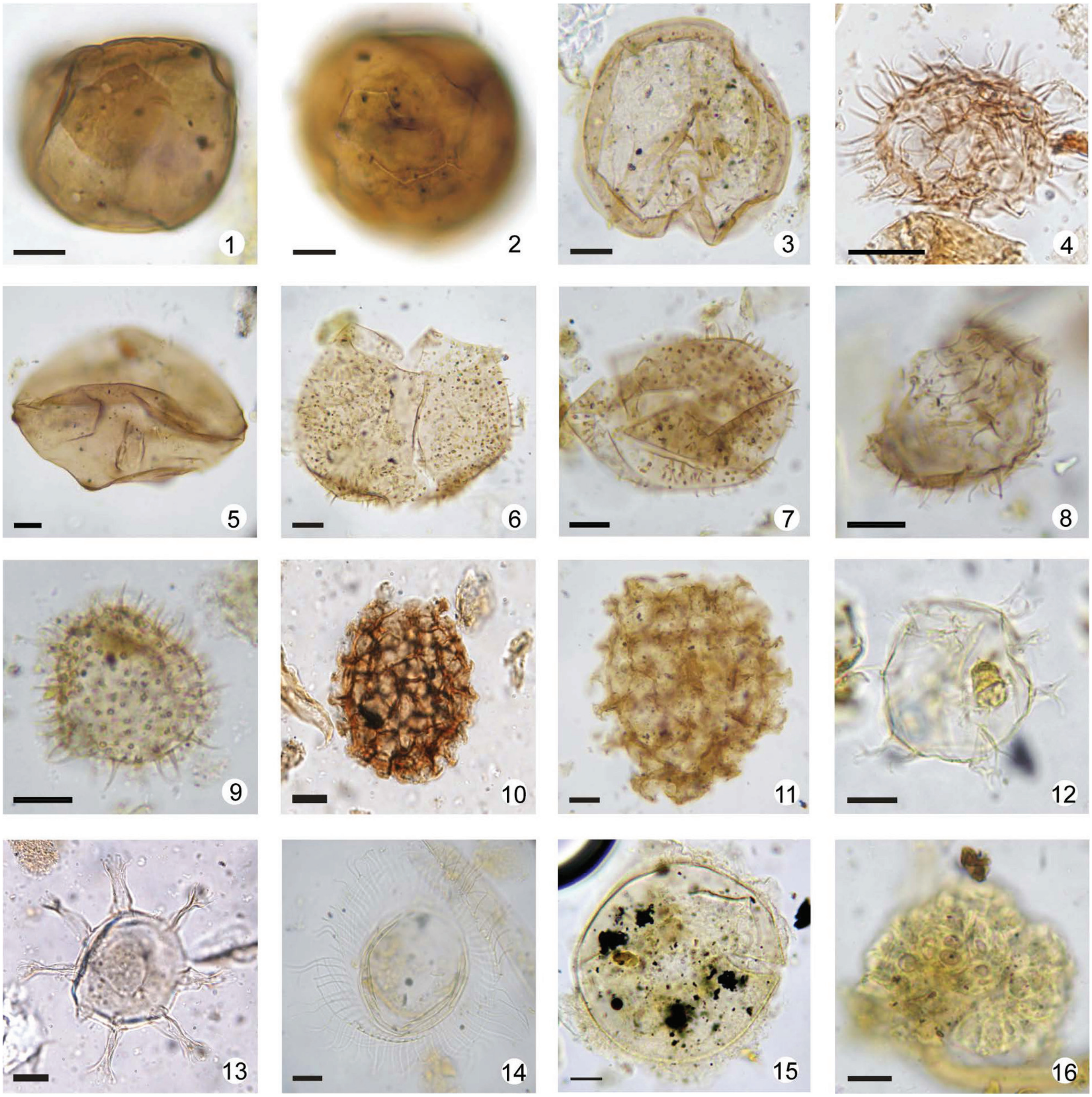

Plate 2. Aquatic palynomorphs from surface sediment samples from the Beagle Channel. Scale bar: 10 µm. Number of sample followed by England Finder coordinates. Figure 1. *Brigantedinium simplex* (Wall 1965) ex Lentin & Williams 1993, UNSP FCB3166, Y30. Figure 2. *Brigantedinium cariacoense* (Wall 1967) Lentin & Williams 1993, UNSP FCB3166, O38/3. Figure 3. *Selenopemphix nephroides* (Benedek 1972) Benedek & Sarjeant 1981, UNSP FCB3166, W14/1. Figure 4. *Selenopemphix quanta* (Bradford 1975) Matsuoka 1985, UNSP FCB2347–2, O56. Figure 5. *Quinquecuspis concreta* (Reid 1977) Harland 1977, UNSP FCB3166, B47. Figure 6. *Votadinium spinosum* (Reid 1977), UNSP FCB2347–4, C28/4. Figure 7. *Islandinium minutum* (Harland & Reid in Harland et al. 1980) Head et al. 2001, UNSP FCB2347–4, Q46/2. Figure 8. *Islandinium cezare* (de Vernal et al. 1989 ex de Vernal in Rochon et al. 1999) Head et al. 2001, UNSP FCB2349–4, Y32/3. Figure 9. *Echinidinium granulatum* (Zonneveld 1997), UNSP FCB3166, Z18/4. Figure 10. *Polykrikos schwartzii* (Bütschli 1873), UNSP FCB2347–5, N29/4. Figure 11. *Polykrikos kofoidii* (Chatton 1914) UNSP FCB2347–4, G60/4. Figure 12. *Spiniferites ramosus* (Ehrenberg 1838) Mantell 1854 sensu lato, UNSP FCB2349–4, V14. Figure 13. *Polyasterias* sp., UNSP FCB2347–5, G24. Figure 14. *Radiosperma corbiferum* (Meunier 1910), UNSP FCB2349–1, M23/1. Figure 15. *Halodinium* sp. UNSP FCB 2347–4, Y27/4. Figure 16. *Botryococcus braunii* (Kützing 1849). UNSP FCB3170, W44.

Table 2. Occurrences of aquatic palynomorphs recorded in the surface samples from the Beagle Channel.

Sector	WESTERN										CENTRAL					EASTERN						
Localities	BL		BG	BU							PR				PP	IG			EIG			
Samples	5	4	6	9	8	7	29	28	27	24	11	22	10	21	3	2	1	4b	16	14	12	13
Dinoflagellate cysts																						
Brigantedinium cariacoense													x			x		x				x
Brigantedinium simplex	x												x	x		x						
Brigantedinium spp.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x
Dinocyst sp. 1	x			x	x	x								x	x	x						
Dubridinium cf. *D.* sp.				x														x				
Echinidinium cf. *E. delicatum*	x				x				x				x		x	x	x					
Echinidinium granulatum	x	x	x		x	x	x	x		x	x	x	x	x	x	x	x	x		x		x
Echinidinium cf. *E. granulatum*	x	x											x			x						
Echinidinium spp.	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x
Islandinium? *cezare*							x			x			x					x				x
Islandinium minutum	x	x		x			x			x	x		x	x	x	x	x	x	x	x	x	x
Pentapharsodinium dalei	x	x		x	x	x					x		x		x	x	x	x	x	x		x
Polykrikos kofoidii	x	x	x								x		x	x	x	x	x					
Polykrikos schwartzii	x						x				x		x	x	x	x		x	x	x		x
Protoperidinioids				x					x		x	x	x	x				x	x	x		x
Quinquecuspis concreta	x										x		x									x
Selenopemphix nephroides	x	x								x	x	x	x	x	x	x		x	x	x		x
Selenopemphix quanta	x	x			x	x	x	x	x	x	x	x	x	x	x	x		x	x	x		x
Selenopemphix cf. *S. quanta*	x	x				x	x	x		x	x	x	x	x			x	x	x	x		x
Spiniferites lazus		x																				
Spiniferites ramosus					x									x							x	x
Spiniferites cf. *S. mirabilis*																		x				
Spiniferites sp.	x																					
Spiniferites spp.	x						x				x		x					x	x	x	x	x
Trinovantedinium cf. *T. applanatum*	x												x									
Votadinium calvum				x									x	x				x				x
Votadinium spinosum	x	x					x	x			x		x	x	x	x		x		x		x
Shannon index (H)	2.231	1.693	1.04	1.207	1.6	1.269	1.628	1.004	0.955	1.079	1.6	0.781	2.455	2.12	1.512	1.776	1.533	2.433	1.4	1.566	0.693	2.198
Acritarchs																						
Acritarch sp. 1											x	x	x	x				x				x
Acritarch sp. 2													x	x								
?*Cyclopsiella* sp.													x									
Halodinium sp.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Zoomorphs																						
Copepod eggs	x			x	x	x		x			x	x	x	x	x	x	x	x	x	x		x
Foraminiferal linings	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x
Other algae																						
Botryococcus braunii									x													
Botryococcus sp.										x	x		x					x	x	x		
Zygnemataceae			x															x	x		x	x
Spirogyra sp.												x										
Tasmanaceae		x																				
Radiosperma corbiferum							x				x		x				x	x	x	x		x
Polyasterias sp.		x									x		x							x		
181-type (van Geel)																						x

4.2. *Central sector of Beagle Channel*

This sector includes Punta Remolino and Punta Paraná. The palynomorph group shows frequency values between 3.7 and 12.6% and it is characterised by the decrease in *Nothofagus* (38–58.2%), and shrubs and herbs between 1.37 to 6.83%. Among the aquatic palynomorphs, the dinoflagellate cysts are well represented with the highest species diversity (Hmax.: 2.455, Table 2) at Punta Remolino locality (sample 10) and high frequencies (10–33.9%), accompanied by organic foraminiferal linings (8.7–17%) and *Halodinium* sp. (5.3–8.85%). Acritarchs, freshwater algae (*Botryococcus* sp.) and brackish-marine algae (*Radiosperma corbiferum* and *Polyasterias* sp.) are present in low proportions (<2%), while copepod eggs vary between 0.95 and 7.6%. The tree pollen concentrations show low values (3517–13,030 grains/g) and shrub and herb concentrations vary between 155 and 1530 grains/g. The aquatic palynomorphs show concentration values between 2227 and 7618 palynomorphs/g.

The phytoclast group is characterised by predominance of amber to medium brown translucent phytoclasts (81.9%), mainly non-biostructured, highly degraded, accompanied by others with relict fibrous structure and, in some cases, banded. The biostructured phytoclasts are mainly represented by fungal hyphae, cuticles and tracheids. The opaque phytoclasts are present in very low proportions (up to 2%), with subrounded to angular equidimensional shapes and small blade-shaped fragments.

The AOM group (26%) is sponge-like and it is accompanied in lesser proportions by amorphous granular and membranous fragments. The zooclasts are poorly represented (<0.8%).

4.3. *Eastern sector of Beagle Channel*

This sector is composed of Isla Gable and External Isla Gable localities. The palynomorphs group (3.9–8.4%) is dominated by *Nothofagus* (51.2–76.5%), associated with shrubs and herbs reaching up to 8.3%. Aquatic palynomorphs are represented by marine dinoflagellate cysts (5–22.2%). In this sector, the genus *Spiniferites* reaches its highest values throughout the channel. In the EIG (External Isla Gable) locality the lowest Shannon index diversity (Hmin.: 0.693) is recorded at surface sample 12 (Table 2). Also, *Halodinium* sp. (1.2–9.7%), foraminiferal linings (3.5–19.1%), copepod eggs (up to 3.1%) and algae (0.8–3.33%) were recorded. The *Nothofagus* pollen concentrations vary between 721 and 29,704 grains/g. Shrubs and herbs (82–815 grains/g) record low concentration values. The concentration values of aquatic palynomorphs range between 180 and 11,672 palynomorphs/g.

The translucent phytoclasts (93.1%) dominate over other components of palynological organic matter. The amber to medium brown non-biostructured phytoclasts show the greatest abundance with pseudoamorphous forms and gelified tissue, accompanied by phytoclasts with fibrous and/or banded structures, highly degraded and in some cases with corroded edges. The biostructures consist primarily of cuticles associated with fungal hyphae and tracheids. The opaque phytoclasts are recorded with values up to 2.8%.

AOM (17.1%) occurs with granular and spongy masses. The zooclast group (2.2%) is represented by skeletal remains of invertebrates such as jaws. Pyrite is present as a framboidal form disseminated on translucent phytoclasts and masses of finely divided material.

5. Discussion

5.1. *Environmental interpretations*

At present, the Beagle Channel waters are influenced by a strong freshwater discharge from rainfall and glaciers through the rivers that drain the intermontane basins associated with cirque glaciers (Isla et al. 1999). Within the palynomorph group, the aquatic palynomorph assemblages identified in the sediments from the Beagle Channel have a comparable composition to those assemblages from the continental shelf of the Arctic Ocean that is strongly influenced by the freshwater input of the rivers in summer (Kunz-Pirrung 2001; Mudie & Rochon 2001). The identified dinoflagellate cyst assemblages reflect fjord (estuarine) environments close to a terrestrial ice field affected by glacier meltwater discharge with anomalously low salinity (Candel et al. 2009, 2011).

According to Matthiessen et al. (2000), the primary riverine influx is more important for discharge of particulate organic matter than coastal erosion by waves and bottom currents. The analysis of the constituents of palynological organic matter in the three sectors (western, central and eastern) along the Beagle Channel shows dominance of translucent phytoclasts accompanied by AOM and, to a lesser extent, by palynomorphs (Figure 2). The high contribution of translucent phytoclasts indicates the proximity of the continental source area to marine environments, with distances and/or times of relatively short transport. The predominance of translucent phytoclasts associated with pyrite suggests reducing conditions on the depositional environment. In humid climates, a nearshore setting close to active fluvio-deltaic sources may show dilution of their opaque content due to a greater supply of larger and ‘fresh’ (more translucent) phytoclasts (Tyson 1995).

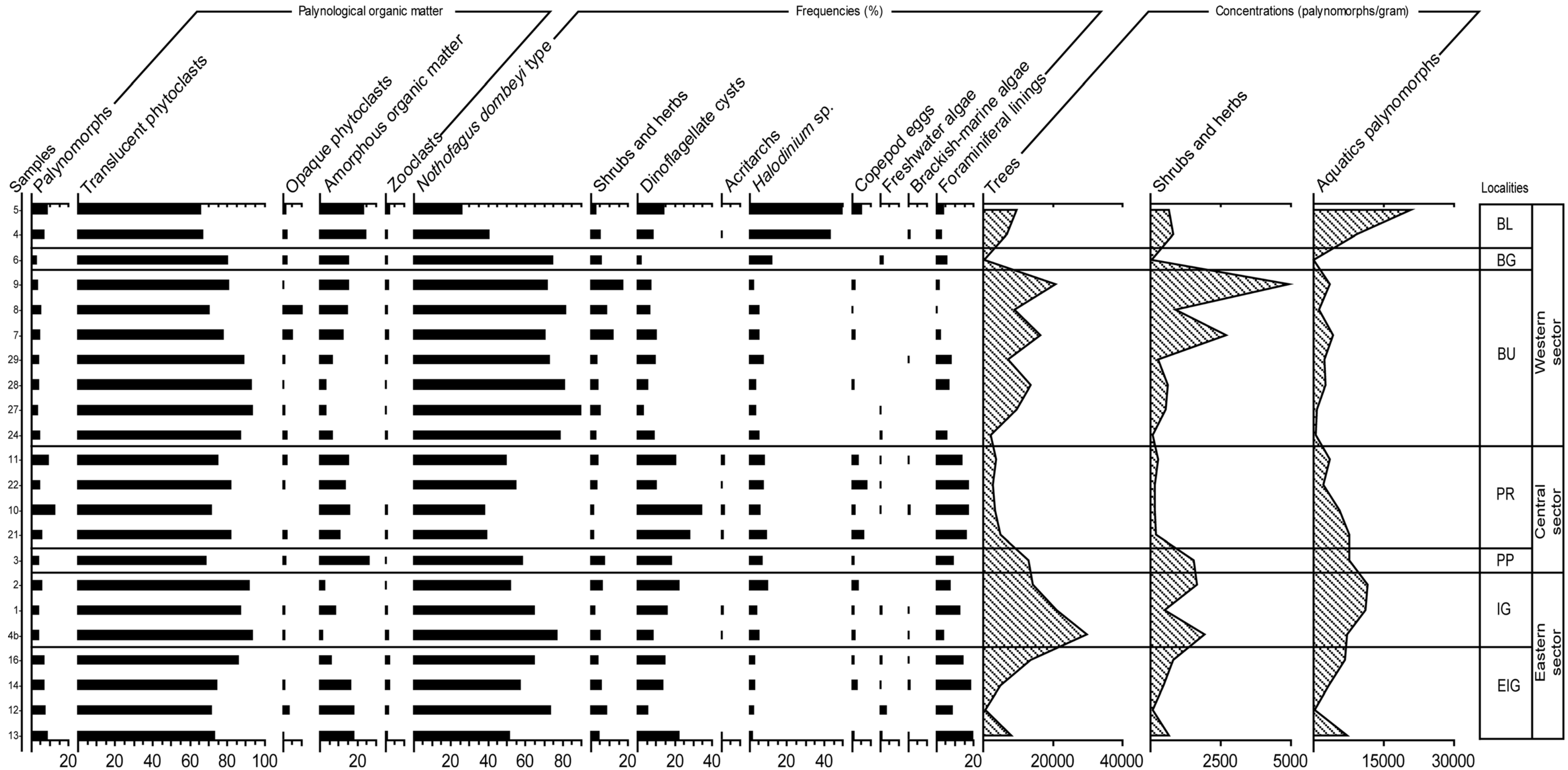

Figure 2. Relative frequencies (%) and concentration of palynofacies and microfloristic associations of surface sediment samples from the Beagle Channel. Surface samples collected at sites are indicated by number.

Taphonomic effects such as long-distance transport, selective degradation or differential preservation have been recognised and utilised for palaeoenvironmental reconstructions (Dale & Dale 1992; Campbell 1999; Bockelmann et al. 2007). According to Pross and Brinkhuis (2005), oxidation is the ultimate enemy of organic materials, especially in sediments characterised by low accumulation rates and long-term exposure to oxygen. In the present study, the opaque phytoclasts are better represented in the western sector, mainly in the Bahía Ushuaia (samples 7 and 8) locality. The highest opaque phytoclast frequencies were recorded in this locality, suggesting significant oxidation before or during final deposition in areas away from the continental source.

The AOM is probably derived from bacterial action on palynomorphs (terrestrial and aquatic) in a marginal-marine environment, where high amounts of organic matter is carried by rivers. In the western and central sectors (Bahía Lapataia and Punta Paraná, respectively) the palynofacies analysis shows the highest AOM concentrations, which indicates proximity of the terrestrial source, high input of organic matter and bacterial action under reducing conditions in the aqueous environment.

The high relative frequencies of *Nothofagus* accompanied by shrubs and herbs correlate well with the dominance of translucent phytoclasts, and are related to the development of forest communities close to the studied site. The decrease in the terrestrial palynomorph values may be related to dilution by the high inputs of terrigenous matter coming from those sites located near the shore (e.g. Bahía Lapataia), as well as by poor preservation of palynomorphs in coarse lithologies (e.g. Bahía Golondrina), under environmental stress due to low and fluctuating salinities (Candel et al., unpublished data). Also, the winnowing effect can be an indicator for the rearrangement of sediments (Holzwarth et al. 2007), and taphonomically this situation could be a result of palynomorph associations with similar hydrodynamic and/or aerodynamic characteristics (density, size, buoyancy, etc.). However, this behaviour has not been observed in the samples along the Beagle Channel. Most of the sediment samples located in the shallow depth areas of the channel are medium-coarse sand and have a low amount of pollen and dinoflagellate cysts. Therefore, these samples have been interpreted in terms of unfavourable conditions of preservation (high energy and oxidising environments) rather than by differential winnowing.

The dinoflagellate cyst assemblages are mainly Peridiniales, suggesting a marginal-marine environment with low to moderate salinity and high nutrient concentrations in surface waters, probably due to freshwater input from glacial meltwater. Also, the presence of *Halodinium* sp., *Radiosperma corbiferum*, *Polyasterias* sp., *Botryococcus braunii* and *Botryococcus* sp., and high frequencies of foraminiferal linings suggest a transitional-marine environment with nutrient-rich waters and variable salinities due to freshwater input by rivers. Dinoflagellate cysts together with foraminiferal linings and copepod eggs show a negative correlation in relation to the AOM (Figure 2). Studies on modern dinoflagellates have shown that oxygen availability exerts a strong control on cyst germination, with anaerobic conditions completely inhibiting the excystment of most taxa (Sluijs et al. 2005 and references therein). The dinoflagellate cyst assemblages may be altered pre- and postdepositionally as a result of species-selective degradation (Zonneveld et al. 1997). The rate of degradation appears to be related to the bottom water oxygen concentration (Zonneveld et al. 2007). But, in the present paper, the presence of pyrite in all samples studied indicates oxygen-depleted bottom waters, so the dinoflagellate cyst assemblages would not be severely affected by aerobic degradation. This is consistent with more dysoxic–suboxic conditions (Figure 3), suggesting the proximity of the terrestrial source with high input of organic matter into the marine environment under restricted circulation conditions. Also, this sector shows the highest percentages of *Halodinium* sp., which could be related to high input of freshwater and nutrients by rivers (de Vernal et al. 1989; Mudie 1992; Mudie & Harland 1996). It could be related to the numerous freshwater streams that received the tributaries from high Andean valleys with cirque glaciers. The contribution of detritus is important and forms plumes of suspended sediment incoming by several hundred metres into the channel (Isla et al. 1999).

5.2. *Comparison with Holocene marine records on the northern coast from Beagle Channel*

The relative frequencies of particulate organic matter for surface samples of the areas studied and two fossil sections of Mid–Late Holocene age (Albufera Lanushuaia and Río Ovando sites) located on the northern coast of the Beagle Channel were plotted in ternary diagrams to evaluate the conditions of terrestrial influx in the marine environment and the content of dissolved oxygen in the column water (after Tyson 1993, 1995 and Roncaglia 2004) and to infer the past environmental conditions from the modern analogues (Birks & Birks 1980).

The samples of Albufera Lanushuaia (ca. 5800 ^{14}C yr B.P.) and Río Ovando (4160–3540 ^{14}C yr B.P.) sites show high frequencies of phytoclasts, mostly

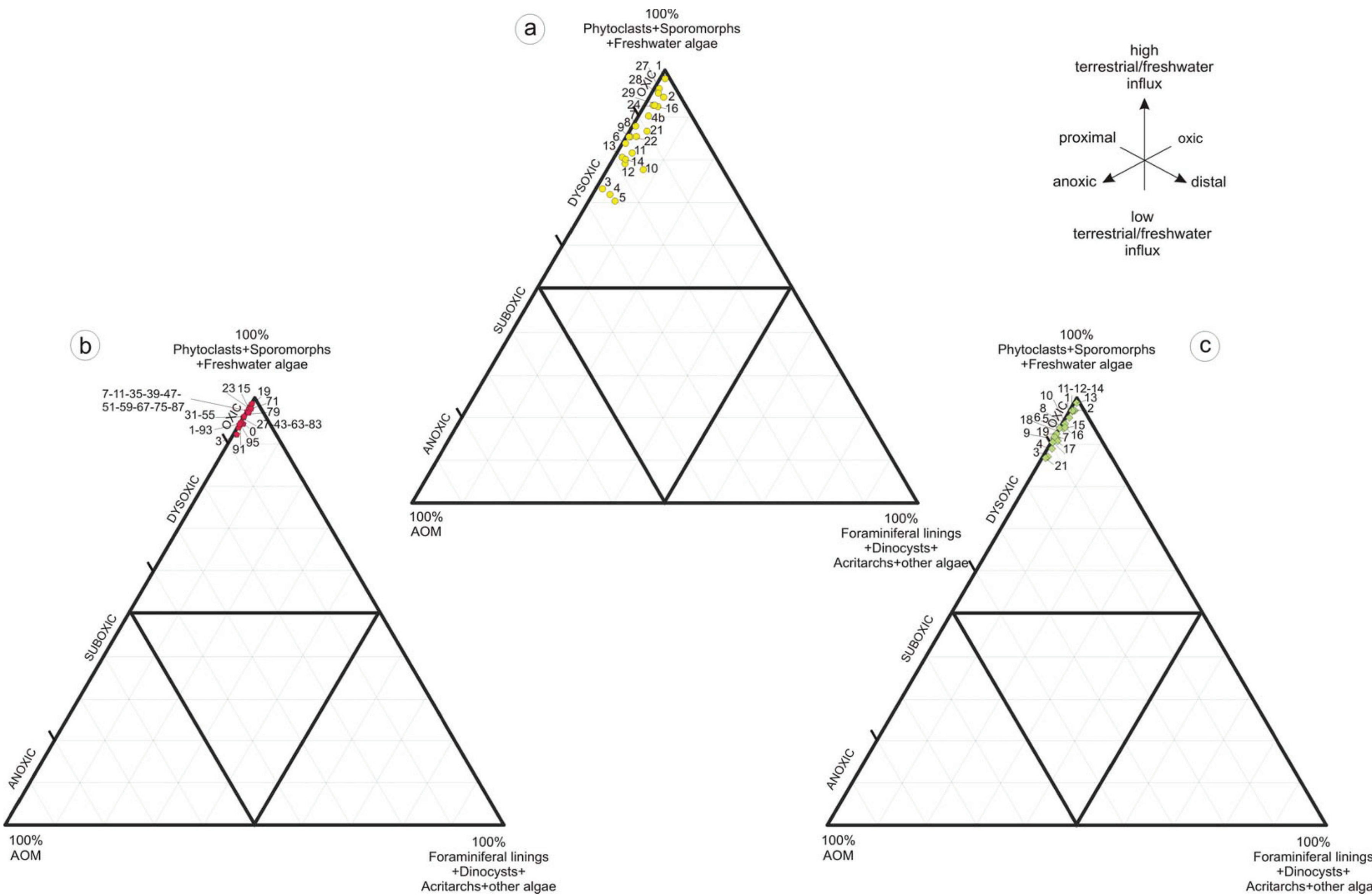

Figure 3. Ternary diagrams based on relative frequencies (%) of total palynological organic matter, modified from Tyson (1993, 1995) and Roncaglia (2004). (a) Surface sediment samples plot; (b) Albufera Lanushuaia site plot; (c) Rio Ovando site plot.

translucent, associated with sporomorphs and freshwater algae (Figure 3), suggesting high fluvial input into the marine environment with relatively short distances and/or times of transport, related to the proximity of the terrestrial source. On the other hand, these samples show low percentages of AOM content suggesting oxic to dysoxic conditions in the depositional environment with good to moderate bottom water ventilation (Roncaglia 2004).

In general, the surface samples show a positive correlation with the fossil samples taking into account the palynological organic matter content (Figure 3). The high frequencies of translucent phytoclasts are coincident with high concentration values of *Nothofagus* and shrubs and herbs (Figure 2), indicating the development of forest communities close to the marginal-marine environment. However, samples 3, 4 and 5 show high frequencies of AOM (23–26%) which is consistent with more dysoxic–suboxic conditions (Figure 3), suggesting the proximity of a terrestrial source with high input of organic matter into the marine environment under restricted circulation conditions. These samples show a negative correlation between the AOM and dinoflagellate cysts frequencies (Figure 2), related to more restricted circulation conditions that favoured the formation of AOM and inhibited the proliferation of dinoflagellates. AOM is a dominant component in suboxic to anoxic conditions; it increases with increasing nutrient availability and decreasing oxygen in water (Tyson 1995). The oxygen availability is a prime factor in controlling diversity and abundance of, particularly, benthic biota. Sediments deposited under low-oxygen conditions show reduced dinoflagellate cyst diversities (Sluijs et al. 2005 and references therein).

According to the organic foraminiferal linings, dinoflagellate cysts, acritarchs and other algae, the channel surface samples 3, 4 and 5 show a slightly higher concentration of these palynomorphs than the other samples (Figure 3), related to high frequencies of copepod egg, foraminiferal linings and *Halodinium* sp., suggesting a marginal-marine environment with availability of nutrients in surface waters probably due to freshwater input from glacial meltwater.

6. Conclusions

The palynofacies analysis shows the dominance of highly degraded translucent phytoclasts, derived from chemical oxidation by air or subaerial exposure of organic matter, associated with AOM and palynomorphs, while the opaque phytoclasts are poorly represented. Thus, the organic constituents indicate the proximity of the continental source area to marine environments, with relatively short distances and/or times of transport. The predominance of translucent phytoclasts associated with pyrite suggests reducing conditions, probably related to marginal-marine environments. Also, high frequencies of AOM indicate the proximity of the terrestrial source with high organic matter input into the aqueous environment and favourable conditions for bacterial action.

The data obtained from the palynological analysis represent the aquatic associations of the sampled areas, as well as the surrounding vegetation communities, showing a significant variability in the composition of palynological spectra. The high *Nothofagus* pollen frequencies reveal the development of forest communities close to the sites studied and indicate high terrestrial organic matter inputs to the marine environment, which correlate well with the high contribution of translucent phytoclasts. Among the aquatic palynomorphs, the dinoflagellate cyst assemblages in the channel surface samples are characterised by dominance of Peridiniales over Gonyaulacales, accompanied by freshwater to brackish-marine algae and high of foraminiferal linings, suggesting a transitional-marine environment with variable salinities and waters rich in nutrients due to high freshwater input by rivers. The negative correlation observed between the AOM and dinoflagellate cyst frequencies, suggest more restricted circulation conditions that favoured the formation of AOM and inhibited the proliferation of dinoflagellates.

The decrease in the palynomorph abundances might be related to dilution by high inputs of terrigenous matter by rivers, or with poor preservation of palynomorphs in coarse lithologies. No indication of winnowing can be detected in surface samples from the Beagle Channel with the exception of a few samples, which showed scarcity of terrestrial and marine palynomorphs, being interpreted in terms of unfavourable conditions of preservation rather than differential winnowing.

The particulate organic matter analysis of fossil marine sediments from Albufera Lanushuaia and Río Ovando sites (Mid–Late Holocene) are similar to those of surface samples from the Beagle Channel, suggesting high fluvial input into the marine environment with relatively short distances and/or times of transport related to the proximity of the terrestrial source. Also, the dinoflagellate cyst assemblages observed in surface samples have similar composition to those observed in fossil sections, suggesting that the environmental conditions during the Mid–Late Holocene remained as at present. However, the species diversity of dinoflagellate cysts preserved in the fossil sediments is lower than today, probably due to taphonomic processes that affected their preservation. Further palynological research based on other fossil marine records and surface sediments of the Beagle Channel will be necessary to refine our palaeoenvironmental knowledgement of the Holocene marine transgression into the Beagle Channel and its inter-oceanic relationships.

Acknowledgements

The authors are grateful to Mirta Quattrocchio (INGEOSUR-CONICET, Universidad Nacional del Sur) for the critical reading on an earlier version of the manuscript. We wish to thank two anonymous reviewers for their constructive comments that helped to improve the final version of the manuscript. We are also grateful to Anne de Vernal and Taoufik Radi from the Centre de recherché en géochimie et géodynamique (GEOTOP-UQAM, Université du Québec à Montréal) for their help in the systematic identifications of dinoflagellate cysts. This study was supported by CONICET (Consejo Nacional de Investigaciones Científicas y Tecnológicas; PIP 02787/02) and the Agencia de Promoción Científica y Tecnológica (PICT Redes 2002-00067) grants to Mirta Quattrocchio and Ana María Borromei, respectively. CONICET (PIP 06/06 6200, PIP 09/011 0533) and Fundación Antorchas (Proyecto A-13672/1-2) provided to Gustavo Bujalesky the financial support for field-work in the Beagle Channel.

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