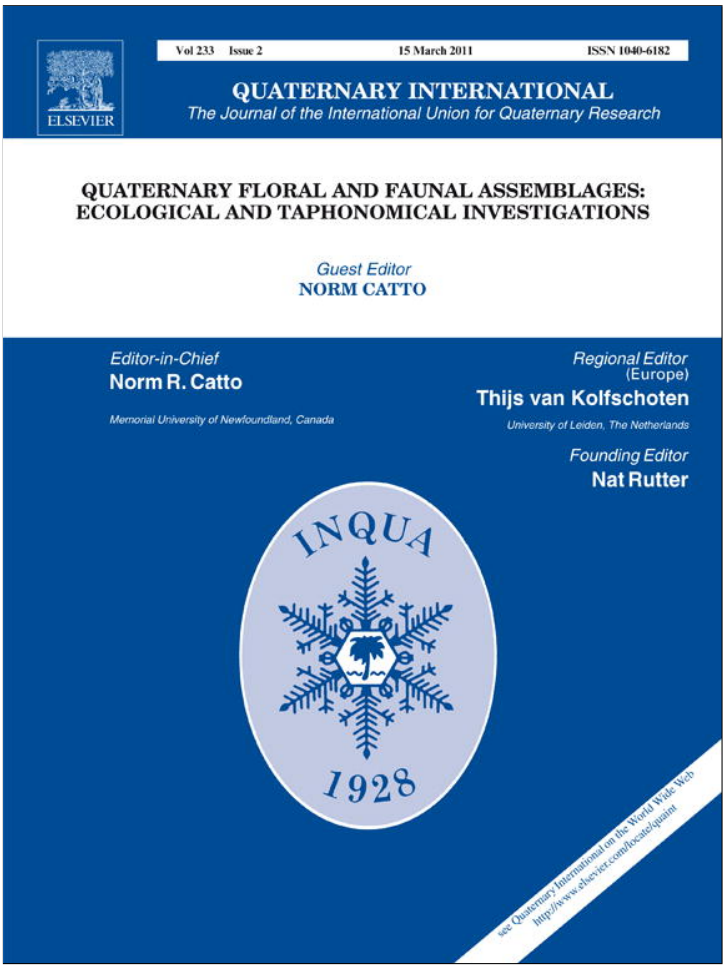

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Late Quaternary palaeoenvironmental change in western Staaten Island (54.5° S, 64° W), Fuegian Archipelago

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ABSTRACT

Late Glacial – Holocene environmental conditions were interpreted in western Isla de los Estados (Staaten Island) from geomorphological and palynological analysis. The geomorphological data from Caleta Lacroix (54°50′ S; 64 40′ W) indicate the presence of a fossil dune field that suggest exposition of a larger land surface and stronger wind intensity predominantly from SW and W probably during Late Glacial times, when sea level was lower than today. Deglaciation and onset of peat formation in the western coastal area began prior to 12,600 cal BP in response to warmer conditions. The pollen data indicates initial treeless herbaceous and paludal vegetation with scarce *Empetrum*/Ericaceae type heaths and scrubs as a result of plant invasion and short-term succession vegetal communities spreading over the shoreline areas under locally more humid conditions. The vegetation between 10,300 and 8300 cal BP included dwarf shrub heaths, scrubs, cushion plants and grasses with scattered trees, under warmer and drier climate conditions than today. After 8300 cal BP, more humid conditions allowed the expansion of an open *Nothofagus* forest associated with dwarf shrub heath communities. It was followed at 6700 cal BP by a gradual closed forest development in association with *Drimys winteri* and shrub and herb vegetation indicative of Subantarctic Evergreen Forest-Magellanic Moorland vegetation transition under cold and wet conditions. After 5500 cal BP, the rate of evergreen beech forest greatly increased with the development of almost pure Subantarctic Evergreen Forest communities. These vegetation changes accompanied a modification of the climate toward colder and wetter conditions. After 2700 cal BP, the closed forest was replaced by an open *Nothofagus* forest indicative of warm and dry conditions. The minimum of *Nothofagus* pollen registered between 1000 and 500 cal BP may correspond to the Medieval Climate Anomaly (MCA) period. All these vegetation changes are in turn related to the positioning and intensity of the Southern Westerlies wind belt, sea-ice Antarctic extent and changes in the sea level.

1. Introduction

Isla de los Estados (54°45′ S, 64°15′ W), is located at the southernmost end of South America, forming part of the province of Tierra del Fuego, Antarctica and South Atlantic Islands. The island, due to its geographical location, conforms a unique and sensitive area for Quaternary palaeoecological and palaeoclimatic studies giving information on the atmospheric and environmental conditions from cold-temperate high latitudes in the Southern Hemisphere.

Pollen records from peat deposits from Isla Grande de Tierra del Fuego (Heusser, 1987, 1989a, 1989b, 1990, 1994, 1995, 1998, 2003; Heusser and Rabassa, 1987, 1994; Markgraf, 1983, 1991a, 1991b, 1993a, 1993b; Markgraf and Anderson, 1994; Borromei, 1995; Quattrocchio and Borromei, 1998; Borromei and Quattrocchio, 2001, 2007, 2008; Borromei et al., 2007, 2010; Pendall et al., 2001; Grill et al., 2002; Mauquoy et al., 2004), have provided palaeoenvironmental and palaeoclimatic information for the late Pleistocene and Holocene. Only two studies report on the palaeoecology and paleoclimate of Isla de los Estados. The first one is a palynological study by Johns (1981) based on three peat cores collected in 1971. No numerical dates are available for these sequences. The second one is based on geochemical analyses from

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a peat core and a lake sediment core from the northern coastal area covering a record of 16,000–10,000 cal BP (Unkel et al., 2008).

This paper focuses on the pollen analysis of a peat-bog located at Caleta Lacroix (Bahía Franklin, western Isla de los Estados) and the geomorphological analysis of the area to infer the palaeoenvironmental and palaeoclimatic conditions during the last 13,000 years. The comparison with other records from high latitudes of Southern South America will contribute to evaluate the similarities and differences in the patterns of the environmental changes during the late Pleistocene-Holocene and their relation with climatic conditions.

2. Regional setting

Isla de los Estados, at the southernmost end of South America, is part of the Argentine Province of Isla Grande de Tierra del Fuego. It is located between 54°38′ S and 54°55′ S and 63°48′ W and 64°46′ W (Fig. 1a) ca. 30 km southeast from Península Mitre, Isla Grande de Tierra del Fuego, and separated from it by the Le Maire Strait. Isla de los Estados has a surface area of 496 km^2, a maximum E–W length of 62 km, and an average width of 6 km (Niekisch and Schiavini, 1998). It is the southeastern end of the Andes range above present sea level. The topography is rugged, with maximum elevation just below 1000 m a.s.l. Overall, the topography is characteristic of terrain repeatedly glaciated during the Quaternary (Ponce, 2009). At the western area of the island, however, the topography is less rugged than at its central and eastern areas.

The current climate of Isla de los Estados is cold and humid. According to García (1987), the climate of the island corresponds to general classification of Oceanic Insular Cold Climate. Summer has a mean temperature of 8.3 °C, with mean daily extremes of 16.2 °C and 3 °C. Winter mean temperature is 3.3 °C, with mean daily extremes of 7.4 °C and −4 °C (Dudley and Crow, 1983). Though no reliable records are yet available, rainfall is estimated to be in the range of 2000 mm/y (Niekisch and Schiavini, 1998), but actual precipitation may be highly variable across the island, particularly by altitude. Prevailing winds are from the southwest and the northwest and they are active throughout the year (Kühnemann, 1976).

In the island, seven vegetation types related to altitude and terrain forms are recognized (Dudley and Crow, 1983). The more protected and lower mountain slopes and valleys show the development of *Nothofagus betuloides* and *Drimys winteri* forest characteristics of the true Subantarctic Evergreen Forest (Fig. 2a). In those sites constantly exposed to continuously strong wind conditions, the main vegetation is the Magellanic Moorland Formation, a mosaic of interfingered and superimposed subunits (*Empetrum rubrum* association, *Caltha* association and *Astelia pumila* association) that may cover a rather small area forming blanket-like patches (Fig. 2b). The Scrub Formation occurs on mountain slopes exposed to the prevailing southwesterly and westerly winds where trees of *Nothofagus antarctica* and shrubs grow low and tortuous. Above approximately 450 m, the so-called Alpine Formation occurs with sparse vegetation cover, and often includes dwarfed forms of *Nothofagus antarctica* and *Empetrum rubrum* (Fig. 2c). Soil conditions also influence the vegetation that characterizes the island. For example, the cold and damp climate favors peat development mainly at low and intermediate elevations (Meadow Formation, Fig. 2d). However, in spite of the constant soil humidity, the topography influences drainage patterns and this is reflected by the composition of the vegetation. Littoral and Maritime Tussock Formations develop along the stony and rocky coastal areas, small peats and soils above the high tide line and in rock crevices at the intertidal zone.

3. Materials and methods

3.1. Pollen analysis

Fossil peat core IDE-1 (Figs. 1b and 3) was taken with a Russian corer. In the laboratory, the core was sub-sampled at 5 cm intervals and the sediments described. A total of 65 fossil pollen samples were obtained. In order to achieve modern pollen data to interpret the palaeovegetation changes from the fossil pollen spectra, 16 surface samples were extracted from the studied area (samples Ms1 to Ms7) and northern coast of the island (samples Ms8 to Ms16) (Fig. 1b). Modern pollen frequencies are plotted in Fig. 4.

For pollen analysis, peat samples were prepared according to standard Faegri and Iversen (1989) techniques. *Lycopodium* spore tablets added to each sample prior to treatment (Stockmarr, 1971) allowed calculation of the pollen concentration per gram of sediment. Frequencies (%) of tree, shrub and herb pollen of terrestrial origin were calculated from sums mostly of ≥300 grains. Pollen of aquatic plants and cryptogams were calculated separately and related to the sum of terrestrial pollen. Fossil frequency and concentration pollen data are plotted in Figs. 5 and 6. Other herbs include taxa with low values, such as Caryophyllaceae, Rubiaceae, *Valeriana*, Scrophulariaceae, *Azorella*, *Acaena*, *Pratia*, *Cardamine*, *Rubus*, *Crassula*, Saxifragaceae, Onagraceae, *Geum* and Solanaceae. Using the Cavalli-Sforza Distance (TGView 2.0.2, Grimm, 2004), a stratigraphically constrained cluster analysis was applied to distinguish pollen zones considering taxa that reach percentages of ≥1% of the sum of terrestrial pollen.

Pollen from the evergreen species *N. betuloides* and the deciduous species *Nothofagus pumilio* and *N. antarctica* are reported as "*Nothofagus dombeyi* type" given the difficulty in species separation Another special case is *Empetrum rubrum*, *Gaultheria/Pernettya* (Ericaceae) and *Lebetanthus myrsinites* (Epacridaceae) which are morphologically similar and occur as tetrads; for these reasons, they are considered as one taxonomic group on the pollen diagrams in the present study, named "*Empetrum*/Ericaceae type".

3.2. Chronology

Five peat samples provided chronologic control for the peat section. The NSF-Arizona AMS Laboratory, U.S.A, undertook the radiocarbon analysis on the samples, and the radiocarbon ages were converted to calendar years BP using the program CALIB 6.0 (Stuiver et al., 2005) and the South Hemisphere curve (SHCal04) (McCormac et al., 2004) (Table 1). A second-term polynomial curve was used to construct an age-depth model for the core (Fig. 7).

3.3. Geomorphology

For the geomorphological analysis was used topographic maps, aerial photographs at scale 1:40.000 of the Servicio de Hidrografía Naval (1971), SPOT satellite images (1995) and free-access, NASA SRTM3 images (S55W065 and S55W064). A barometer provided elevation control for field sites and checked against elevations from the SRTM3 digital model.

4. Caleta Lacroix, Bahía Franklin

4.1. Geomorphology and stratigraphy of the studied area

The area is located at the western sector of the island, in Caleta Lacroix, inside of Bahía Franklin (54°50′ 50.6″ S; 64° 39′ 27.4″ W) (Figs. 2a–d and 3). The site encloses a dune field in an elongated depression limited to the NW and SE by rocky valley sides with steep slopes close to 20°, connecting northeastwards with the

widely extended *Astelia* peatlands. These landforms end abruptly on their southeasterly edge, where they are intercepted by a local, NW-trending stream, which drains into the sea. The dunes are composed by nine main dunes, of larger size and better definition, and another group of three smaller dunes, of lesser topographic expression, located immediately to the NE. Most observations were done within the firstly cited group. This set of landforms is characterized by well preserved, rectilinear crests, elongated in an N 65°–70° direction (Fig. 2g). Some of the dunes may be laterally connected defining a typical "Y" shaped bifurcation opened to the SW (lee-side), though in other cases they unite generating an "X" shaped design. The longest dune is 1.5 km, the mean length is 0.9 km and the shortest one is 0.5 km long. The average height is around 15–20 m, the mean width at the base is of 50 m and the

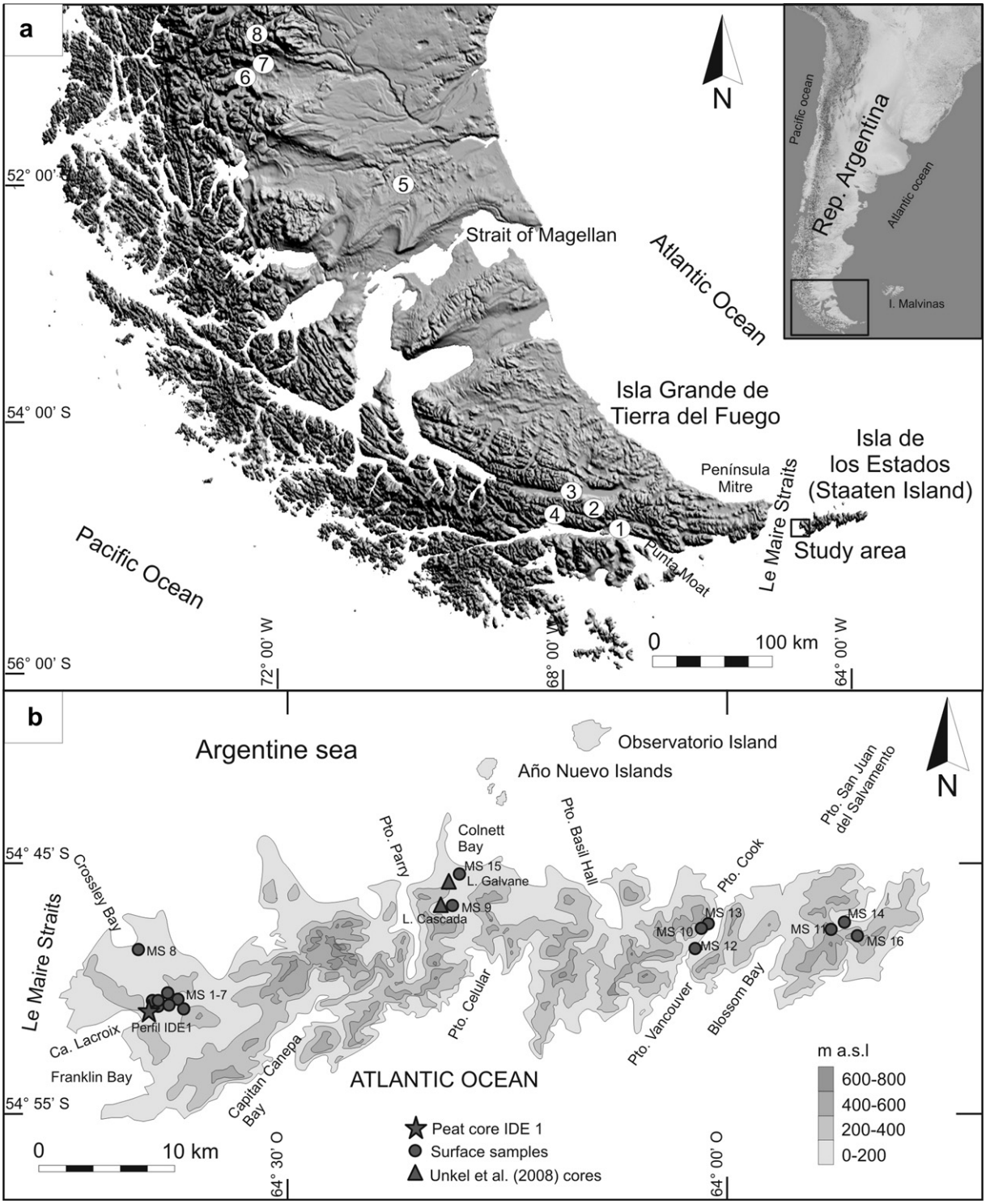

Fig. 1. Location map. (a) Southern Patagonia illustrating the location of the sites mentioned in the text: (1) Puerto Harberton (Heusser, 1998), (2) Las Cotorras (Borromei et al., 2010), (3) Lago Fagnano (Borromei et al., in preparation), (4) Valle de Andorra (Mauquoy et al., 2004), (5) Laguna Potrok Aike (Wille et al., 2007), (6) Lago Guanaco (Moreno et al., 2009), (7) Vega Ñandú (Villa-Martínez and Moreno, 2007), (8) Cerro Frías (Tonello et al., 2009). (b) Isla de los Estados showing the location of IDE-1 peat core and surface samples.

mean separation (the interdune areas) is 10–15 m. The total surface occupied by the dune field is less than 2 km^2 and the accumulated sand volume has been estimated as 2.5 $\times$ 10^6 m^3. The dunes are bordered by a dense, mature-grown *Nothofagus betuloides* forest and the intermediate dune areas contain grassy patches and peatlands.

Though the dune crests present a marked longitudinal symmetry, the proximal ends, in contact with the beach, are clearly eroded. Tongues of contemporary sand which originate at the beach advance landwards by Aeolian action, burying neighboring grasslands and peatlands, including older dunes as well (Fig. 2d).

4.1. IDE-1 pollen section

The IDE-1 pollen section (54° 50′ 46.5″ S; 64° 38′ 50.8″ W; 27 m a.s.l.) is located in the interdune area (Fig. 3). Between the base at 330 and 155 cm depth, the core consists of highly humified dark brown peat with fibrous. Between 155 and 110 cm depth, compact highly humified peat and dark brown sandy sediments

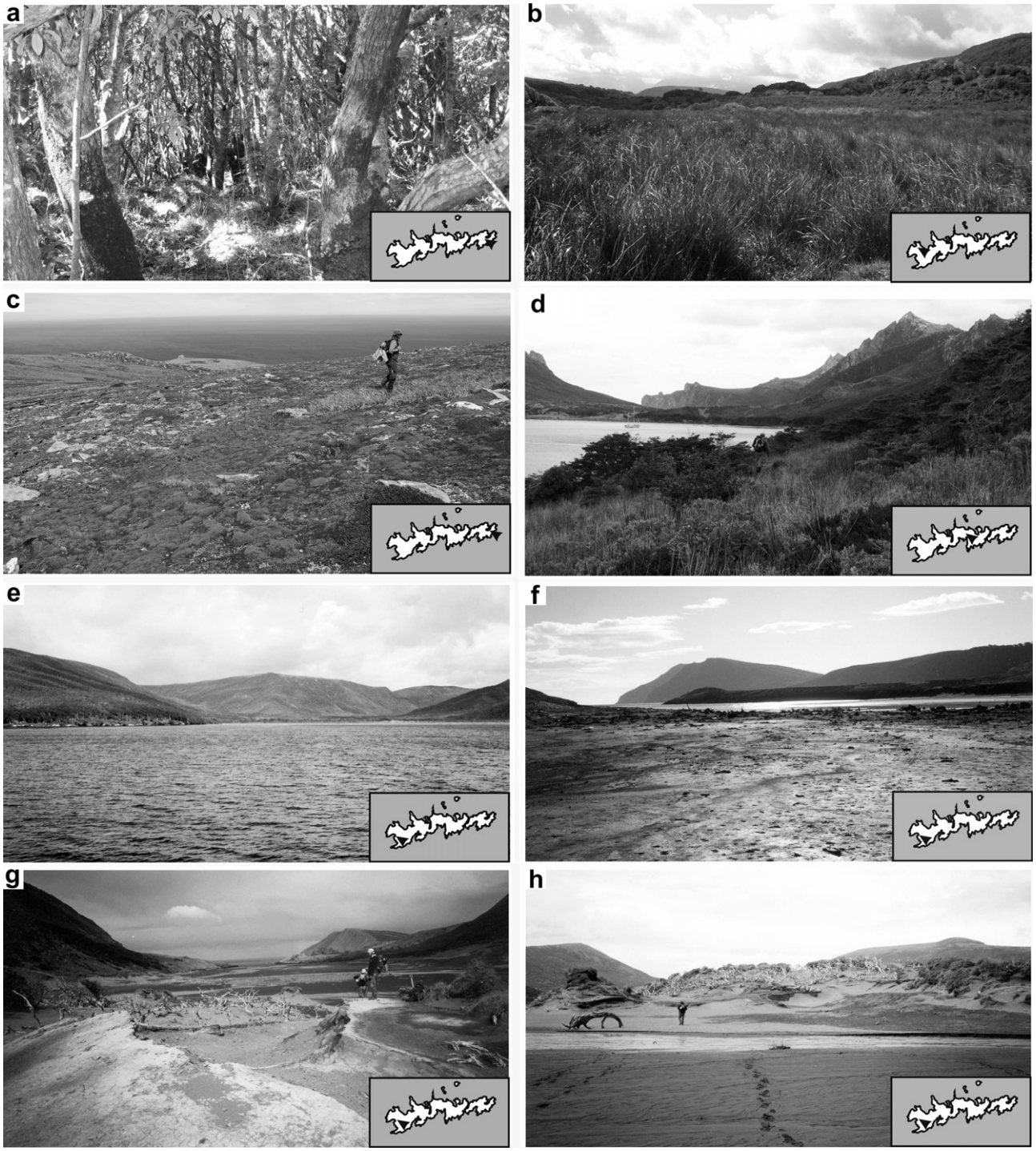

Fig. 2. Vegetation: a - Closed *Nothofagus* forest, b - Magellanic Moorland, c - Andean tundra, d - Open *Nothofagus* forest. Caleta Lacroix, Bahia Franklin: e - studied site, f - deltaic beach, g- aeolian active, h - fossil dune.

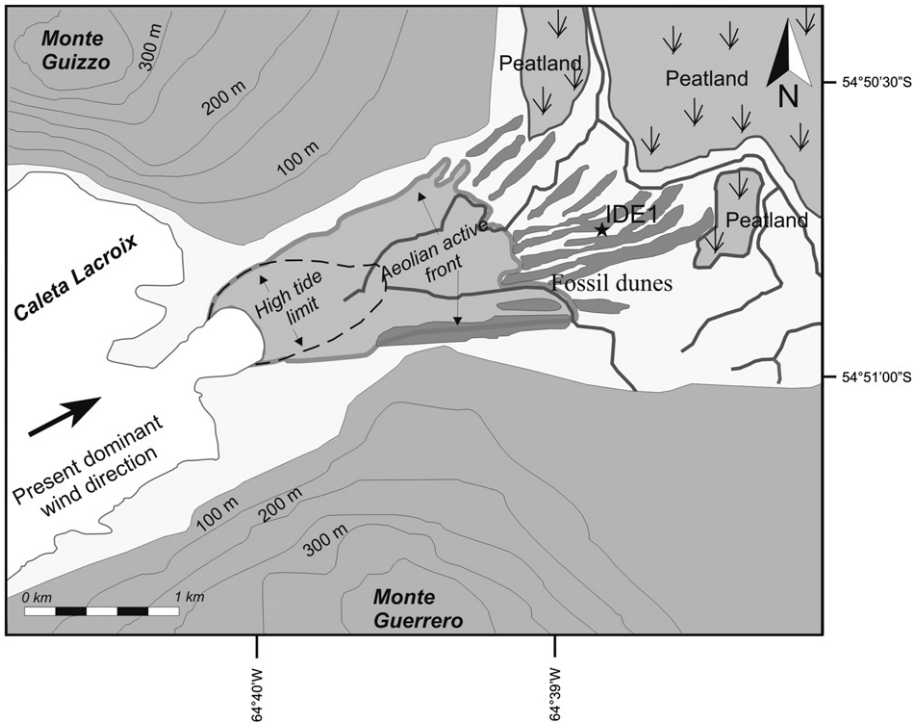

Fig. 3. Geomorphological map and IDE-1 peat core, Caleta Lacroix.

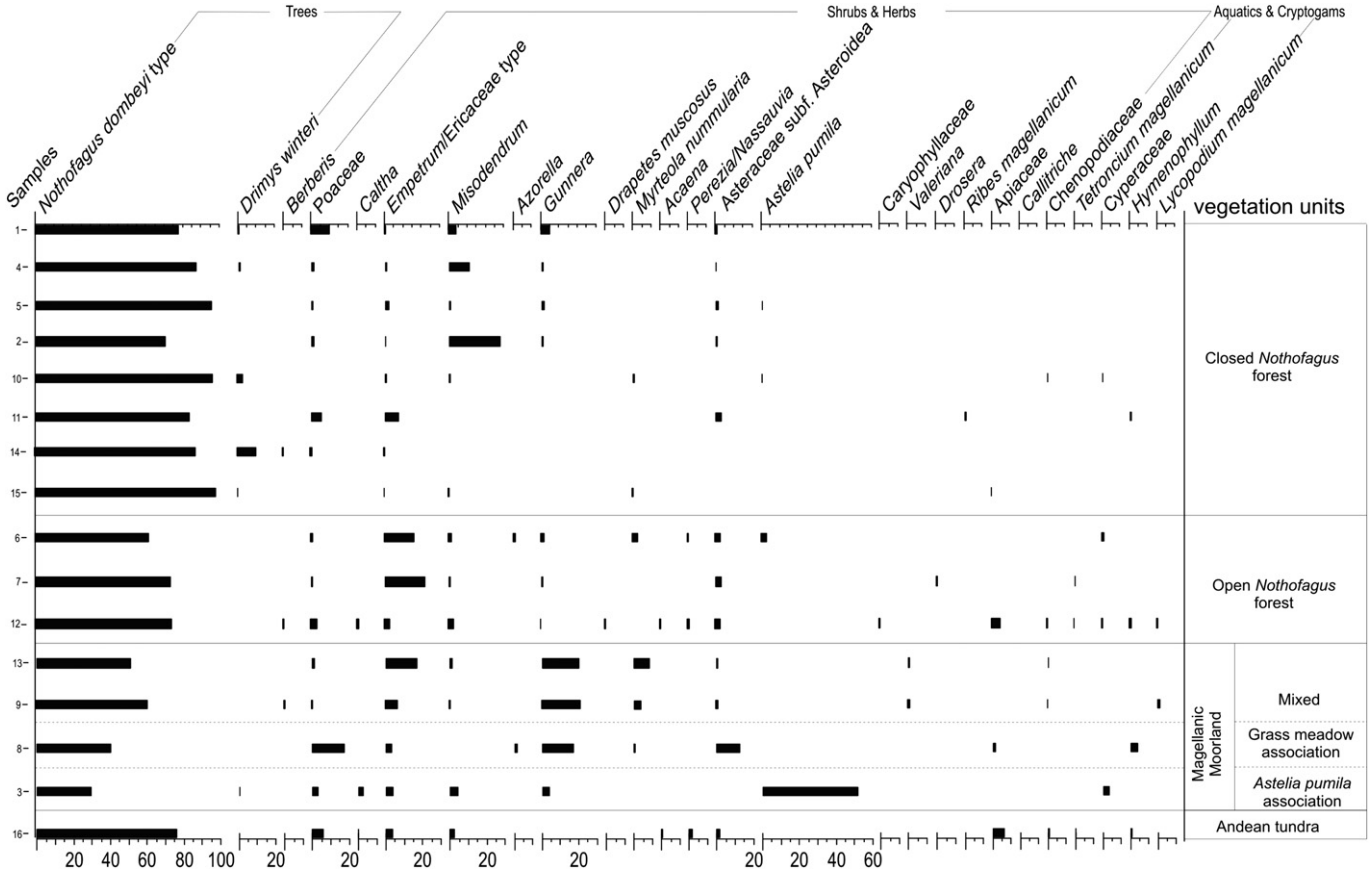

Fig. 4. Surface pollen frequency diagram (%). Surface samples collected at sites are indicated by number.

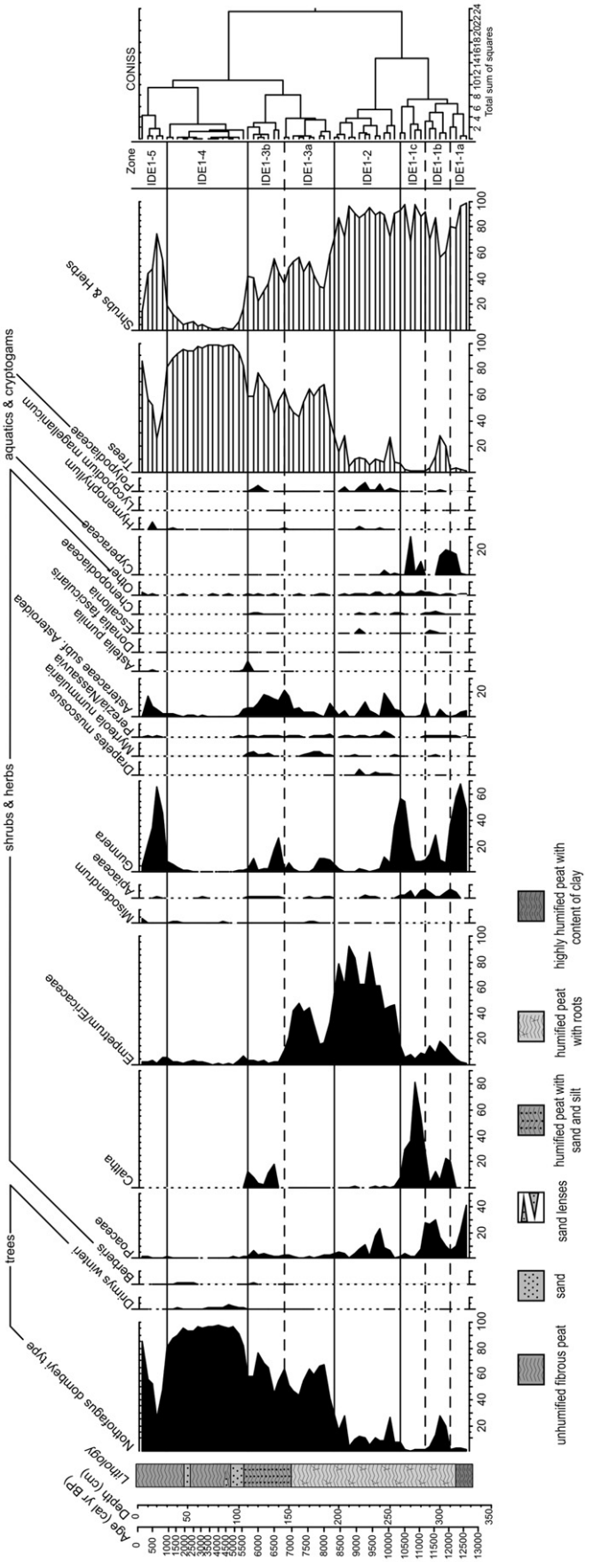

Fig. 5. Fossil pollen/spore frequency diagram (%) and stratigraphy at IDE-1 section, Caleta Lacroix.

are found. Dark compact peat layers interspersed with dark gray sand lenses are present between 110 and 75 cm depth. The upper 75 cm consists of dark brown to bluish gray brown unhumified fibrous peat.

5. Results

5.1. Modern pollen data

The pollen spectra from surface samples (Fig. 4) represent the principal units of vegetation found in the island: *Nothofagus* forest, Magellanic Moorland and Andean vegetation. The pollen concentration values of surface samples are not shown in Fig. 4.

1 Closed *Nothofagus* forest: characterized by the highest percentages of *Nothofagus dombeyi type* (73–98%). The data reveal the relative importance of *Drimys winteri* (9%) and *Misodendrum* (27%) and, the lowest values of *Empetrum*/Ericaceae type. Poaceae with values of 10% are related to grass meadows close to the sampled site. Total pollen concentration values are high (1,746,000–51,000 grains/g) contributed mainly by *Nothofagus dombeyi* type (up to 825,000 grains/g). Quantities of *Drimys winteri* pollen indicate the presence of Subantarctic Evergreen Forest (*Nothofagus betuloides-Drimys winteri* association) that extends toward the outer coastal zone of heavy precipitation (800–>1000 mm/year) (Pisano, 1977). Records of the beech parasite *Misodendrum* (27%) suggest local establishment of forest elements.
2 Open *Nothofagus* forest: dominance of *Nothofagus dombeyi* type pollen characterized this vegetation unit with values up to 74%, accompanied by *Empetrum*/Ericaceae type (22%) and great diversity of herbs and shrubs. In this forest, such species as *Empetrum* may become locally sub-dominant in the more open facies (Moore, 1983). Total pollen concentration values are lower than of the previous unit varying between 600,000 and 46,300 grains/g. The *Nothofagus* concentration records a maximum of 226,600 grains/g.
3 Magellanic Moorland: This vegetation unit is represented by three different bog communities: mixed, grass meadow and *Astelia pumila* associations. In general *Nothofagus dombeyi* type reaches pollen values up to 60%. Peaks of *Empetrum*/Ericaceae type (21%), *Gunnera* (21%) and *Myrteola nummularia* (8%) reflect the character of mixed bog communities. High values of *Astelia pumila* (52%) characterize the most notable community of this unit, which probably is fed by an annual precipitation of more than about 2000 mm and, comprises a dense low covering cushion plants. Grass meadow association shows the relative importance of Poaceae (17%), *Gunnera* (17%) and Asteraceae subf. Asteroideae (12%). The latter association conforms distinctive grassland vegetation that occurs on sheltered coastal localities, which show a markedly oceanic influence (Moore, 1983). Total pollen concentration values recorded in this unit range between 127,000 and 10,200 grains/g.
4 Andean tundra: vegetation of this unit lies at and just above timberline (450 m a.s.l.). The Andean communities consist of sparse and scattered plants that occur mainly in sheltered hollows and peat pockets between rocks (Dudley and Crow, 1983). Increased quantities of *Nothofagus dombeyi* type pollen (up to 75%) are indication of great atmospheric dispersion at this altitudinal site and, also the presence of “krummholz” stands formed by *Nothofagus antarctica* species at the altitudinal limit of forest are inferred. Cushion and heath plants such as *Azorella* (6%) and *Empetrum*/Ericaceae type (3%) are present. Close associates include Poaceae, *Acaena*, Asteraceae subf. Asteroideae and *Nassauvia*. The total pollen concentration

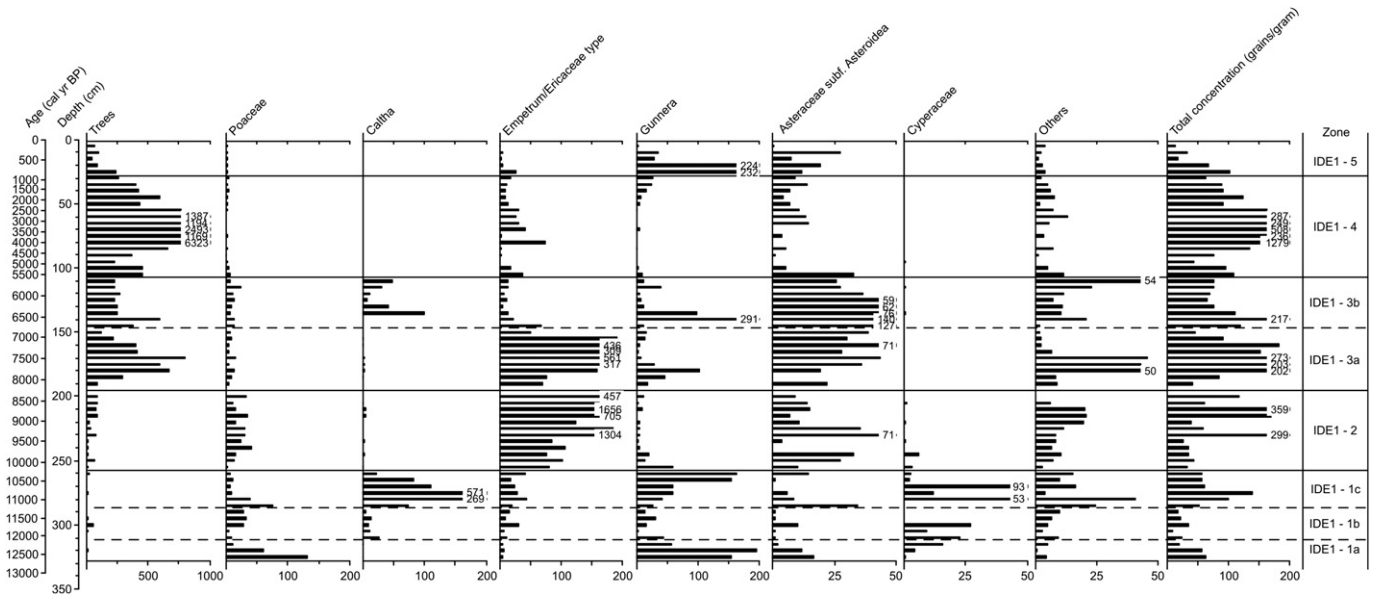

Fig. 6. Fossil pollen concentration (grains/g) diagram at IDE-1 section, Caleta Lacroix.

reaches 352,000 grains/g with the highest values corresponding to *Nothofagus dombeyi* type (134,000 grains/g).

5.2. Fossil pollen data. IDE-1 section

Cluster analysis recognized five main zones: IDE1-1 to IDE1-5 based on conspicuous changes in the pollen stratigraphy (Fig. 5). In order, from the lower to the upper part of the section, they are:

- *Zone IDE1-1* (330–260 cm, *ca.*12,600–10,300 cal BP): The non-arboreal pollen dominates the zone with high values (57–98%) while the arboreal pollen displays low values (<27.7%). Three subzones can be differentiated based on changes in the proportions of non-arboreal and arboreal taxa. The initial subzone (IDE1-1a: 12,600–12,000 cal BP) is dominated by *Gunnera* (36–68%) and Poaceae (6–42%). The middle subzone (IDE1-1b: 12,000–11,200 cal BP) shows an increase in *Nothofagus dombeyi type* (28%), *Caltha* (22%) and *Empetrum*/Ericaceae type (18%) percentages accompanied by Poaceae (30%) and *Gunnera* (29%). The upper subzone (IDE1-1c: 11,200–10,300 cal BP) displays an increase in *Caltha* and *Gunnera* percentages (up to 82 and 57% respectively), whereas *Nothofagus dombeyi* type decreased to 7% and Poaceae to 8%. Cyperaceae are present, although fluctuating, with peaks of 30%. Total pollen concentration (Fig. 6) is moderate (<650,000 grains/g) in the subzone IDE1-1a, contributed mainly by *Gunnera* (195,000 grains/g) and Poaceae (132,000 grains/g). A decline in total values occurs in subzone IDE1-1b (354,000 grains/g), with an arboreal concentration peaks of 49,000 grains/g accompanied by Poaceae, *Empetrum*/Ericaceae type and *Gunnera* (32,000 grains/g). Within subzone IDE1-1c, *Caltha* dominates, achieving a maximum of 571,000 grains/g and-contributing to the bulk of the total concentration values (1,400,000 grains/g).
- *Zone IDE1-2* (260–195 cm, 10,300–8300 cal BP): Non-arboreal pollen maintains high percentages (95.8%). The zone features the dominance of *Empetrum*/Ericaceae type (43–92%) accompanied by *Nothofagus dombeyi* type (28%), Poaceae (23%) and Asteraceae subf. Asteroideae (19%). Increasing total pollen concentration values, as high as 3,590,000 grains/g, are caused primarily by *Empetrum*/Ericaceae type (1,650,000 grains/g) and secondarily by *Nothofagus dombeyi* type (91,500 grains/g) (Fig. 6).
- *Zone IDE1-3* (195–105 cm, 8300–5500 cal BP): This zone shows the co-dominance of arboreal and non-arboreal taxa. Two subzones can be identified on the basis of their proportional changes. Subzone IDE1-3a (8300–6700 cal BP) is dominated by *Nothofagus dombeyi* type (41–66%) and *Empetrum*/Ericaceae type (11–47%) accompanied by low proportions of Asteraceae subf. Asteroideae (16%) and *Gunnera* (11%). Subzone IDE1-3b (6700–5500 cal BP) shows a decrease in *Empetrum*/Ericaceae type values to 3% and increase in *Nothofagus dombeyi* type values (up to 76%) accompanied by *Gunnera* (27%), Asteraceae subf. Asteroideae (21%) and *Caltha* (18%). *Drimys winteri* appears in low values (0.8%) but becomes continuous through the sequence. Total pollen concentration recorded higher values during subzone IDE1-3a (2,730,000 grains/g) and decreased in subzone IDE1-3b (662,000 grains/g) (Fig. 6).
- *Zone IDE1-4* (105–30 cm, 5500–1000 cal BP): The arboreal taxa dominate the zone. *Nothofagus dombeyi* type exhibits the highest values (97%) in the entire peat core accompanied by

Table 1
AMS ^{14}C dates and calibrated ages of selected samples from IDE-1 section, Caleta Lacroix.

Depth (m)	Laboratory No	^{14}C BP	Calibrated BP (median probability)	1σ range	2σ range	Material
0.30	AA72174	1081 ± 34	990	955–1004	933–1056	peat
1.05	AA75398	4811 ± 49	5525	5476–5540	5464–5645	peat
2.00	AA72175	7645 ± 45	8434	8390–8457	8382–8540	peat
2.60	AA75399	9174 ± 51	10,340	10,313–10,394	10,235–10,439	peat
3.30	AA62509	10,670 ± 39	12,607	12,566–12,636	12,548–12,686	clay gyttja

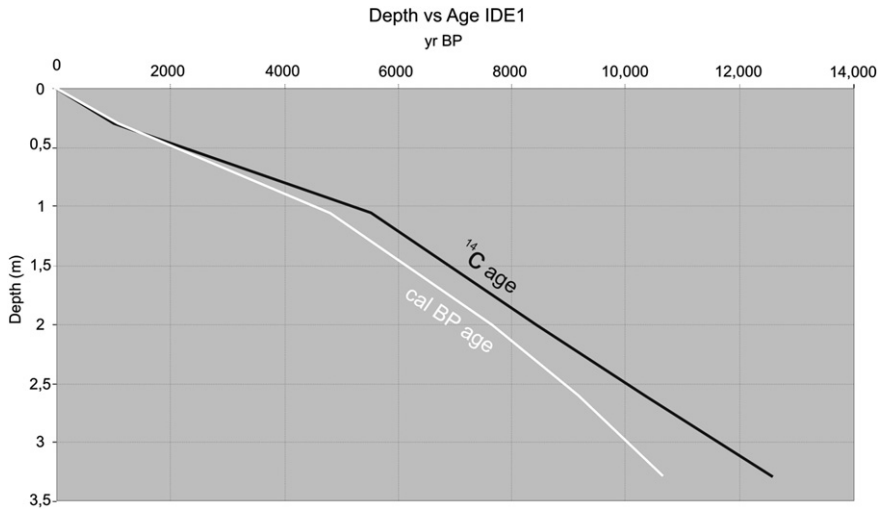

Fig. 7. Age-depth curve from IDE-1 pollen section showing radiocarbon (black) and calendar (white) dates.

Drimys winteri that also records its maximum values (3%). Total pollen concentration (Fig. 6) values range between 12,792,000 and 450,000 grains/g. *Nothofagus dombeyi* type gains prominence between 4000 and 2700 cal BP, achieving a maximum of 6,323,000 grains/g.

- *Zone IDE1-5* (30–0 cm, 1000–0 cal BP): Non-arboreal taxa dominate the zone. The record of *Nothofagus dombeyi* type suddenly drops to 25% and later, climbs up to 86% toward the end of the zone. Also, *Gunnera* frequency rises to 66% and later, declines to 4%. Close associates include Asteraceae subf. Asteroideae (17%). Total pollen concentration values (Fig. 6) decrease abruptly reaching a minimum of 142,000 grains/g. *Nothofagus* records 45,300 grains/g and *Gunnera* peaks at 232,000 grains/g.

6. Discussion

6.1. Reconstruction of palaeoenvironmental conditions

During the Last Glacial Maximum (LGM; ca. 24 ka BP; Rabassa, 2008) sea levels were probably stable around 120 and 140 m below present sea level. Under these conditions, Isla de los Estados was connected to the rest of the continent as Isla Grande de Tierra del Fuego was (Unkel et al., 2008; Ponce, 2009; Ponce et al., 2009). The northern coastline of Isla de los Estados, during the LGM, was found at around 100 km on a straight line north of its present position (Ponce et al., 2009). As well, the southern paleo-coast line of this island was located only ca. 5 km S of its present position, due to the existence of a deep continental talus very close to the island (Ponce et al., 2009). The Beagle Channel, a drowned glacial valley, was formerly occupied by a large outlet glacier from the Cordillera Darwin, the "Beagle Glacier". The LGM is represented by a complex system of terminal moraines at Punta Moat (Fig. 1a). This event was named the Moat Glaciation (Late Wisconsinan, MIS 2, but perhaps Stage 4 as well) (Rabassa et al., 2000; Rabassa, 2008). The position and extent of the Fuegian mountain ice field during the LGM did not reach Isla de los Estados, although local glaciers may have occupied large parts of the island (Unkel et al., 2008; Ponce, 2009).

In the Beagle Channel, deglaciation processes would have started before ~18,000 cal BP according to the basal date of 14,640 ^{14}C BP (17,693 cal BP) from the Puerto Harberton site (Heusser, 1998). By this time, the "Beagle Glacier" had retreated from its maximum full-glacial positions at the Punta Moat locality (Fig. 1a) (Heusser, 1998) under the global increasing temperature trend (McCulloch et al., 2000; Pendall et al., 2001).

The opening of the Le Maire Strait, with the subsequent separation of Isla de los Estados and Isla Grande de Tierra del Fuego would have taken place approximately at around 15,000 cal BP, when sea level rose above −85 m a.s.l (Ponce, 2009).

At Bahía Franklin, according to the basal age of the peat core analyzed, the fossil dunes surrounding the mire could have originated prior to 12,600 cal BP and probably when sea level was still lower than today. According to the geomorphological evidence, the fossil sand dunes would have been deposited at Caleta Lacroix as a result of land surface exposure and strong winds from the west-southwest.

The warming climate trend that favored deglaciation processes and peat formation in the Canal Beagle area before 18,000 cal BP (Heusser, 1998) and in the coastal area from Isla de los Estados before 16,000 cal BP (Unkel et al., 2008), probably was also favorable to stabilize the fossil dunes and promote the mire formation at Caleta Lacroix before 12,600 cal BP. Initial pollen assemblage (Fig. 5) shows the dominance of pioneer herbs like *Gunnera* and Poaceae, spreading into the treeless lowland areas (subzone IDE1-1) between 12,600 and 10,300 cal BP. The increase of hydric *Caltha* indicates a probable shift toward locally more humid environments during subzone IDE1-1c. Meanwhile, the record of Cyperaceae suggests minerotrophic conditions and water availability. The vegetation, in addition, would have included heath (*Empetrum*/Ericaceae type) and scrub (Asteraceae subf. Asteroideae) communities. Presence of shrubby littoral vegetation related to present shoreline areas in sheltered bays (Dudley and Crow, 1983), also can be seen by minor but significant occurrence of *Escallonia* pollen (subzone IDE1-1b). All these communities are developed in locally wet settings such as flat-lying areas of slow-moving and impeded drainage, possible affected by snowmelt runoff from local glacier meltwater discharge, and reflect a variety of succession sequences on these deglacial landscapes following glacier recession. The low frequency and concentration values of *Nothofagus* (Fig. 6) imply sources from regional (Prentice, 1985) forest refuges and/or low pollen production due to unsuitable environmental conditions for tree growth. Compared with minima in the early part of the record, *Nothofagus* frequencies in subzone IDE1-1b are higher (28%) (Fig. 5). This assemblage (subzone IDE1-1b) dated between 12,000 and 11,200 cal BP is possibly the result of short-term plant invasion from some proximal forest stand or westerly wind intensification

that favored the long-distant atmospheric transport from distant sites.

Between 10,300 and 8300 cal BP *Nothofagus* trees gradually started to spread in the landscape. It is probable that *N. antarctica* were involved in the processes of colonization first, occupying those sites less favorable to growth. According to modern analogues in southern of Chile, *N. antarctica* is a pioneer species that colonizes the deglaciated land first (Donoso, 1993, in Fesq-Martin et al., 2004). It has wider ecological amplitude than *N. pumilio* and is prominent where shallow soils, high water table and aridity prevail (Moore, 1983). Close associates of the opener forest communities are the occurrence of the parasite *Misodendrum* and the epiphitic *Hymenophyllum* fern that grow on the forest floor (Dudley and Crow, 1983). During this interval, the expansion of dwarf shrub heath (*Empetrum*/Ericaceae type) communities (zone IDE1-2) indicates low exchange capacity and pH conditions on the mire (Fig. 5). *Empetrum* is a dominant species that develops over acid, shallow and well-drained soils (Moore, 1983) in association with *Drapetes muscosus* and *Myrteola nummularia* (Moore, 1983). Openness in landscape is also inferred by the record of light-dependent Polypodiaceae ferns (Heusser, 1998). A comparable plant assemblage can be found today in Fuego-Patagonian steppe where mean annual precipitation values do not surpass 400 mm/year and summer temperatures average between 11 and 12 °C (Pisano, 1977). This evidence suggests an increase in temperature and effective moisture, in spite of precipitation which continued to be lower than today.

An abrupt rise of arboreal taxa occurred between 8300 and 5500 cal BP, as indicated by high percentage and concentration of *Nothofagus* pollen values (zone IDE-3) (Figs. 5 and 6). The arboreal pollen show frequent, large-amplitude fluctuations that indicate high variability in forest cover near the studied site. Between 8300 and 6700 cal BP (subzone IDE-3a), the landscape displays a physiognomy of a closed *Nothofagus* forest interspersed with dwarf shrub heath (*Empetrum*/Ericaceae type, *Myrteola nummularia*), scrub (Asteraceae subf. Asteroideae) and herb (*Gunnera*, Poaceae) communities related to increased effective precipitation. Analogous communities exist today in the Subantarctic Deciduous Forest in connection with *Sphagnum* bogs and their setting at lower altitudes from south of Isla Grande de Tierra del Fuego where mean annual precipitation totals between 500 and 800 mm and mean annual temperature averages 7 °C (Pisano, 1977; Heusser, 1998).

After 6700 cal BP (subzone IDE-3b), the record of *Drimys winteri*, a typical associate of *Nothofagus betuloides*, along with an increase of *Caltha*, a drop of *Empetrum*/Ericaceae type and record of cushion bog (*Astelia pumila*, *Myrteola nummularia*) and prostate dwarf shrub (*Berberis*, Asteraceae subf. Asteroideae) communities indicate the establishment of Subantarctic Evergreen Forest-Magellanic Moorland transition (Dudley and Crow, 1983; Moore, 1983). The development of this vegetation unit implies further increase in precipitation that culminated with the establishment and persistence of closed-canopy forest communities of Subantarctic Evergreen Forest between 5500 and 1000 cal BP (zone IDE1-4). The highest concentration values of *Nothofagus* pollen similar to those of the surface samples from the closed *Nothofagus* forest are recorded between 4000 and 2700 cal BP (Fig. 6) implying that precipitation reached its maximum level of the record. Modern manifestation of these communities are found in the extreme southeastern and outer coastal zone of the Fuegian Archipelago where mean annual precipitation is on the order of 800 − >1000 mm and mean annual temperature averages 6.5 °C (Heusser, 1998).

This highly humid and cool conditions ended when *Nothofagus* pollen declined abruptly after 2700 cal BP reaching minimum values at 500 cal BP (zone IDE1-5). The pollen record suggests a forest reduction and expansion of *Gunnera* and scrubs (Asteraceae subf. Asteroideae) in the area probably related to warmer and drier conditions. After 500 cal BP, the *Nothofagus* forest shows a recovery and the landscape displays a physiognomy of an open forest as can be seen by the low tree concentration values (Fig. 6) similar to those of the surface samples from the open *Nothofagus* forest unit.

6.2. Comparison with other studies

The geomorphological data from Bahía Franklin (western Isla de los Estados) showed the development of a large fossil sand dunes field prior to 12,600 cal BP, under arid and windy conditions due to larger land surface exposure and lower sea level than today. Similar paleoenvironments were also suggested in the paleoclimate record from northern coast of the island. In the peat core from Lago Galvarne bog (Fig. 1b) the geochemical analysis indicated that, after 16,000 cal BP, windy conditions with permafrost were succeeded by gradually warmer and wetter conditions until 14,500 cal BP followed by arid conditions culminating around 12,800 cal BP (Unkel et al., 2008). Meanwhile, a Late Glacial steppe/tundra vegetation spread into the landscape westward in the Canal Beagle area, southern Isla Grande de Tierra del Fuego (Heusser, 1998) as well as northward in the central Strait of Magellan area (53° S) (McCulloch and Davies, 2001).

The final Late Glacial (after 12,800 cal BP) period in Isla de los Estados was characterized by gradually warmer and fairly arid conditions according to the geochemical data from northern island (Unkel et al., 2008). The pollen data from Bahía Franklin show the development of treeless vegetation dominated by grasses, shrubs and scrubs between 12,600 and 10,300 cal BP suggesting also dry conditions in the island. The low frequency and concentration values of *Nothofagus* registered in the pollen record indicate that at least this part of the island was not an ice-age forest refuge. The Late Glacial early presence of *Nothofagus* forest in the Puerto Harberton pollen record (Heusser, 1998) 170 km west of the Bahía Franklin site (Fig. 1a), points to greater proximity of ice-age refugia at that site. The possibility of several ice-age refuges in southwestern Andean valleys at lower altitudes during the last glaciation has been confirmed by chloroplast DNA markers from Andean populations (Marchelli and Gallo, 2006).

During the early Holocene (10,300 and 8300 cal BP), *Nothofagus* forests apparently expanded slowly at first on the landscape from their westward locations and formed patches into the heath, scrub and grass communities as a signal of increasing temperature and precipitation in spite of the humidity levels were lower than today. Similar climate conditions, documented in the northern coast of the island (Unkel et al., 2008), were correlated with the onset of the Antarctic thermal optimum (Bentley et al., 2009). To the north, the low values of reconstructed annual precipitation from Cerro Frías pollen record (50° S) located in the southwest of Argentine Patagonia (Fig. 1a), were related to a weakening and southward shift of the westerlies during the early Holocene (Tonello et al., 2009). Compilation of paleoclimate proxies from Southern Ocean sediment cores and Antarctic ice core suggested that the surface water warming, sea-ice retreat and southward migration of the westerlies was a general feature of the Southern Ocean during the early-Holocene Climate Optimum (Divine et al., 2010).

During the mid-Holocene (8300 and 5500 cal BP), the *Nothofagus* pollen data at Bahía Franklin record indicate strong rainfall variability in the area with humid and dry intervals. Increase in *Empetrum*/Ericaceae type and decrease in *Nothofagus* at 7500–6800 cal BP suggest a short-term fluctuation to drier conditions. Similar variable moisture conditions were recorded at Puerto Harberton site, eastern Beagle Channel (Pendall et al., 2001) and also to the north, at Cerro Frías (SW Argentine Patagonia, 50° S) (Tonello et al., 2009) and Vega Ñandú (southern Chilean Patagonia,

51° S, Fig. 1a) (Villa-Martínez and Moreno, 2007) sites. These climate conditions were related to a highly variable position and/or intensity of the westerly winds in the southwest of Andean region between 50 and 55° S (Villa-Martínez and Moreno, 2007; Borromei et al., 2010).

In the studied record, the abrupt rise of arboreal pollen concentration at 8000 cal BP suggest the local establishment of a closed *Nothofagus* forest under higher moisture availability. Subsequent pulses at 6700 and 5500 cal BP led to maximum precipitation levels between 4000 and 2700 cal BP at times of Subantarctic Evergreen Forest dominance. These data correlate well with paleoclimate studies from southern Patagonia at Cerro Frías (Argentina, 50° S; Tonello et al., 2009) and Lago Guanaco (Chile, 51° S; Moreno et al., 2010) pollen records (Fig. 1a) and also, within dating uncertainties, with the early onset of neoglacial advances in central Patagonia at 46.57° S (Douglass et al., 2005). All these paleoclimate evidences point to northerly latitudinal change and strengthening of the westerlies at these latitudes.

The maximum arboreal concentration values recorded at 4000 cal BP in Isla de los Estados and at ca. 4500 cal BP in southern Isla Grande de Tierra del Fuego (Beagle Channel area) (Heusser, 1989a, 1990, 1998) indicate maximum levels of precipitation and suggest that the core of the westerlies might be focused at 55° S during this time. The marine sediment core and Antarctic ice core data showed several sea-ice readvances in the course of the mid- to late Holocene. In particular, the pronounced cooling after ca. 4000 cal BP was related to the steepening of the summer sea surface temperature (SSST) gradient across the Antarctic Polar Front (APF), strengthening of the westerlies and a northerly shift of the westerly wind belt to its present day latitude (Divine et al., 2010).

The abrupt decline in *Nothofagus* pollen values after 2700 cal BP suggest warmer and drier conditions perhaps by a weakening of the westerlies. Similar climate conditions were mirrored in the pollen record from the Cerro Frías site showing a *Nothofagus* forest retraction after 3000 cal BP and a grass steppe expansion after 800 cal BP related to weakened westerlies (Mancini, 2009). According to the pollen data from Lago Guanaco site, the relative opening of the *Nothofagus* woodlands also indicated that precipitation decrease in pulses centered at 2300–1300 and 1000–570 cal BP (Moreno et al., 2009). Toward eastern parts of southern Patagonia such as Laguna Potrok Aike site, located in extra-Andean Patagonia (51° S) (Fig. 1a), the pollen record displayed the development of grassy vegetation after 2300 cal BP suggesting higher moisture availability (Wille et al., 2007) probably due to a stronger easterly moisture influence into the lowland southeastern Patagonia by weakening of westerly wind intensities.

In the studied pollen record, the *Nothofagus* forest reduction reached a minimum between 1000 and 500 cal BP suggesting an intensification of warm and dry conditions. This forest reduction coincides with the "Medieval Climate Anomaly" (MCA) chronozone. Similar climate event was also recorded in Isla Grande de Tierra del Fuego. The palynological and geochemical data from the Lago Fagnano sediment core (54° S, Fig. 1a) documented warmer and drier conditions between 1100 and 574 cal BP related to the "Medieval Climate Anomaly" (MCA) (Borromei et al., in preparation). These conditions were also documented from inner Andean valleys like Valle de Andorra peat-bog (180 m altitude, Fig. 1a) (Mauquoy et al., 2004). Further south, the proxy data from Antarctic Peninsula marine cores have registered a period of warmer climate between ~1200 to 600 cal BP equivalent to the "Medieval Warm Period" (MWP) (Bentley et al., 2009).

After 500 cal BP, the recovery of *Nothofagus* forest indicates cooler and wetter conditions in coincidence with the "Little Ice Age" (LIA) chronozone. This climate event has been further recognized in Isla Grande de Tierra del Fuego from inner Andean valleys such as Valle de Andorra peat-bog (180 m altitude) (Mauquoy et al., 2004) and from Las Cotorras mire located at 420 m altitude, in a high Andean valley (Borromei et al., 2010).

7. Conclusions

The Caleta Lacroix section, located on the westernmost tip of Isla de los Estados provides a unique opportunity to trace the floristic and chronological development of the local and regional vegetation and paleoclimate of the Fuegian realm during late Pleistocene and Holocene. The following conclusions can be drawn from the geomorphological and pollen analyses:

1 Modern pollen spectra reflect the principal units of vegetation found in the island: *Nothofagus* forest, Magellanic Moorland and Andean vegetation.
2 The presence of the fossil dune field suggests larger land exposure in proximity to the studied area and stronger wind intensity predominantly from SW and W probably during the Late Glacial times, when sea level was lower than today.
3 The Late Glacial - early Holocene warming climate trend favored deglaciation processes and promote the fossil dune stabilization and peat formation at Caleta Lacroix.
4 Low frequency and concentration values of *Nothofagus* were recorded during the early Holocene, suggesting that at least this part of the island was not an ice-age forest refuge.
5 *Nothofagus*, by inference belonging to *N. antarctica* species, gradually started to spread on the landscape between 10,300 and 8300 cal BP, suggesting an increase in temperature and effective moisture, in spite of precipitations continued lower than today.
6 The modern manifestation of the forest communities at Isla Grande de Tierra del Fuego allows inference of a shift from scarce *Nothofagus* trees prior to 8300 cal BP toward a probable transitional mixture of *N. pumilio* and *N. betuloides* - *Drimys winteri* in the arboreal communities between 8300 and 5500 cal BP, followed by the dominance of *N. betuloides* - *D. winteri* between 5500 and 2700 cal BP when climate conditions changed toward an increased westerly precipitation.
7 The abrupt rise of *Nothofagus* concentration values at 8000 cal BP may be a signal of the onset of westerly activity.
8 The highest concentration of *Nothofagus* pollen at 4000 cal BP suggests that the core of the westerlies would have been focused at the latitude of Isla de los Estados (55° S) during that time.
9 The minimum values of *Nothofagus* pollen at 1000–500 cal BP coincides with the "Medieval Climate Anomaly" (MCA), although evidence for the "Little Ice Age" (LIA) after 500 cal BP, is less clear.
10 The vegetation development is related to changing episodes of temperature and precipitation. These fluctuations may have been related to the positioning and intensity of the Southern Westerlies wind belt, the sea-ice Antarctic extent and changes in sea level.

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