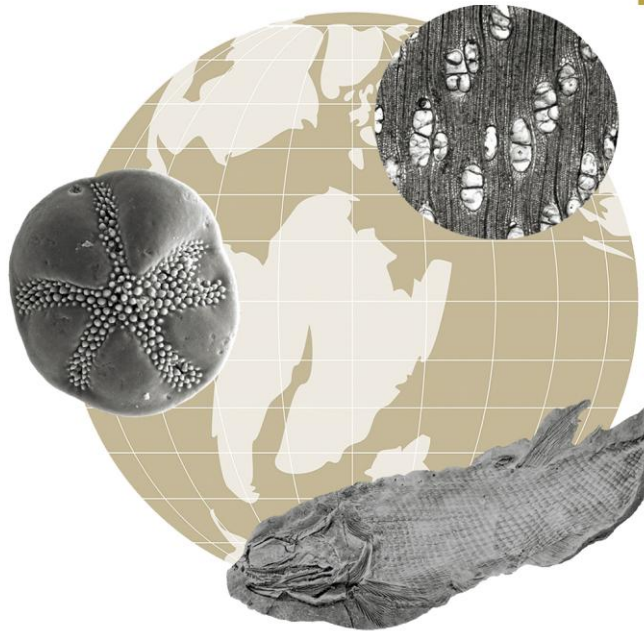




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**PALYNOLOGICAL EVIDENCE FOR HOLOCENE
PALEOENVIRONMENTAL CHANGES ON THE ATLANTIC COAST OF
TIERRA DEL FUEGO (ARGENTINA): THE ARROYO GAMMA RECORD**

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ALLI ET AL.: FUEGIAN ATLANTIC COAST PALYNOLOGY

Holocene environmental evolution of the Fuegian Atlantic coast inferred from
palynological, sedimentological, and multivariate statistical analyses.

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Abstract. This study presents a paleoenvironmental reconstruction of the Atlantic coast of Tierra del Fuego based on the analysis of a 170-cm-thick sedimentary sequence exposed along the lower reach of Arroyo Gamma (AG, 53°27'46" S, 68°05'21.2" W). During the middle Holocene, this area likely constituted a bay that was subsequently sheltered from ocean wave action by the development of beach-ridge plains. Through an integrated approach combining palynological, sedimentological, and multivariate statistical analyses, two palynological zones were identified. AG-1 was characterized by the predominance of Chenopodiaceae, accompanied by Poaceae, *Empetrum rubrum*, freshwater algae, and scarce marine dinocysts, indicating the development of halophytic communities associated with tidal salt-marsh environments. The occurrence of fine-grained sediments and rhythmic stratification supports the interpretation of a low-energy setting corresponding to a transitional coastal system. AG-2 recorded an increase in Caryophyllaceae, Poaceae, *Acaena*, and Asteraceae, an assemblage comparable to the herbaceous communities that currently characterize the Fuegian steppe. Freshwater algae occurred throughout the sequence, indicating the recurrent presence of shallow water bodies. The transition from coastal environments dominated by halophytic vegetation and tidal influence to more continental conditions characterized by herbaceous steppe communities is consistent with paleoenvironmental and vegetation changes reconstructed from other coastal sequences in the region, providing further insights into the evolution of coastal systems in Southern Patagonia.

Keywords. Holocene. Palynology. Paleoenvironmental reconstruction. Coastal evolution. Tierra del Fuego. Southern Patagonia.

Resumen. EVIDENCIAS PALINOLÓGICAS DE LOS CAMBIOS

PALEOAMBIENTALES DEL HOLOCENO EN LA COSTA ATLÁNTICA DE

TIERRA DEL FUEGO (ARGENTINA): EL REGISTRO DEL ARROYO

GAMMA

Este estudio presenta una reconstrucción paleoambiental de la costa atlántica de Tierra del Fuego, basada en el análisis de una secuencia sedimentaria de 170 cm de espesor expuesta a lo largo del tramo inferior del Arroyo Gamma (AG, 53°27'46" S, 68°05'21,2" O). Durante el Holoceno medio, este sector habría constituido una bahía que posteriormente quedó protegida del oleaje oceánico por el desarrollo de cordones litorales. Mediante un abordaje que integra análisis palinológicos, sedimentológicos y estadísticos multivariados, se identificaron dos zonas palinológicas. La zona AG-1 se caracterizó por el predominio de Chenopodiaceae, acompañada por Poaceae, *Empetrum rubrum*, algas dulceacuícolas y escasos dinoquistes marinos, indicando el desarrollo de comunidades halófitas asociadas a ambientes de marisma costera bajo influencia mareal. La presencia de sedimentos finos y estratificación rítmica respalda la existencia de un ambiente de baja energía correspondiente a un sistema costero de transición. La zona AG-2 registró un incremento de Caryophyllaceae, Poaceae, *Acaena* y Asteraceae, asociación comparable con las comunidades herbáceas que actualmente caracterizan a la estepa fueguina. Las algas dulceacuícolas se registraron a lo largo de toda la secuencia, indicando la presencia recurrente de cuerpos de agua someros. La transición desde ambientes costeros dominados por vegetación halófitas e influencia mareal hacia condiciones más continentales, caracterizadas por comunidades herbáceas de estepa, es consistente con los cambios paleoambientales y de vegetación reconstruidos a partir de otras secuencias costeras de la región, aportando nueva evidencia para comprender la evolución de los sistemas costeros de la Patagonia Austral.

Palabras clave. Holoceno. Palinología. Reconstrucción paleoambiental. Evolución costera. Tierra del Fuego. Patagonia austral.

INTRODUCTION

Patagonia is a vast and diverse region of southern South America extending from approximately 40° S to the tip of the continent, encompassing the subantarctic Andes and Isla Grande de Tierra del Fuego (IGTDF, 53°–55° S, 66°–74° W). Within this context, IGTDF is of particular interest for the study of past environmental change because it represents the southernmost continental landmass.

The island's climate is primarily controlled by its latitudinal position, the oceanic influence of the Antarctic Circumpolar Current, and the dynamics of the Southern Westerly Winds (SWW), which modulate regional precipitation and vegetation patterns. The physiography of the IGTDF generates a marked southwest–northeast precipitation gradient, resulting in progressively drier conditions toward the northeastern sector. This gradient directly determines the spatial configuration of present-day vegetation patterns (Schneider *et al.*, 2003; Garreaud *et al.*, 2013).

Late Quaternary paleoenvironmental research in Tierra del Fuego has extensively studied postglacial shifts through palynological records from terrestrial and marine sequences, focusing primarily on the forested south-central sector of the island (Markgraf, 1993; Heusser, 2003; Mauquoy *et al.*, 2004; Markgraf & Huber, 2010; Borromei *et al.*, 2014, 2016; Waldmann *et al.*, 2014; Musotto *et al.*, 2017, 2022, among others). These findings indicate that following the Last Glacial Maximum (LGM, ~24,000 yr BP), areas currently occupied by *Nothofagus* forests were dominated by tundra-steppe vegetation (Ponce *et al.*, 2011).

During the early Holocene, warmer and drier conditions associated with the reduction in the intensity of the Southern Westerly Winds, known as the Early Holocene Westerly Minimum (EHWM), promoted the development of forest-steppe environments. According to Coronato *et al.* (2022), increased effective moisture during

the late Holocene favored the expansion and consolidation of *Nothofagus*-dominated forests across the region.

Despite the relative abundance of paleoenvironmental studies from southern Tierra del Fuego, Holocene records from the northern part of the island remain scarce and spatially limited. Available studies include, Heusser (1993), Borromei *et al.* (2018), Fernández *et al.* (2018), Laprida *et al.* (2021), and Musotto *et al.* (2022, 2025). Within the central-northern sector of the island, environments associated with the Holocene marine transgression have been documented using tephrochronological, palynological, paleoecological, and sedimentological evidence (Auer, 1974; Markgraf, 1993; Porter *et al.*, 1984; Bujalesky, 2007; Montes *et al.*, 2020; Candel *et al.*, 2020; Alli *et al.*, 2025).

This study presents the first palynological record from the AG (53°27'46" S, 68°05'21.2" W; Fig. 1), providing new insights into the Late Quaternary environmental evolution of northern Tierra del Fuego and complementing previous geomorphological research.

Specifically, this research aims to: (1) reconstruct the environmental history of the AG area based on the analysis of its sedimentary section; (2) evaluate its paleoenvironmental relationship with the previously published nearby Río Fuego (RF) record to determine whether both sequences reflect a common regional coastal evolution; and (3) characterize changes in palynological assemblage composition and diversity through multivariate ordination and diversity analyses.

Institutional abbreviations. CADIC, Centro Austral de Investigaciones Científicas, Ushuaia, Tierra del Fuego, AeIAS, Argentina.

Geographical units and sites. IGTDF, Isla Grande de Tierra del Fuego; AG, Arroyo Gamma; RF, Río Fuego; LLV, Laguna Las Vueltas; LA, Laguna Arturo; LM, La Misión; PdH, Puerto del Hambre.

124 **Climatic and atmospheric terms.** **SWW**, Southern Westerly Winds; **LGM**, Last
125 Glacial Maximum; **EHWM**, Early Holocene Westerly Minimum.

126 **Geochemical parameters.** **TOC**, Total Organic Carbon; **LOI**, Loss on Ignition.

127 **Palynology.** **NPPs**, pollen and non-pollen palynomorphs; **PZ**, palynological zones.

128 **Statistical tools abbreviations.** **PCA**, Principal Component Analysis; **CA**, Cluster
129 Analysis; **CONISS**, Constrained Incremental Sum of Squares; **J**, Pielou's evenness;
130 **DCA**, Detrended correspondence analyses.

131 **ENVIRONMENTAL SETTING**

132 The AG is located in the northern Fuegian steppe, south of the Carmen Silva
133 Hills. Its lower course meanders across a low-gradient floodplain (<1%) before
134 discharging into a lagoon connected to the Atlantic Ocean. The stream occupies pre-
135 existing valleys incised during the LGM into Oligocene–Miocene sandy silt deposits of
136 the Cabo Domingo Group (Olivero & Torres Carbonell, 2021), as well as Quaternary
137 glacial, glaciﬂuvial, and littoral deposits.

138 The AG sedimentary section is exposed in an erosional scarp along the lower
139 course of Arroyo Gamma. According to the geomorphological reconstruction proposed
140 by Montes (2015), this area formed part of a sheltered bay during the middle Holocene
141 and was subsequently isolated from direct ocean wave action by the progradation of
142 beach-ridge plains extending southward from Punta Sinaí.

143 The region has a cool temperate climate, with mean summer and winter
144 temperatures of 10.1 and 0.8 °C, respectively (Quiroga, 2018). Mean annual
145 precipitation ranges from approximately 250 mm in northern Tierra del Fuego to about
146 328 mm near Río Grande (Servicio Meteorológico Nacional, 2024; Villarreal, 2024).
147 Winds blow almost continuously, predominantly from the west and northwest, with a
148 mean annual wind speed of 23 km/h recorded in Río Grande (Villarreal, 2024). An

Aridity Index of 0.75 indicates a cold subhumid oceanic hydric regime in the study area (Coronato *et al.*, 2008).

Plant communities in northern Tierra del Fuego are broadly divided into two main groups, acidophilous/mesotrophic and neutrophilous vegetation, based on landscape units, edaphic characteristics, and land use (Collantes *et al.*, 1999). Acidophilous vegetation is dominated by *Empetrum rubrum* heathlands, *Chilietrichum diffusum*, and tussock-forming *Festuca gracillima*. Neutrophilous communities are characterized by grasses (*Poa* spp., *Festuca gracillima*, *Carex* spp.), cushion plants (*Azorella monantha*, *A. trifurcata*), and low-growing herbs (*Acaena pinnatifida*, *Perezia recurvata*, *Nassauvia darwinii*, *Colobanthus subulatus*). Wetlands (vegas) include rush and reed marshes and wet grasslands, often with *Caltha sagittata* and cushion plants such as *Azorella trifurcata* (Collantes *et al.*, 2009). The vegetation surrounding the AG sedimentary section is predominantly acidophilous steppe vegetation.

MATERIAL AND METHODS

Sampling and sediment analyses

Eighty-five samples were collected from an erosional scarp exposed along the lower course of Arroyo Gamma. The sedimentary sequence is 170 cm deep from the base to the surface and was sampled with a high-resolution interval of 2 cm. The texture, structure, and contacts of the studied sedimentary section were described through field observations. Sediment colour was assessed according to the Munsell Colour Charts. Detailed grain-size analyses were carried out at the CADIC laboratory using a Malvern Mastersizer 2000 laser diffractometer after mechanical disaggregation of the samples with a mortar. No chronological data is currently available for the AG sedimentary section. Consequently, the absence of direct chronological control prevents the assignment of specific ages to the inferred paleoenvironmental changes, and their

timing remains tentative. Therefore, the paleoenvironmental interpretation is based on stratigraphic relationships and regional comparison with dated coastal records. Additional chronological data in future studies will help to further constrain the timing of these changes.

Organic matter content was determined using the Loss on Ignition (LOI) method. Samples were first dried at 105 °C for 24 h and subsequently combusted at 500 °C for 5 h in a muffle furnace. Organic matter values were calculated as the percentage of mass lost during ignition relative to the initial dry sediment weight (Heiri *et al.*, 2001).

Palynological analysis

Samples were processed for palynological analysis following the protocol of Louwye *et al.* (2004). Carbonates and silicates were removed using 19% HCl and 40% HF, respectively. No oxidation and heavy-liquid treatments were applied in order to preserve fragile non-pollen palynomorphs. Two *Lycopodium clavatum* tablets (Batch No. 3862) were added to allow the estimation of palynomorph concentrations (grains/g dry weight; Stockmarr, 1971). Organic residues were filtered through a 10 µm nylon mesh to concentrate palynomorphs, dehydrated in alcohol, and mounted on microscope slides using a UV-curable acrylate as the mounting medium following the methodology of Noetinger *et al.* (2017). The palynological slides and residues analyzed are curated at CADIC under repository number AG2023, where AG refers to the Arroyo Gamma section and 2023 to the year of sampling.

Examination under transmitted light at 400×–1000× allowed the identification of pollen and non-pollen palynomorphs (NPPs), mainly green algal colonies (*Pediastrum*, *Botryococcus*, Zygnemataceae zygospores, and Zygnemataceae-type), as well as organic-walled dinoflagellate cysts, acritarchs, and zoomorphs.

The total pollen sum reached a minimum of 200 grains counted when possible. Each taxon was expressed as a percentage of the total pollen sum. NPP frequencies were calculated in relation to the total pollen sum plus the NPPs sum. A stratigraphically constrained cluster analysis (CONISS) was performed using the square-root transformation, which yields the Edwards and Cavalli-Sforza chord distance, to distinguish palynological zones (PZs).

Palynomorph percentage and concentration calculations, diagram plotting, and cluster analyses were conducted using TGView 2.6.1 software (Grimm, 2019). The identified palynomorphs were grouped into trees, herbs and shrubs, hydrophytes, spores, freshwater algae, dinocysts, acritarchs, and zoomorphs. Their identification was based on specialized literature, including Heusser (1971), Markgraf & D'Antoni (1978), Rochon *et al.* (1999), van Geel (2001), Head *et al.* (2005), Roncaglia (2004), Punt *et al.* (2007), Fensome *et al.* (2008), Candel & Borromei (2013), Zonneveld *et al.* (2013), Zonneveld & Pospelova (2015), among others.

Multivariate analysis

In order to identify vegetation patterns and/or changes in the AG palynological assemblage and to compare them with those from the RF sedimentary section of Alli *et al.* (2025), a set of several statistical tools was applied, including evenness indices, rarefaction and principal component analyses in order to evaluate possible correlations between these two records and their vegetation dynamics. Even though the RF dataset was previously published (Table 1), the statistical analyses are presented here for the first time and will be used for comparison with the patterns discussed in the Discussion section.

Pielou's evenness (J) was calculated from absolute palynomorph counts using PAST 4.16 (Hammer *et al.*, 2001) to evaluate the distribution of taxa abundances within

each sample. Due to low palynomorph counts, a subset of statistically representative samples was selected, resulting in a total of 29 and 30 samples for the AG and RF sections, respectively.

Taxonomic richness was estimated using rarefaction. This analysis is a useful tool for estimating taxonomic richness when sample counts differ in size within the same stratigraphical sequence or among different sequences (Birks & Line, 1992; Jaramillo, 2008). This numerical method allows the estimation of the number of taxa that would be expected if all samples had the same count size (Birks & Line, 1992; Birks *et al.*, 2016). To standardize the counts from the AG and RF sites and enable their comparison, rarefaction analysis was performed in R (version 4.4.1; R Core Team, 2024), using the vegan package (version 2.7-2; Oksanen *et al.*, 2025), with a minimum of $N \geq 200$ palynomorphs per sample.

Detrended correspondence analyses (DCA) were conducted in R (version 4.4.1; R Core Team, 2024), using the vegan package (version 2.7-2; Oksanen *et al.*, 2025), to evaluate gradient lengths and assess the appropriate ordination models for the AG and RF datasets. In both cases, the first-axis gradient lengths were short (AG: 1.71 standard deviation length; RF: 2.83 standard deviation length). Following the established criteria of Legendre & Legendre (2012) and Borcard *et al.* (2018), these values fall within the range of linear response models. Therefore, principal component analysis (PCA) was considered appropriate as a descriptive ordination method to reduce the dimensionality of the palynological dataset and visualize major compositional gradients and patterns of variation in palynomorph assemblage composition.

The PCA was conducted using the free-access PAST 4.16 program (Hammer *et al.*, 2001) based on the same matrix used for the rarefaction and evenness analyses. A matrix of square-root-transformed relative frequencies was used in order to reduce the

influence of dominant taxa. Two PCAs were performed for each dataset. The first aimed at examining all the variable loadings. Only variables with loadings greater than 0.2 were selected for a second PCA to be carried out, therefore including only the taxa that most contributed to the variability among samples.

RESULTS

Sedimentology and Organic Matter

The AG sedimentary section is a 170-cm-thick succession that exhibited variable redoximorphic features and abundant root traces (Fig. 2). It consisted of finely laminated clayey silts with gray (10YR 5/1) and light yellowish brown (10YR 6/4) colors, overlain by sandy silts with prismatic structures and a yellowish brown (10YR 5/4) color. The clayey silts unit extended from the base of the section at 170 cm to 32 cm depth. From the base of the AG section to 79 cm depth, this unit exhibits rhythmic lamination (rhythmites), characterized by alternating fine- and coarse-grained laminae. This interval also contains abundant root traces and ochre mottles associated with iron precipitation, with clay contents reaching up to 35%. From 79 to 32 cm depth, the clayey silt unit lacks rhythmic lamination. From 32 cm depth to the surface, the succession consists of sandy silts, with clay contents ranging from 5 to 12%, silt from 38 to 67%, and sand from 20 to 56%. A thin (0.5 cm), discontinuous tephra layer occurred at 24 cm depth and was observed in the field to extend laterally up to 1.3 km east of the AG section.

Total Organic Carbon (TOC) values ranged from 0.13% to 30.93% throughout the section. In the lower clayey silts unit, TOC values remained consistently below 5%. Above 25 cm depth, within the sandy silt unit, TOC values increased progressively from 7.18% to a maximum of 30.93% at 6 cm depth

Palynological analysis

274 Based on cluster analysis (CONISS) of the AG sedimentary section, two
275 palynological zones (AG-1 and AG-2) were identified from the base of the profile (170
276 cm depth) to the surface (Fig. 3). Samples from 111–107 cm, 95–83 cm, and 79–71 cm
277 were sterile or showed very low palynological content, thereby precluding statistical
278 analysis.

279 **Zone AG-1 (170–48 cm)**

280 **Subzone AG-1a (170–116 cm).** This subzone is dominated by Chenopodiaceae (21–
281 62.3%), accompanied by Poaceae (2.9–17.3%), *E. rubrum* (<5%), Asteraceae subf.
282 Asteroideae (up to 3%), and Caryophyllaceae, with values ranging between 0.5 and
283 7.2%. *Nothofagus dombeyi*-type is recorded with percentages ranging from 26.1 to
284 60.5%, while *Drimys winteri* occurs at very low values (<0.5%). Lycopodiaceae (<8%)
285 and Polypodiaceae spores (<1.4%) are also present. Among aquatic palynomorphs,
286 freshwater algae (*Spirogyra* sp., Type-128 and Type-181) reach 7.8%, whereas marine
287 dinocysts (*Spiniferites* spp.) show low values (<1%).

288 **Subzone AG-1b (116–48 cm).** High proportions of Chenopodiaceae (53.2–88.7%)
289 characterize the assemblage, while Poaceae reach values of up to 17.2%, similar to
290 those recorded in the previous subzone. *E. rubrum*, Asteraceae subf. Asteroideae, and
291 Caryophyllaceae together account for less than 9%, and *Gunnera* reaches up to 1%.
292 *Nothofagus dombeyi*-type decreases (<31%), whereas *Drimys winteri* maintains similar
293 values (0.5–1%). Polypodiaceae spores show a slight increase (0.9–2.2%). Freshwater
294 algae decrease (<3%), and dinocysts remain at low percentages (<1%).

295 **Zone AG-2 (48–0 cm)**

296 This zone is dominated by Caryophyllaceae (20.5–65.3%), accompanied by Poaceae
297 (18.1%) and Chenopodiaceae (6.4–47.5%). Asteraceae subf. Asteroideae show an
298 increase (<13%), while *E. rubrum* remains at low values (<3%). In the upper part of the

zone, Asteraceae subf. Cichorioideae (<17.8%), *Acaena* (<9.5%), and *Drimys winteri* (<1.2%) are recorded. Long-distance taxa display relative frequencies fluctuating between 9.5 and 49.5%, reaching their highest values at the base of the zone. *Myriophyllum* reaches values of up to 3%, and Lycopodiaceae spores up to 5.3%. Freshwater algae (*Spirogyra* sp., Type-128 and Type-181) show a slight increase, reaching up to 5%, whereas marine dinocysts (*Spiniferites* spp.) remain at low values (<1%).

Multivariate analysis

AG sedimentary section

Principal component analysis (PCA) of the AG dataset shows that PC1 and PC2 explain 82.66% of the total variance (57.16% and 25.50%, respectively). PC1 reflects a strong gradient contrasting samples dominated by Chenopodiaceae with those dominated by Caryophyllaceae, whereas PC2 differentiates samples more strongly influenced by *Nothofagus dombeyi*-type, *Empetrum rubrum*, and Poaceae (Fig. 4A).

The evenness analysis shows that Zone AG-1 is characterized by a greater variability in its values (0.33–0.69), including the lowest recognized (0.33; Fig. 5A). After reaching this minimum, evenness gradually increases and remains relatively stable toward the top of the zone. The transition from AG-1 to AG-2 is accompanied by an increase in evenness, with Zone AG-2 displaying consistently higher values (0.55–0.79; Fig. 5A).

The palynological rarefaction curves show an increase in taxonomic richness with increasing palynomorph counts at both sedimentary sections (AG and RF; Fig. 5B). At the standardized count size ($N \geq 200$), the RF section exhibits higher rarefied richness than the AG section. Because the curves are generated only statistically representative samples, they do not represent the total diversity of either site, but rather

assess whether the sampling effort is sufficient to capture the diversity present in the analyzed samples.

Río Fuego sedimentary section

Principal component analysis (PCA) of the RF dataset shows that PC1 and PC2 explain 94.59% of the total variance (84.75% and 9.84%, respectively). The grouping pattern is consistent with the stratigraphic clusters defined by Alli *et al.*, (2025). PC1 reflects a strong gradient contrasting Chenopodiaceae with Poaceae and Caryophyllaceae, whereas PC2 distinguishes marginal marine components from terrestrial taxa, including crustacean eggs and foraminiferal linings, as well as terrestrial components such as *Nothofagus dombeyi*-type pollen grains and Lycopodiaceae spores (Fig. 4B).

Evenness varies throughout the RF section. Zone RF-1 exhibits greater variability (0.27–0.75), whereas Zone RF-2 shows consistently higher and less variable values (0.50–0.69; Fig. 5A). Overall, the transition from RF-1 to RF-2 is characterized by a marked reduction in evenness variability (Fig. 5A).

DISCUSSION

Paleoenvironmental evolution at Arroyo Gamma

The northeastern coast of Tierra del Fuego was shaped by Quaternary glaciations and subsequent marine transgressions (Bujalesky & Isla, 2006). During the LGM (ca. 24,000 yr BP), sea level stood 120–140 m below its present position, exposing extensive areas of the Atlantic continental shelf and promoting the development of cold, arid, permafrost-affected landscapes (Ponce *et al.*, 2011; Violante *et al.*, 2014). Simultaneously, the northward displacement of the Southern Westerlies Winds (SWW) favored the expansion of the Fuegian ice sheet and significantly reduced regional humidity (McCulloch *et al.*, 2000; McCulloch & Davies, 2001).

349 The palynological assemblage of the AG section is characterized by a
350 predominance of terrestrial over aquatic palynomorphs. The high variability of the
351 evenness values recorded throughout Zone AG-1 may reflect stronger compositional
352 fluctuation in the palynological assemblage (Fig. 5A). The dominance of
353 Chenopodiaceae in subzone AG-1a (170–116 cm depth) is consistent with the
354 development of halophytic vegetation associated with saline coastal soils. The
355 accompanying pollen assemblage, composed of grasses (Poaceae), heath (*Empetrum*
356 *rubrum*), shrubs and herbs (Asteraceae subf. Asteroideae, Caryophyllaceae, *Acaena*,
357 *Gunnera*, and Asteraceae subf. Cichorioideae), and pteridophytes (Lycopodiaceae),
358 suggest relatively dry environmental conditions. The presence of freshwater algae
359 (*Spirogyra* sp., Type-128, and Type-181) suggests the existence of shallow freshwater
360 bodies in the area. The predominance of clayey silt indicates a low-energy depositional
361 environment, compatible with the presence of shallow freshwater bodies. The marine
362 palynomorph assemblage is represented exclusively by Gonyaulacales dinocysts
363 (*Spiniferites* spp.), which, together with rhythmic sedimentation, suggests tidal
364 influence on the depositional environment. During subzone AG-1b (116–48 cm depth),
365 halophytic communities expanded, as indicated by increased Chenopodiaceae values,
366 while grasslands (Poaceae) and heath vegetation (*Empetrum rubrum*) decreased and
367 herbaceous taxa (Caryophyllaceae) remained poorly represented. This shift occurred
368 within a sedimentary context dominated by fine-grained deposits, suggesting the
369 persistence of low-energy coastal environments. Samples from 111–107 cm, 95–83 cm,
370 and 79–71 cm depth contained very little or no palynological content. Low
371 palynomorph concentrations may reflect reduced pollen and spore input resulting from
372 sparse vegetation cover, low pollen production, and/or unfavorable taphonomic
373 conditions for preservation (Campbell & Campbell, 1994). Furthermore, clayey silt

374 sediments predominate throughout zone AG-1 and in the lower part of zone AG-2,
375 compatible with low-energy deposition, possibly under tidal influence. Taken together,
376 the evidence described above suggests the development of a transitional coastal system
377 under the combined influence of continental and marine processes.

378 A marked change in the pollen assemblage is observed in Zone AG-2 (48–0 cm depth),
379 where herbaceous communities, represented mainly by Caryophyllaceae and *Acaena*,
380 dominate, accompanied by grasses (Poaceae), halophytic vegetation (Chenopodiaceae),
381 and shrubs (Asteraceae subf. Asteroideae). The transition to zone AG-2 is accompanied
382 by a more balanced distribution in the palynological assemblage, indicated by relatively
383 stable evenness values (Fig. 5A). This assemblage closely resembles modern Fuegian
384 steppe communities that occupy the Atlantic coastal sector (Collantes *et al.*, 1999,
385 2009), consistent with the present-day setting of the study site, located approximately 3
386 km inland from the shoreline. TOC values below 10% may reflect reduced biological
387 productivity or relatively drier environmental conditions, characterized by limited
388 organic matter accumulation in the sediments (Mansilla *et al.*, 2016). Freshwater algae,
389 represented by Type-181, Type-128, and *Spirogyra* sp., indicates the continued presence
390 of shallow freshwater bodies, as recorded in Zone AG-1. Sparse occurrences of marine
391 dinocysts (*Spiniferites* spp.) could be explained by the influence of marine spray rather
392 than direct marine incursions. The occurrence of sandy silt toward the upper part of the
393 profile suggests increased depositional energy, whereas ochre mottles throughout the
394 sequence are consistent with periodically waterlogged conditions and reduced oxygen
395 availability, characteristic of poorly drained soils (Davison, 1993; Koinig *et al.*, 2003).
396 Throughout the entire profile, long-distance transported *Nothofagus* pollen exhibits
397 values comparable to those recorded in modern surface samples from steppe
398 environments located near the steppe–ecotone boundary. As reported by Trivi de

Mandri *et al.* (2006) and Musotto *et al.* (2022), relative frequencies in these settings range between 20% and 30%. This pattern may indicate the presence of ecotonal communities closer to the study site than today, despite its current location approximately 45 km east of the forest–steppe ecotone. In contrast, intervals with higher *Nothofagus* values (30–60%) may reflect periods of stronger westerly winds and/or a greater regional extent of *Nothofagus* woodlands.

Regional implications

Following the LGM (ca. 24,000 yr BP), sea level rose rapidly, and the Late Glacial–Holocene transition was marked by pronounced climatic variability, alternating between humid and dry phases (Coronato *et al.*, 2011; Borromei *et al.*, 2018). After 19,000 cal yr BP, subaerial conditions persisted at Laguna Las Vueltas (LLV; Candel *et al.*, 2020), while Laguna Arturo (LA) documents a relatively wetter phase between ~17,100 and 14,000 cal yr BP (Fernández *et al.*, 2020).

During the early Holocene, a weakening of the Southern Westerlies (ca. 11,500–7500 cal yr BP) reduced the west–east precipitation gradient and influenced hydrological balance across Tierra del Fuego (Fletcher & Moreno, 2011; Moreno *et al.*, 2021). Consistently, LLV records shrubland development around a shallow freshwater body under temperate conditions and low effective moisture (11,600–8500 cal yr BP; Candel *et al.*, 2020), while LA indicates stable water levels and the development of paleosols Ps2 (11,268 cal yr BP) and Ps3 (8384 cal yr BP), suggesting reduced aeolian activity and enhanced environmental stability (Coronato *et al.*, 2020, 2022).

At the RF site (Fig. 1), after ca. 10,000 cal yr BP (302–200 cm depth; Zone RF-1), the pollen assemblage reflects the establishment of halophytic saltmarsh communities dominated by Chenopodiaceae, alternating with grass-dominated phases, likely in response to shoreline oscillations and coastal reorganization. The associated

dinocyst assemblage indicates the development of a marginal marine to inner neritic environment, with fluvial nutrient input and episodic stratification. The increase in foraminiferal linings towards the top of RF-1 further suggests relatively high productivity under low-energy conditions (Alli *et al.*, 2025). These paleoenvironmental interpretations are consistent with the ordination results. The PCA reproduced the stratigraphic zonation previously obtained with CONISS (Alli *et al.*, 2025), indicating that the major compositional gradients identified statistically are consistent with the palynological succession. PC1 mainly reflects changes from Chenopodiaceae-dominated halophytic communities to assemblages characterized by Poaceae and Caryophyllaceae, whereas PC2 expresses variations in the relative contribution of marine and terrestrial components. Together, these gradients suggest that vegetation composition was mainly related to changes in coastal influence associated with relative sea-level rise (Fig. 4B). At the AG section (Fig. 1), geomorphological evidence indicates that the study area formed part of a bay during the middle Holocene and was subsequently sheltered from direct ocean wave action by the development of beach ridges extending southward from Punta Sinaí. A nearby coastal sequence associated with this geomorphological setting was dated to ca. 6091 ± 50 yr BP (Montes, 2015). The age of the AG sedimentary section is tentatively constrained by its geomorphological setting and by palynological correlation with the nearby RF section, for which radiocarbon ages are available.

At the AG sedimentary section, zone AG-1 records halophytic and grass-dominated communities comparable to those observed in RF-1, developed under coastal influence (Table 1). The greater representation of *Nothofagus* observed in the PCA, together with the presence of *Drimys winteri*, may reflect periods of intensified westerly influence. The occurrence of *Spiniferites* spp. further suggests tidal influence during

deposition (Alli, 2025). The changes identified by the PCA are accompanied by shifts in the structure of the palynological assemblage, where the high variability in evenness values throughout Zone AG-1 reflects strong fluctuations in compositional structure, whereas the transition to Zone AG-2 is marked by a more balanced distribution of the taxa.

Overall, both sites record early Holocene coastal environments influenced by relative sea-level rise. Both AG and RF sections record a similar trend in their evenness values, characterized by a transition from highly variable ranges in the lower zones (AG-1 and RF-1), to higher and more stable evenness values in the upper zones (AG-2 and RF-2; Fig. 5A). This pattern could suggest an evolution from less stable conditions toward more stable ones for both sections, with a more even distribution in the taxa composing the palynological assemblage in the upper sections. However, the magnitude and pattern of the transition differ between them, RF-1 exhibiting a broader range of values, suggesting stronger fluctuations than in AG-1 (Fig. 5A). In contrast, the AG section showed a gradual recovery in evenness values before the establishment of consistent scores in AG-2, whereas the RF records indicate a more abrupt reduction in its variability (Fig. 5A). Despite these similar trends, both sections differ in their taxonomic richness, with RF exhibiting higher rarefied richness than AG (Fig. 5B).

In northern Tierra del Fuego, in the central sector of the Strait of Magellan (Puerto del Hambre, PdH, 53°36' S, 70°55' W; Fig. 1), the Holocene marine incursion reached a maximum between ca. 7420–7340 cal yr BP and extended until ca. 4420 cal yr BP, under shallow marine conditions inferred from the diatom record (McCulloch & Davies, 2001). Along the Atlantic coast of Tierra del Fuego at LLV, between 8500 and 8100 cal yr BP a lagoon system partially connected to the sea developed, characterized by halophytic vegetation and the presence of neritic dinocysts. Between ca. 8100 and

7000 cal yr BP, tidal influence persisted with freshwater inputs, whereas after 7000 cal yr BP, during the regressive phase, the formation of a bay barrier and strandplain deposits permanently isolated the lagoon, promoting the expansion of grasslands (Candel *et al.*, 2020; Montes *et al.*, 2020).

According to Bujalesky (2007), this regressive phase led to the deposition of beach ridges and cheniers along the Atlantic coast, coastal progradation, cliff retreat, and reorganization of river mouths, including the Río Fuego (Montes & Martinioni, 2017). This coastal reconfiguration may be related to the intervals with sterile or extremely low palynomorph concentrations recorded in both the AG and RF sections. At the AG section (111–107 cm, 95–83 cm, and 79–71 cm depth), intervals with absent or very low palynomorph content were recorded, although preservation was generally good. These discontinuities may reflect differential preservation of organic matter and taphonomic biases related to subaerial exposure or sediment resuspension. Similarly, at the RF site, between 200 and 43 cm depth, samples were sterile or yielded very low concentrations, often with poor preservation, likely due to mechanical transport and syn- and post-depositional compaction processes associated with tidal channels. The sterile intervals identified in both sections may be related to the regressive phase documented at LLV (Candel *et al.*, 2020; Fig. 1), although the lack of chronological control at AG prevents a direct correlation. The PCA gradient for the Arroyo Gama contrasting Caryophyllaceae and Chenopodiaceae suggests shifts between slightly different substrate or moisture regimes rather than major reorganizations of the regional vegetation. In general, the AG assemblage maintains a more balanced composition than RF. In the RF section, the PCA gradient was dominated by Chenopodiaceae, Caryophyllaceae and Poaceae, suggesting that vegetation composition continued to respond primarily to salinity and substrate conditions associated with coastal processes.

Nevertheless, both records indicate depositional changes associated with coastal regression, which influenced palynomorph preservation and assemblage composition.

At La Misión (LM, 53°30' S, 67°50' W; Fig. 1), located ~30 km north of the RF site, a sediment core recovered from a Pleistocene glaciofluvial valley incised into Cabo Domingo Group rocks revealed marine levels dated between 9443 and 260 cal yr BP, with diatom and ostracod assemblages indicative of brackish–marine environments (Markgraf, 1993). Consistent with other regional records, these data suggest that the maximum extent of the marine transgression occurred around 8500 cal yr BP. However, in the Río Fuego valley, sea level was already close to its present position by 10,045 cal yr BP, when tidal flats and lagoonal environments developed behind gravel beach ridges formed between former sedimentary headlands and islands (Alli *et al.*, 2025). In the interior of the Fuegian steppe, LA records between 7250 and ca. 6200 cal yr BP a shift towards mesohaline conditions, indicated by the dominance of *Thalassiosira patagonica* and the presence of the ostracod *Lymnocythere rionegrensis*. Although the lagoon remained a permanent water body, it began transitioning to a negative hydrological balance, which intensified after ca. 6000 cal yr BP, when the assemblage became dominated by *Surirella tuberosa*, a species typical of nearly dry environments. This suggests increased salinity and a lowering of water level under a seasonal regime linked to the intensification of the westerly winds (Fernández *et al.*, 2020).

On the Atlantic coast, at the LLV site, after ca. 4500 cal yr BP, vegetation changes—including a slight increase in shrubs (Asteraceae subf. Asteroideae) and the expansion of halophytes—together with a moderate rise in algae (*Pediastrum*, *Botryococcus*) and geochemical variations, suggest less humid conditions. During the last ca. 2000 cal yr BP, proxy data indicates the development of grasslands and herbs, associated with a shallow water body showing seasonal level fluctuations under higher

effective moisture conditions (Candel *et al.*, 2020). At the RF site, after 1227 cal yr BP (zones RF-2 and RF-3), the palynological assemblage indicates vegetation changes marked by the development of grasses (Poaceae) and herbs (Caryophyllaceae) that colonized alluvial environments, together with the presence of shallow freshwater bodies in the study area, while the coastline acquired a configuration similar to the present one. The PCA results remain consistent with this interpretation. The principal compositional gradient continues to be structured mainly by Chenopodiaceae, Poaceae and Caryophyllaceae, indicating that substrate salinity and soil moisture remained the primary ecological controls. However, compared with RF-1, aquatic components become less significant along PC2, suggesting reduced marine influence and greater stability of terrestrial settings during the late Holocene.

At AG, zone AG-2 exhibits palynological similarities to those identified in zones RF-2 and RF-3, but the assemblage shows a relatively higher representation of halophytic and shrub taxa. Diversity indices indicate higher evenness and lower dominance compared with RF, supporting the interpretation of a more balanced community structure. The PCA gradient contrasting Caryophyllaceae- and Chenopodiaceae-dominated samples persists, but without evidence of marked ecological restriction. This pattern likely reflects its closer proximity to the coast combined with comparatively stable depositional conditions during the late Holocene.

Although the rarefaction curves do not reach a clear asymptote, the pattern of taxonomic richness—consistent with the diversity indices and the non-parametric estimator—suggests that the differences observed between sites are unlikely to be explained solely by sampling effort. These results support, although do not conclusively demonstrate, the paleoenvironmental inferences derived from the PCA and diversity

analyses. In addition, barren samples yielded taxa absent from fertile ones, which may reflect depositional or taphonomic processes that require further evaluation.

CONCLUSIONS

The palynological record from the AG sedimentary section provides new evidence for the Holocene environmental evolution of the central–northern sector of the Fuegian Atlantic littoral, contributing to the understanding of coastal responses to Holocene transgressive–regressive dynamics.

At the base of the AG section, the AG-1 zone records the development of coastal environments influenced by marine processes, characterized by the expansion of halophytic communities and the presence of shallow freshwater bodies. The occurrence of *Spiniferites* spp., together with sedimentological evidence, suggests tidal influence within a low-energy coastal setting. Variations in halophyte abundance throughout this zone may reflect changes in coastal conditions and shoreline position during the Holocene transgressive phase. The upper AG-2 zone records a transition towards more terrestrial conditions, characterized by steppe-related herbaceous communities, including Caryophyllaceae, Poaceae, and *Acaena*, together with freshwater indicators. This assemblage resembles the development of a landscape comparable to the present-day Atlantic coastal steppe. The record of long-distance *Nothofagus* pollen throughout the AG sequence is consistent with an extra-regional contribution transported by westerly winds. Variations in its abundance may reflect changes in atmospheric circulation intensity and/or fluctuations in the contribution from forest–steppe ecotonal vegetation. The palynological composition of AG shows similarities to the RF section, supporting a tentative correlation between both sequences, contributing to a broader spatial interpretation of Holocene coastal environmental changes. The combined use of statistical tools helped characterize variations in the palynological assemblages

throughout the studied section, including shifts in taxonomic composition, community structure and diversity. Together, these patterns may suggest that vegetation dynamics at AG were influenced by relative sea-level fluctuations, substrate conditions, and coastal processes, with no clear evidence in this record of major regional changes in temperature or effective moisture. Because the AG sedimentary section lacks direct chronological control, the timing of the inferred paleoenvironmental changes remains tentative. Additional chronological data in future studies will help to further constrain the timing of these changes.

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Figure captions

Figure 1. A, Location of the study area in South America; **B**, Studied sedimentary
section and other sites referred to in the text. Abbreviations: AG, Arroyo Gamma
(yellow circle); RF, Río Fuego; LA, Laguna Arturo; LLV, Laguna Las Vueltas; LM, La
Misión; PdH, Puerto del Hambre (blue circles). Base map: GoogleSatellite.

Figure 2. Sedimentology, Granulometry and Total Organic Carbon from AG
sedimentary section.

Figure 3. Relative frequencies (%) diagram of palynomorphs identified in the AG
sedimentary section (modified from Alli, 2025).

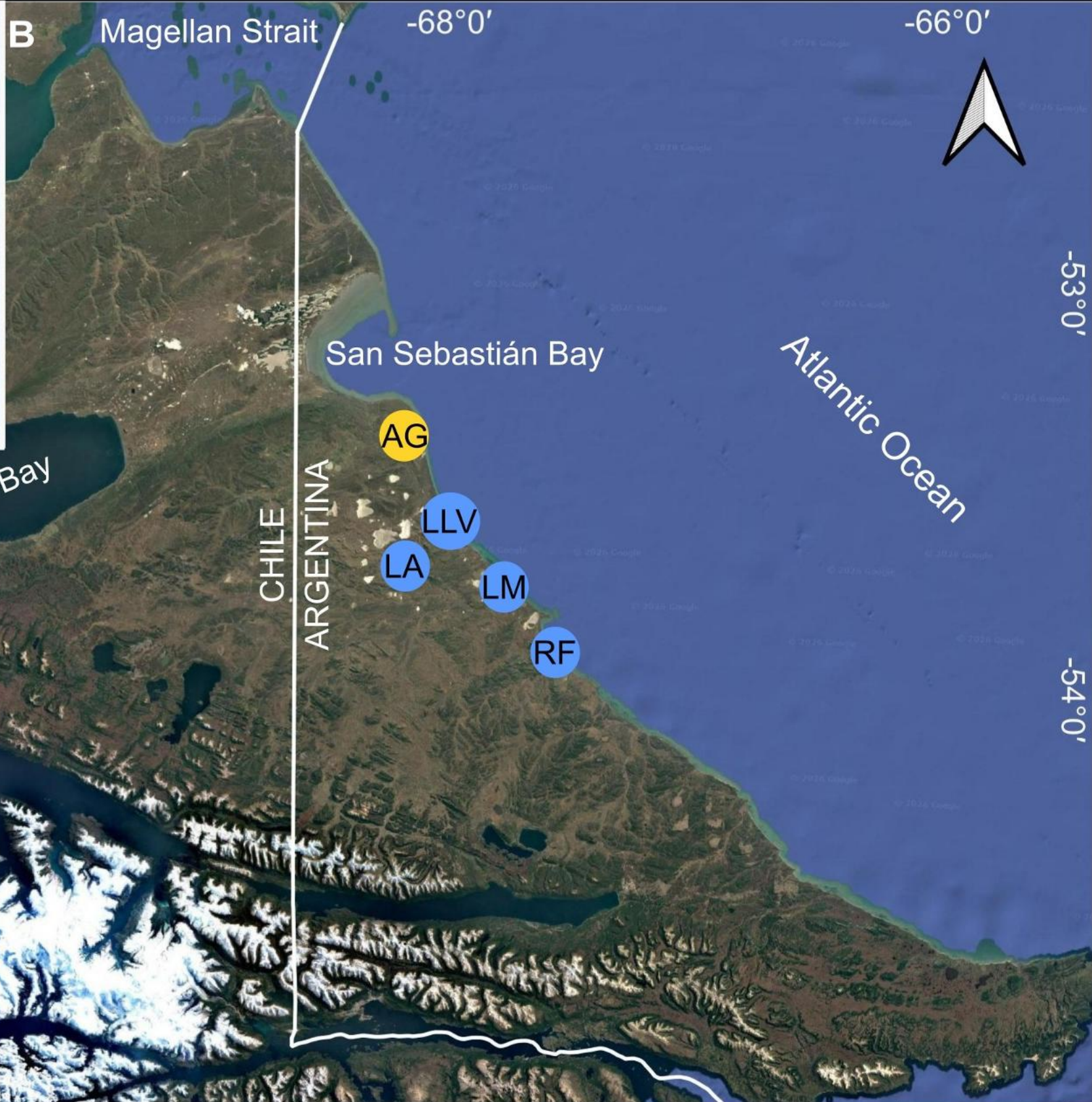
Figure 4. A, PCA biplot of the AG sedimentary section. Blue squares and sky-blue
circles represent CONISS-defined Zones 1 and 2, respectively, as defined by the two
distinct zones identified by the CONISS analysis based on the palynological data. **B**,
PCA biplot of the RF sedimentary section. Orange triangles and yellow circles represent
CONISS-defined Zones 1 and 2, respectively, as defined by the two distinct zones
identified by the CONISS analysis based on the palynological data.

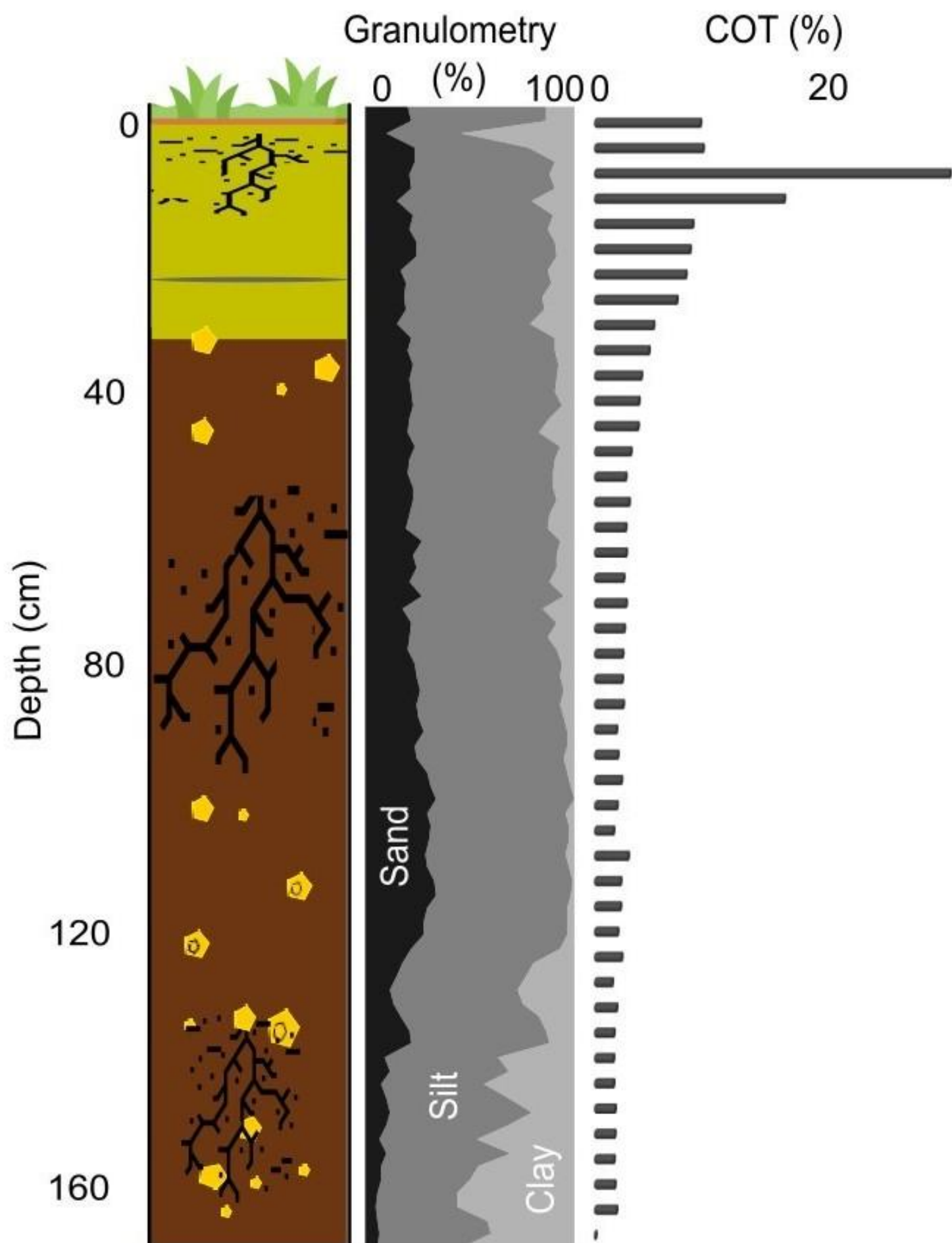
Figure 5. A, Evenness index for the AG (left) and RF (right) sections. The colors
correspond to the CONISS-defined Zones 1 and 2, in order to highlight changes in
evenness across the palynological zones in both sections; **B**, Rarefaction curves for the
RF (green) and AG (gray) sites. Shaded areas indicate 95% confidence intervals. Only

840 samples containing $N \geq 200$ palynomorphs were included in the rarefaction analysis to
841 standardize sampling effort between the AG and RF sedimentary sections.

842 **Tables**

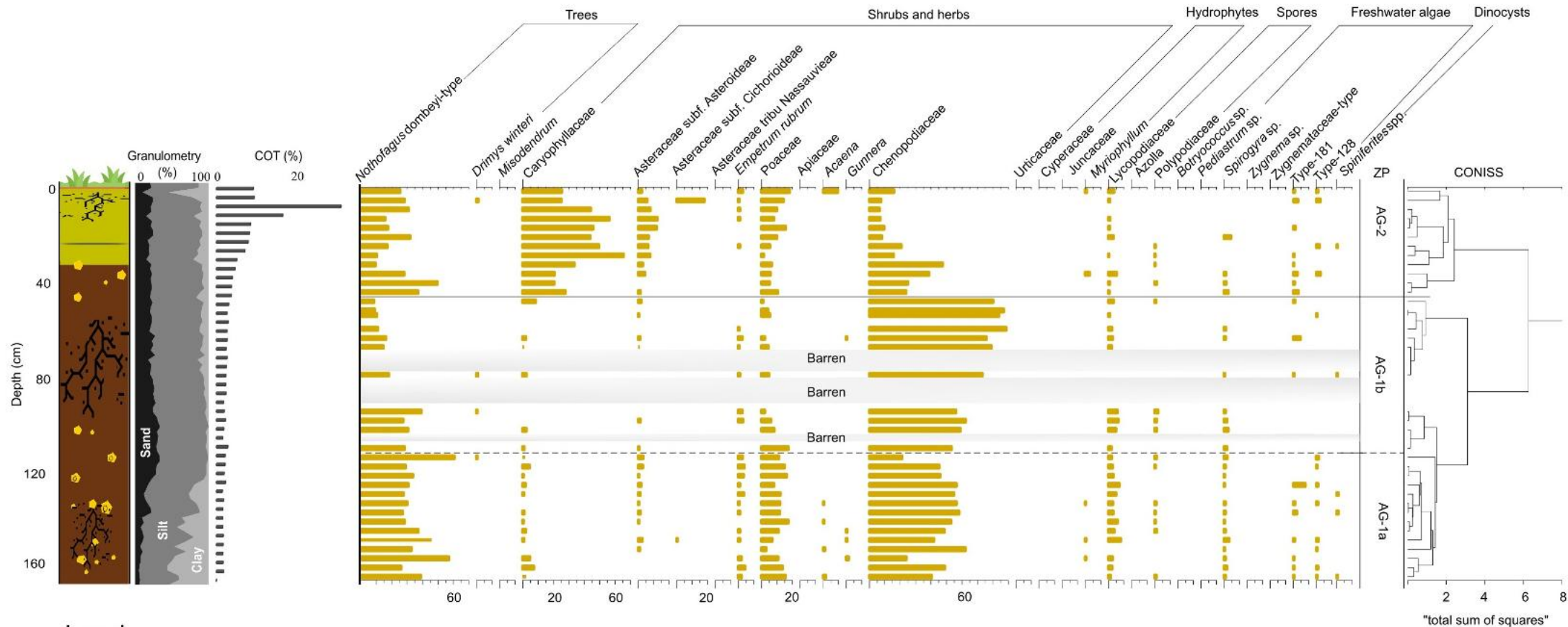
843 **Table 1** Terrestrial and aquatic palynomorph zones and palaeoenvironmental
844 interpretation of the RF section (modified from Alli *et al.*, 2025).





Legend

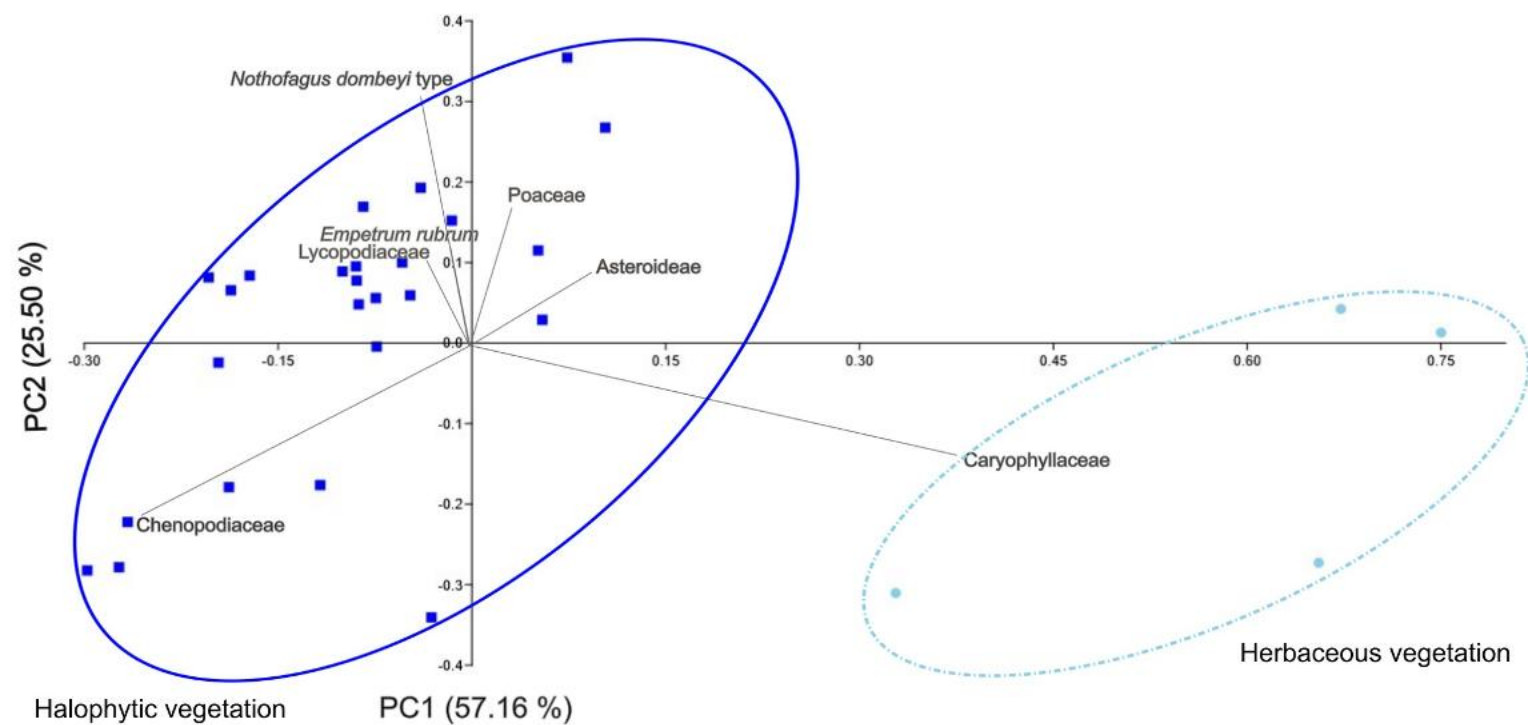
- Clayey silt
- Tephra layers
- Sandy silt
- Roots
- Ochre moles



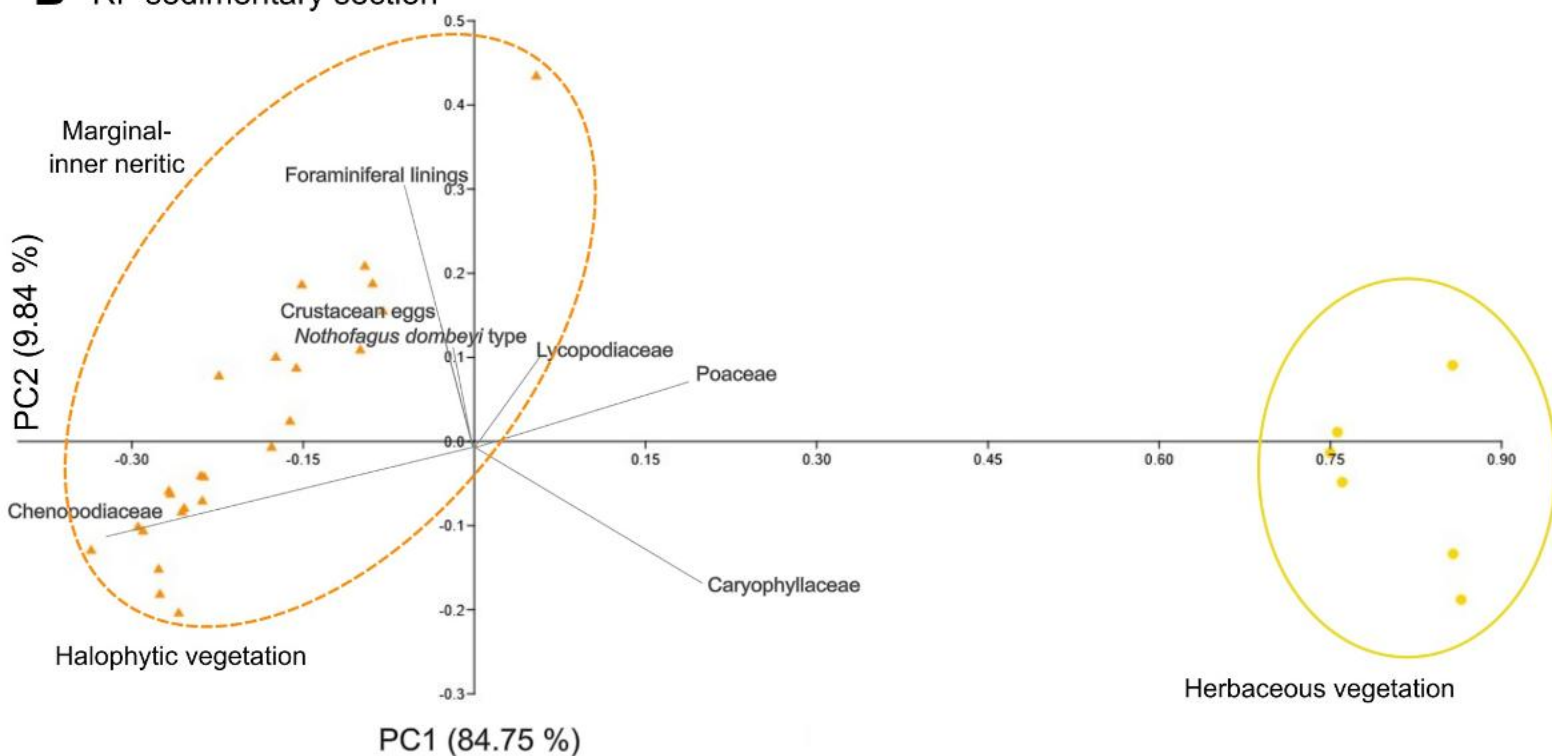
Legend

- Clayey silt
- Tephra layers
- Sandy silt
- Roots
- Ochre motes

A AG sedimentary section



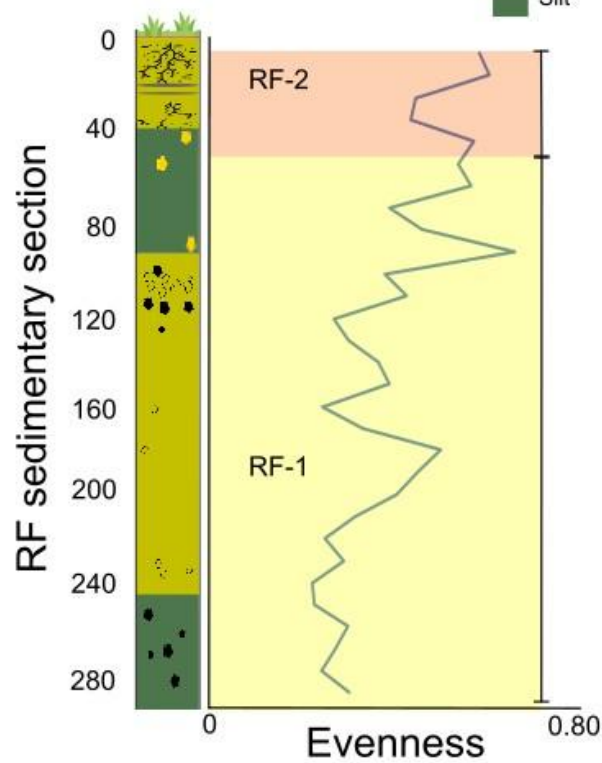
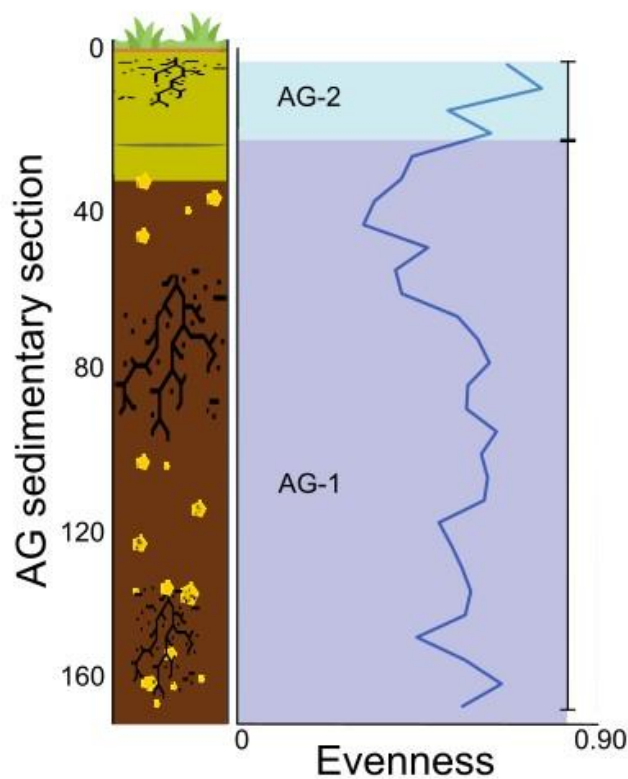
B RF sedimentary section



A

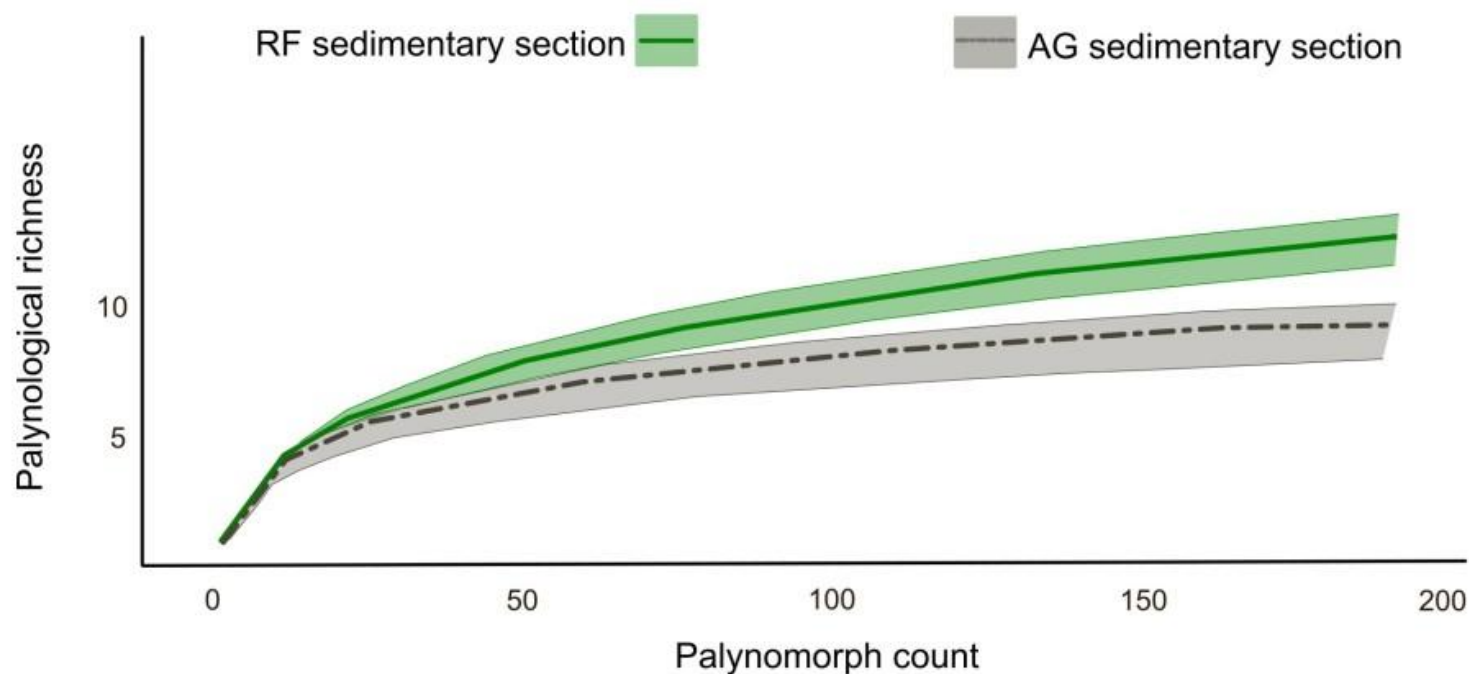
Legend

- Clayey silt
- Sandy silt
- Tephra layers
- Silt
- Roots
- Ochre motes



B

Palynological rarefaction curve



PZ-RF	Age cal. BP	Terrestrial and Aquatic palynomorph zone characteristics	Palaeoenvironmental interpretation
3	Present	Poaceae (48%) and Caryophyllaceae (38.9%) accompanied by <i>Nothofagus</i> (32.8%). <i>E. rubrum</i> (1.5%). Slight increase of Chenopodiaceae (5.1%). <i>Myriophyllum</i> (1%), Lycopodiaceae (3.9%) and <i>Azolla</i> (0.7%) are also present. Freshwater algae (9.2%)	Development of grassland and herbaceous vegetation, associated to alluvial environments. Ecotonal forest communities are inferred by the increase in the <i>Nothofagus</i> pollen.
2b		Poaceae increases (55.8%) and Caryophyllaceae declines (26.8%). <i>Nothofagus</i> (12.3%). Lycopodiaceae decline to 7.8%. Freshwater algae are present (14.2%)	
		Barren	
2b		Caryophyllaceae increases (54.3%) and Poaceae declines (41.3%). <i>Nothofagus</i> (12.3%)	Development of grassland (Poaceae) and herbaceous (Caryophyllaceae) vegetation, accompanied by the record of pteridophytes (Lycopodiaceae). The record of long-distance pollen is related to the influence of westerly winds. Presence of freshwater aquatic palynomorphs suggests shallow freshwater bodies near to the study area.
2a	1227	Dominance of Poaceae (74.6%) accompanied by Caryophyllaceae (19.4%). Chenopodiaceae (1.8%) and <i>E. rubrum</i> (0.4%). <i>Nothofagus</i> decreases (9.1%). Lycopodiaceae rise up to 12.2%. Freshwater algae show an increase (5.7-14.9%)	
		Barren	
1d		Chenopodiaceae vary between 40.6 and 78.4% and Poaceae between 24.2 and 9.9%. Asteraceae subf. Asteroideae (4.6%) and <i>E. rubrum</i> (7.3%). Caryophyllaceae, Asteraceae subf. Cichorioideae and <i>Gunnera</i> reach up to 1%, respectively <i>Nothofagus</i> increases (21%). <i>Myriophyllum</i> (1.8%) and Lycopodiaceae (5.8%). Freshwater algae (1.6%). Marine dinocysts (<8%). Acritarchs (4.3%). Crustacean eggs and foraminiferal organic linings increase (7.3% and 25.9%, respectively)	Development of halophytic vegetation (Chenopodiaceae) in the coastal area accompanied by grasses, shrubs, dwarf shrub heaths, and herbs. Retraction and expansion of halophytes suggest fluctuations in the coastline. The record of long-distance taxa is linked to the westerly winds. Increase in the subzones RF-1b and RF-1d of extra-regional pollen (<i>Nothofagus</i>) probably suggest an intensified influence of westerlies in the study area.
1c		Chenopodiaceae rises to 89.8% accompanied by Poaceae (11%), <i>E. rubrum</i> (3.8%), and Asteraceae subf. Asteroideae (1.6%). <i>Nothofagus</i> decreases (14.5%) and <i>Drimys winteri</i> records up to 1%. <i>Myriophyllum</i> (1.2%). Lycopodiaceae increase (3.1%). Freshwater algae (<1%). Marine dinocysts (1.3%). Acritarchs (0.7%). Crustacean eggs (3.4%) and foraminiferal organic linings vary between 1.3 - 12.9%.	
1b		Chenopodiaceae drops to (55.1%) and Poaceae increases (14.6%) along with <i>E. rubrum</i> (7.8%), Asteraceae subf. Asteroideae (2.6%) and <i>Acaena</i> (1.4%). <i>Nothofagus</i> records 18.3% and <i>Misodendrum</i> 0.3%. Lycopodiaceae (1.7%). Freshwater algae (<1%). Marine dinocysts (<1%). Acritarchs (0.6%). Crustacean eggs (1.6%) and foraminiferal organic linings (4.9%) are also present.	Aquatic palynomorphs assemblage in this zone RF-1 (mainly round brown cysts, <i>Brigantedinium</i> spp., <i>Operculodinium centrocarpum</i> , <i>Spiniferites</i> spp.) evidences a marine environment with variable salinities and nutrient availability. The record of <i>Halodinium</i> sp. in the subzone RF-1b probably is related to the freshwater discharge into the marine environment. The higher proportion of zoomorphs in the subzones RF-1c and RF-1d suggest combined effects of high productivity and organic carbon fluxes in low energy environments.
1a	10,045	Dominance of Chenopodiaceae (up to 87.5%) accompanied by Poaceae (8.1%), <i>E. rubrum</i> (3.2%). Long-distance taxa like <i>Nothofagus</i> (13%) and <i>Drimys winteri</i> (<0.3%), are recorded along with <i>Misodendrum</i> (0.3%). Lycopodiaceae (<2%). Freshwater algae (0.3%). Marine dinocysts (0.6%). Acritarchs (0.3%). Crustacean eggs (0.6%) and foraminiferal organic linings (<1.3%) are also present.	