Accepted refereed manuscript ofMcCulloch RD, Mansilla CA, Martin F, Borrero L, Staff RA & Tisdall EW (2021) The nature and timing of landscape change at Cerro Benítez, Última Esperanza, southern Patagonia (52°S): New insights into the history of megafaunal extinctions and human occupation. *Quaternary International*, 601, pp. 116-129. https://doi.org/10.1016/j.quaint.2021.07.018

The nature and timing of landscape change at Cerro Benítez, Última Esperanza, southern Patagonia (52°S): New insights into the history of megafaunal extinctions and human occupation

Robert D. McCulloch [a, b, *], Claudia A. Mansilla [c], Fabiana Martin [d], Luis Borrero [e], Richard A. Staff [f], Eileen W. Tisdall [g]

[a] Centro de Investigación en Ecosistemas de la Patagonia, Coyhaique, Aysén, Chile
[b] School of GeoSciences, The University of Edinburgh, Edinburgh, Scotland, UK
[c] Centro de Investigación Gaia Antártica (CIGA), Universidad de Magallanes, Punta Arenas, Magallanes, Chile
[d] Instituto de la Patagonia, Universidad de Magallanes, Punta Arenas, Magallanes, Chile
[e] CONICET-IMHICIHU, Saavedra 15, Piso 5, 1083 ACA, Buenos Aires, Argentina
[f] Scottish Universities Environmental Research Centre, University of Glasgow, East Kilbride, Scotland, UK
[g] Biological and Environmental Sciences, University of Stirling, Stirling, Scotland, UK

* Corresponding author.
E-mail address: robert.mcculloch@ciep.cl (R.D. McCulloch).

Abstract

A new Late glacial – Holocene palaeoenvironmental record from Cerro Benítez (51°33'S 72°35'W), Seno Última Esperanza, is presented. A pollen and spore record, from a closed basin mire, provides insight into the dramatic landscape changes spanning the past ~16,000 years. AMS radiocarbon dating, supplemented by the application of tephrochronology, provides robust age constraint. Our record of landscape change is set alongside a summary of the archaeofaunal records from the suite of caves and rock shelters that surround Cerro Benítez. Our record begins *c*. 16.3 ka, sometime after glacier retreat from the area, and describes a treeless landscape favoured by large grazing animals. At *c*. 14.9 ka, southern beech trees began to migrate into the area, but the landscape remained open with sufficient open ground for grazers. At *c*. 12.0 ka there was a dramatic expansion of woodland, but the decline of large mammals appears to have started some ~700 years earlier and is coincident with the arrival of hunter-gatherers in the area *c*. 12.7 ka. However, there is no archaeological evidence for human induced mass killing events, and it is likely that Cerro Benítez was a marginal resource area for early hunters that fell in and out of favour as the landscape changed during the Holocene; initially, less favourable during the early Holocene dry period (*c*. 11.0-8.0 ka) and more in favour during the mid- to late Holocene, although increasingly supplemented by more distant (~5-10 km) materials, including marine resources from the Golfo Almirante Montt.

Keywords

Pollen analysis; Palaeoenvironments; Late glacial; Holocene; Megafaunal extinctions; Cave archaeology

1. Introduction

Patagonia exhibits a complex geography as a result of its geology, climate (dominated by the southern westerly winds, SWWs) (Garreaud et al., 2013), and its glacial history (Davies et al., 2020). This has produced a myriad of marginal landscapes, particularly where there are extremes of temperature and precipitation. During the last glacial – interglacial transition (LGIT) the geography of Patagonia dramatically changed as the large coterminous Patagonian ice sheet rapidly retreated and divided into its present smaller ice fields (McCulloch et al., 2000) (Fig. 1a). Palaeoecological evidence indicates that the deglaciated terrain was rapidly colonised and the boundaries and composition of vegetation ecotones underwent significant changes (see Markgraf, 1985; Heusser, 1995; Moreno, 2004; Markgraf, 2007; Mansilla et al., 2018; McCulloch et al., 2020 and references therein). During this transition, the archaeological records indicate the arrival of early humans in the region (Martin et al., 2015; 2019). Also, during the same period there were significant changes in the South American fauna when ~52 genera of Pleistocene fauna (>44 kg) became extinct (Brook and Barnosky, 2012; Villavicencio et al., 2015). As the Patagonian landscape transformed in response to climate change, faunal communities may have found themselves increasingly vulnerable in new marginal areas at the same time as humans were exploring the region. Therefore, reconstructing the changing Patagonian landscape and disentangling the nature and timing of influences on the fauna, such as climate and the impact of humans, is our challenge.

Much has been written about the coincidence of the arrival of humans, rapid climate reorganisation and large-scale vegetation changes, principally the loss of grassland to forest leading to increased vulnerability of many of the now extinct fauna (Markgraf, 1985; Villavicencio et al., 2015; Metcalf et al., 2016). Pollen analysis can add to this debate because pollen records can be continuous: they describe in similar ways all points in time and are good descriptors of landscape change (Tipping et al., 2008). Pollen analyses can define a landscape where archaeological data may be intermittent or absent (Whittington and Edwards, 1994). Land cover is not necessarily comparable to settlement, and even less so in Patagonia as agriculture was not practiced during the Holocene, leaving fire, as evidenced through the charcoal records, the only tentative signal of human agency in palaeoecological records. However, land cover, or our preferred more holistic term "landscape", in Patagonia, is more directly affected by changing climatic conditions (Moreno et al., 2012).

Cerro Benítez is an important site in the Patagonian narrative of environmental change, faunal extinctions and early peopling of southern Patagonia (Martin et al., 2015). Located approximately 19 km north-west of Puerto (Pto.) Natales, Cerro Benítez is a relatively small hill (~550 m asl) located within the eastern foothills of the Andean cordillera and at the mouth of Seno Última Esperanza (Fig. 2a). The hill is comprised of conglomerates of the Cerro Toro formation (Romans et al., 2011), smoothed by successive glacial advances draining the south-eastern ice-shed of the South Patagonian icefield. The last glacial advance that probably overrode Cerro Benítez was during the Last Glacial Maximum (LGM) and is marked by two moraine systems: the Río Turbio limit, dated to 39-37 ka (ka = 1000 years before present (BP = AD 1950)), and the inner Arauco moraine limit, dated to sometime before 17.5 ka (Sagredo et al., 2011) (Fig. 1b). Glacier retreat after the LGM was characterized by the formation of a large ice-dammed proglacial lake (proglacial Lago (lake) Puerto Consuelo) which formed the raised shoreline terraces at ~150 m asl. These terraces ring Cerro Benítez, indicating that it was an island surrounded by a proglacial lake after glacier recession sometime before *c*. 17.5 ka (Fig. 2a). The lake level lowered several times between *c*. 15.2-12.8 ka and *c*. 12.8-10.3 ka before final drainage at *c*. 10.3 ka (Sagredo et al., 2011; Stern et al., 2011). Along the eroded backwall above the palaeoshoreline there are a number of caves and rock shelters eroded into the conglomerates (Fig. 2a). The cave floor deposits have been the focus of a series of archaeological investigations that have identified faunal and megafaunal remains and evidence for human occupation (Hauthal, 1899; Nordenskjöld, 1996 [1900]; Emperaire and Laming, 1954; Salmi, 1955; Saxon, 1979; Markgraf, 1985; Borrero et al., 1991; Prieto, 1991; Heusser et al., 1992; Borrero and Massone, 1994; Nami and Nakamura, 1995; Borrero et al., 1997; Martin, 2013, Martin et al., 2013, 2015, 2019).

Cerro Benítez and its close surrounding environment has been the focus of two high-resolution palaeoecological studies from Lago Eberhart and Pantano Dumestre (Moreno et al., 2012) (Fig. 1b) and these studies have been compared to the faunal and human records reconstructed from the Cerro Benítez cave sediments (Villavicencio et al., 2015). However, the published records from Lago Eberhart and Pantano Dumestre only span 12.8 - 10.6 ka and 14.3 - 10.0 ka, respectively. Further to the north, within the Parque Nacional Torres del Paine, there are other palaeoenvironmental records from Vega Ñandu (Villa-Martinez and Moreno, 2007), Lago Guanaco (Moy et al., 2008), Lago Cipreses (Moreno et al., 2014; 2018), and Lago Pintito (Moreno et al., 2021) and, to the south, Río Rubens (Markgraf and Huber, 2010), but the focus of these studies are inferences regarding latitudinal shifts in the SWWs and the reconstruction of the fire history of the region. Therefore, the landscape history of Cerro Benítez, from the last glaciation to present, given the complexity outlined above, has not thus far been well described both spatially and temporally. Here we present a continuous record from *c*. 16,000 cal yr BP from a mire located immediately above the caves and above the level of the proglacial lake, Lago Puerto Consuelo, to provide insights into the changing nature of the landscape and resources encountered by the fauna and early humans during the LGIT and during the Holocene.

2. Materials and methods

2.1. Study area: Cerro Benítez

The core site (51°33’40.45”S, 72°35’10.24”W, altitude 211 m asl) is a mire within an elongated closed bedrock basin orientated north-south (~260 m wide x 400 m long; although shallow peat / sediments probably extend further northwards (Fig. 2b)). The current mire surface is seasonally dry and characterised by juncus and grasses. There are scattered trees of *Nothofagus antarctica* (southern beech) on the drier surfaces of the peat bog, particularly over the shallow peats located at the margins of the basin. The landscape surrounding the basin is covered by deciduous *Nothofagus pumilio* forest with a high abundance of the hemiparasite *Misodendrum* (Fig. 2b). The small catchment and closed nature of the basin suggests that the site will be sensitive to changes in precipitation.

2.2 Sediment coring and laboratory methods

A 50 cm long D-section Russian corer 5.5 cm in diameter (Jowsey, 1966) was used to obtain a 1100 cm continuous core from the site. The stratigraphy of each section was recorded in the field, and cores sealed in layflat tubing, returned to the University of Stirling, and stored at a constant 4°C. The organic content was estimated by loss-on-ignition with 2 cm thick contiguous samples dried and then combusted at 550°C for 4 hours (LOI_{550}) (Fig. 3). Sub-samples (1 cm^3) were taken from the core at a resolution of between 16 cm and 4 cm and prepared for pollen analysis using standard techniques (Moore et al., 1991). Basal mineral rich samples were treated with 40% Hydrofluoric acid. The identification of pollen grains and spores was supported by a pollen reference collection and supplemented by microphotographs (Heusser, 1971; Villagrán, 1980; Wingenroth and Heusser, 1984; Moore et al., 1991). A minimum total of 300 land pollen (TLP) grains was identified from each sample, excluding Cyperaceae, aquatics, spores and algae. The pollen percentage data was divided into local pollen assemblage zones (LPAZ) based on major changes in Land Pollen (>2% TLP) and stratigraphy and constrained by cluster analysis (CONISS) (Grimm, 1987). The pollen results are presented using Tilia software version 2.6.1 (Grimm, 2011) (Fig. 4).

Pollen concentrations were estimated by adding a known quantity of *Lycopodium clavatum* to each sample (Stockmarr, 1971). The concentration values (grains cm^3) and approximate sediment accumulation ($cm\ a^{-1}$) were used to calculate the pollen and charcoal accumulation rates (influx: No. grains or particles $cm^2\ a^{-1}$) (Fig. 5). Charcoal particles between 10 and 180 µm were also counted alongside the pollen and spores on the microscope slides as an indicator of past fire activity (Whitlock and Larsen, 2001).

The physical condition of fossil pollen within the sediment was also assessed as a further indicator of the environmental conditions in which it was deposited (Berglund and Ralska-Jasiewiczowa, 1986; Tipping, 1987, 2000; Mansilla et al., 2018; McCulloch et al., 2020).

Pollen grains are well-preserved in acidic and anaerobic conditions such as lakes and waterlogged mires. Corroded and degraded pollen grains suggest degrees of chemical deterioration and microbial digestion which indicate a drier aerobic environment. Broken and crumpled pollen suggest mechanical damage, most probably due to abrasion during transportation. Land pollen was assigned to a single hierarchical category: normal, broken, crumpled, corroded, and degraded (Fig. 6). This tends to emphasize the higher deterioration types (corroded / degraded) (Lowe, 1982), but can be applied quickly and consistently and does not contain subjective elements (Tweddle and Edwards, 2010).

Tephra layers were identified during pollen identification and as mineral residue during the LOI_{550} assays. Tephra layers were concentrated by acid digestion of the organic content (Dugmore et al., 1992) and the mineral content of each sample was then assessed using light and polarizing microscopy. Volcanic glass shards were identified based on morphology, vesicularity and isotropism under plane-polarised light. The major element geochemical composition of each tephra sample was determined by electron microprobe analysis using the SX100 Cameca Electron Microprobe at The University of Edinburgh (Hayward, 2012). A minimum of 10 glass shards were analyzed to provide a representative geochemical signature (Hunt and Hill, 1993). Tephra identification was carried out through comparisons with geochemical data from previous studies (McCulloch and Bentley, 1998; Mansilla, et al., 2016, 2018) (Table S1).

3. Results and analysis

3.1 Stratigraphy

The Cerro Benítez stratigraphy (Fig. 3) comprises bluish-grey clays and silts at the base, between 1100-1087 cm, probably deposited during the retreating stages of the Seno Última Esperanza glacier. This is overlain by lacustrine mud which increases from LOI_{550} <10% at 1087 cm to ~40% organic content by 1046 cm suggesting increasing bioproductivity under relatively warmer conditions. Between 1046 and 1034 cm there is the abrupt deposition of a pale-grey silt / sand layer, probably derived from a heavy rainfall event washing sediment further into the lake basin. The inwash layer is overlain by a 23 cm thick creamy-white fine silt layer which was identified as tephra. The tephra then grades into more pale-grey silt / sand suggesting further inwashing. Above 986 cm a more organic lacustrine mud accumulates which initially peaks at ~45% LOI_{550} and then declines to between ~20-30% LOI_{550} by ~950 cm and continues to 785 cm, punctuated by several sub-centimetre thick grey silt / sand layers, again likely inwash events. At 785 cm there is a rapid increase in organic content to ~50% LOI_{550} which then continues to gradually increase, reaching ~60% LOI_{550} by ~539 cm. Between 539 and 516 cm there is a transition to a compact well-humified peat which then continues to the present surface. Two cryptotephra layers were identified at 260 cm and 620 cm and as peaks of mineral residue in the LOI_{550} samples.

3.2 Chronology

The chronology of the Cerro Benítez record is constrained by nine AMS radiocarbon dates from 0.5cm thick, ~2 cm^3 samples processed by Beta Analytic (Table 1). The cryptotephra at 260-261 cm is geochemically correlated to a late Holocene eruption of Volcán (Vn) Aguilera. A sample enclosing the cryptotephra is here dated to 4750±30 ^{14}C yr BP. The second cryptotephra is geochemically linked to an eruption of Vn Reclus and is undated. Our mean modelled age for this tephra is *c*. 13,150 cal yr BP. The 23 cm thick creamy-white fine silt tephra layer is geochemically correlated to the eruption of Vn Reclus, which has been previously dated to between 12,638±60 and 12,627±48 ^{14}C yr BP (McCulloch et al., 2005; Sagredo et al., 2011; Stern et al., 2011) and these tephra ages are used to supplement the radiocarbon chronology. The Cerro Benítez age-depth model was constructed using the Bayesian chronological package OxCal ver.4 (Bronk Ramsey et al., 2009) and implementing the southern hemisphere calibration curve SHCal20 (Hogg et al., 2020) with instantaneous events such as the inwash layers and tephra layers removed. A Poisson-process "P_Sequence" deposition model was applied, using a model averaging approach to objectively determine the variability in deposition rate (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013), and a "General" outlier model applied to objectively down-weight any radiocarbon determinations deemed to be inconsistent with the others (Bronk Ramsey et al., 2010).

The estimated minimum age for deglaciation from the site is *c*. 18,180 cal yr BP (from a basal radiocarbon determination of 14,850±40 ^{14}C yr BP). However, there is a large degree of uncertainty at the base of the age-depth model, with ~2000 years of sedimentation

Table 1. Conventional radiocarbon ages, calibrated age ranges, and modelled age ranges for the Cerro Benítez record. The SHCal20 calibration curve was applied (Hogg et al. 2020) and a Poisson process (“P_Sequence") deposition model performed using OxCal ver.4 (Bronk Ramsey 2009), as described in the main text.

Laboratory code	Core depth (cm)	“Event-removed” depth (cm)	Material	^{14}C yr BP (1σ)	δ^{13}C(‰)	Unmodelled (calibrated) age range (95.4%) cal yr BP	Modelled (calibrated) age range (mean) at 95% confidence (cal yr BP)
Beta-470863	119	119	Plant fibres	2510±30	-24.4	2367 – 2719	2367 – (2558) - 2718
Beta-505607[1]	261	261	Plant fibres	4750±30	-26.5	5322 – 5578	5321 – (5439) - 5580
Beta-470864	388	388	Plant fibres	7800±30	-27.1	8429 – 8599	8425 – (8528) - 8602
Beta-470865	538	538	Plant fibres	10,340±30	-19.9	11,889 – 12,434	11,885 – (12,053) – 12,433
Beta-470866	676	676	Organic sediment	12,050±40	-14.9	13,796 – 14,029	13,792 – (13,900) – 14,032
Beta-470867	820	-	Organic sediment	(12,530±40)	-18.7	-	-
Beta-470868	908	-	Organic sediment	(12,500±40)	-17.3	-	-
Beta-470869	956	785	Organic sediment	12,540±40	-17.2	14,360 – 15,039	14,504 – (14,809) – 15,032
Vn Reclus[2]	1011	814	-	12,627±48	-	14,578 – 15,181	14,842 – (15,024) – 15,202
Beta-470870	1063	832	Organic sediment	13,050±40	-16.8	15,371 – 15,750	15,359 – (15,578) – 15,754
Beta-470871	1083	852	Organic sediment	13,520±40	-19.1	16,069 – 16,410	16,058 – (16,252) – 16,422
Beta-470872	1087	856	Organic sediment	14,850±40	-21.8	17,994 – 18,249	17,948 – (18,123) – 18,253

[1] N.B., sample from the depth from which the Volcán Aguilera cryptotephra layer was identified (this study).

[2] Age for Volcán Reclus tephra R1 layer from Sagredo et al. (2011).

implied between 1087 cm and 1082 cm. Therefore, our palaeoenvironmental record more confidently begins at 1082 cm (*c*. 16,250 cal yr BP). The radiocarbon ages between ~956 cm (12,540±40 ^{14}C yr BP) and 819 cm (12,530±40 ^{14}C yr BP) suggest that ~150 cm of sediment accumulated as a near instantaneous event. This plateau in sediment ages was also identified by Sagredo et al. (2011) at a slightly shallower part of the mire. We can only speculate as to the exact process that created the age-depth plateau, but it is probable that geomorphic processes led to rapid sediment accumulation. The LOI$_{550}$ profile suggests breaks in the stratigraphy at 957 cm and 785 cm that likely mark the beginning and end of the homogeneous unit and this thickness has been removed from the age-depth model. The mean ages (cal yr BP) of the resulting age-depth model are used to constrain the stratigraphical data (Fig. 3).

3.3 Pollen Stratigraphy

Seven Local Pollen Assemblage Zones (LPAZs) are indicated by CONISS based on the percentage pollen data (Fig. 4) and these LPAZs are applied to the pollen influx (Fig. 5) and pollen preservation data (Fig. 6) to aid comparison.

3.3.1. LPAZ CB-1 (1082 - 785 cm; c. 16,250 - 14,810 cal yr BP)

The basal land pollen assemblage (LPAZ CB-1) comprises well-preserved Poaceae, *Empetrum rubrum* and smaller proportions of *Acaena* and Asteraceae Subf. Asteroideae. Plant diversity is very high with small but persistent amounts of Apiaceae, *Adesmia*, Caryophyllaceae, *Gunnera*, Lilliaceae, *Plantago*, *Rumex* and Saxifragaceae. The basin was occupied by the aquatic *Myriophyllum* and the algae *Pediastrum*. Although the organic content increases in the first half of the LPAZ, pollen influx is very low (~300 grains cm^2 a^{-1}). The combined stratigraphic evidence suggests that the basin was initially colonised by cold-tolerant heathland and steppe vegetation and was treeless. The site itself was a small lake which as climatic conditions warmed supported shallow rooting *Myriophyllum* and the algae *Pediastrum* which favours clear post-glacial water bodies (Komárek and Jankovská, 2001).

Towards the top of the zone there is the 23 cm thick Vn Reclus tephra layer sandwiched between two coarse silt layers. There is a peak in crumpled Poaceae pollen grains immediately above the tephra layer, likely due to reworking leading to the increase in land pollen and mechanical damage to the pollen grains within the silt / sand inwash layer. This probably reflects a short period of increased instability of the slopes around the basin caused by the impact of the tephra on the surrounding vegetation and soils. There is also a large peak in *Myriophyllum* immediately above the tephra, probably due to shallowing of the littoral zone from the rapid influx of sediment. The pollen samples between 957 cm and 785 cm (sampled at 8 cm resolution) are dominated by well-preserved Poaceae, *Empetrum rubrum* and Subf. Asteroideae and little variation in the assemblages consistent with this being a homogeneous unit. The presence of *Myriophyllum* and *Pediastrum* and the accumulation of lacustrine mud reflects a lake environment, and the high proportions of normal pollen in these samples is also consistent with rapid transport to an anaerobic depositional environment. Instantaneous events produce anomalously large total pollen influx values and so the values from the homogenous unit (957-785 cm) were removed from the TLP influx curve (Fig. 5).

3.3.2. LPAZ CB-2 (785 - 538 cm; c. 14,810 - 12,050 cal yr BP)

LPAZ CB-2a (*c*. 14,810 – 13,900 cal yr BP) continues to be dominated by relatively well preserved Poaceae pollen. *Myriophyllum,* which rapidly peaked at the end of LPAZ CB-1, rapidly declined to trace amounts by *c*. 14,300 cal yr BP and Cyperaceae virtually disappeared. *Pediastrum* rapidly increased to ~65% TLP+taxon and then declined but remained above ~40% TLP+taxon during this sub-zone. At the start of the LPAZ the organic content rapidly peaked to levels similar to LPAZ CB-1 (~50% LOI_{550}) before declining slightly (~45% LOI_{550}) towards the top of this sub-LPAZ. Although stability appears to have returned to the basin catchment, the level of vegetation diversity seen in LPAZ CB-1 was not restored.

The persistent presence of *Nothofagus dombeyi* type pollen (~10% TLP) from *c*. 14,810 cal yr BP marks the arrival of scattered stands of *Nothofagus* woodland. Land pollen influx values are high (~2000 grains cm^2 yr^{-1}) and there was a step increase in the organic content (~50% LOI_{550}) of the lacustrine sediment. The land pollen assemblage continues to reflect the dominance of cold-tolerant grassland and heath, but the virtual disappearance of the shallow rooting *Myriophyllum* probably suggests an increase in water depth reducing the available habitat and / or a shift to cooler climatic conditions. This may also suggest that the expansion of the *Nothofagus* woodland was probably constrained by lower temperatures rather than a lack of effective moisture.

Sub-LPAZ CB-2b (*c*. 13,900 – 13,580 cal yr BP) marks a brief period of expansion of *Nothofagus dombeyi* type pollen (~35% TLP) and a corresponding drop in Poaceae. Towards the end of sub-LPAZ CB-2b and into CB-2c there are higher levels of TLP influx, a small increase in organic content of the lacustrine sediments and a sustained peak in well-preserved land pollen (~80% normal). *Pediastrum* declined to <20% TLP+taxon and *Myriophyllum* continued to be virtually absent but there is a small peak in Polypodiaceae.

These changes suggest a short period of climatic warming that enabled the expansion of woodland and polypod ferns, albeit against a backdrop of continued cooler Late glacial climate in comparison to the Holocene.

Sub-LPAZ CB-2c (*c*. 13,580 – 12,050 cal yr BP) marks the re-expansion of Poaceae and the corresponding decline in *Nothofagus* to ~20% TLP. At *c*. 12,720 cal yr BP there was a rapid return of *Myriophyllum* to ~80% TLP+taxon. During sub-LPAZ CB-2c land pollen influx declines to the lowest value of the entire record and there is also a drop in the proportion of well-preserved pollen and a corresponding increase in the proportion of corroded pollen. The sequence of pollen changes suggests a lowering of lake level and expansion of habitat for the shallow rooting *Myriophyllum* under relatively drier conditions, which may have also been promoted by a shift to warmer climate.

Between *c*. 12,780 and 12,350 cal yr BP land pollen influx values declined (~270 grains cm^2 yr^{-1}) and two samples from this section of the core were uncountable. The core material of these samples almost solely comprised of matted *Myriophyllum* fibres, which we believe accumulated rapidly. During sub-zone CB-2c Poaceae continued to dominate but the aquatic taxa and algae rapidly declined as the lake transitioned to a peat bog. It is likely that the natural infilling of the basin by sediment accumulation and development of the mire vegetation was assisted by the continued lowering of the water level, in response to the persistence of a drier climate.

3.3.3. LPAZ CB-3 (538 - 484 cm; c. 12,050 - 10,780 cal yr BP)

Sub-LPAZ CB-3a (*c*. 12,050 - 11,540 cal yr BP) is dominated by the rapid rise of *Nothofagus dombeyi* type pollen (to ~68% TLP) and a corresponding decline in Poaceae and reduction in the diversity of taxa. Although *Myriophyllum* has virtually disappeared from the record before this sub-LPAZ, *Pediastrum* continues to be present in smaller proportions (~5% of TLP+taxon) suggesting the persistence of pools of water as the site transitioned from a lake to a fen and the LOI_{550} reached >80% organic content at *c*. 11,720 cal yr BP. TLP influx peaked at ~1500 grains cm^2 a^{-1} and the proportions of normal pollen also reached the highest levels of the entire record (normal ~90% of TLP). These peaks probably reflect the switch to increasing input of the local component (see Moore et al., 1991) that was well preserved in the wet fen.

During sub-LPAZ CB-3b (*c*. 11,540 – 10,780 cal yr BP) *Nothofagus dombeyi* type declined from the peak in the preceding sub-LPAZ to a nadir of ~23% at *c*. 10,880 cal yr BP. Poaceae correspondingly increased and Cyperaceae also peaked at ~94% of TLP+taxon. This shift in pollen assemblages is typical of the continued transition from lake to fen and to a peat bog and the increase in Poaceae and Cyperaceae likely reflects the spread of grasses and sedges over the emerging mire surface.

3.*3.4. LPAZ CB-4 (484 – 268 cm; c. 10,780 - 5610 cal yr BP)*

At the beginning of Sub-LPAZ CB-4a (c.10,780 - 8720 cal yr BP) *Nothofagus dombeyi* type rapidly increased and fluctuated between ~48% and 74% TLP. Proportions of Poaceae and Cyperaceae initially rapidly declined followed by a more gradual fall. *Misodendrum*, the hemiparasite of deciduous *Nothofagus* woodland, was more consistently present along with *Embothrium coccineum* and moist ground taxa such as *Gunnera* and polypod ferns. This LPAZ also marks the persistent rise in deteriorated pollen and a corresponding downwards trend in normally preserved pollen for most of the remaining record. Taken together, the changing pollen assemblages and deteriorating pollen indicate a shift to reduced mire surface wetness (MSW). This is also reflected in the accumulation of very black, well-humified amorphous peat at this time. Also, during this LPAZ there is the first of a series of brief peaks in charcoal which occur episodically through the remainder of the record. It is probable that open *Nothofagus* woodland was able to migrate over the drier mire surface at the expense of the grasses and sedges with *Gunnera* and polypod ferns favouring the shaded damp areas of the woodland floor and *Embothrium* the lighter, drier open areas.

During Sub-LPAZ CB-4b (*c*. 8720 - 7170 cal yr BP) there is a significant reduction of *Nothofagus dombeyi* type and corresponding increase in Poaceae. It is notable that other taxa such as *Misodendrum*, *Embothrium coccineum*, *Gunnera*, Rhamnaceae and others are virtually absent from this LPAZ. The proportion of normally preserved pollen also steeply declines during this sub-LPAZ. We interpret from this phase, a significant shift to drier conditions leading to a contraction of the *Nothofagus* woodland cover and moist ground covering taxa. Between *c*. 8240 and 8040 cal yr BP there was a peak in *Nothofagus* which suggests a brief period of woodland expansion in response to an increase in humidity.

During sub-LPAZ CB-4c (*c*. 7170 - 5610 cal yr BP) the proportions of *Nothofagus dombeyi* type rapidly recovered to levels similar to LPAZ CB-4a, prior to the drier phase during LPAZ CB-4b. There was also a more gradual improvement in the preservation of pollen suggesting a shift to wetter conditions and this is also reflected in the return of *Embothrium coccineum* and the moist woodland floor taxa present in LPAZ CB-4a. However, the proportion of normal pollen declines towards the top of the sub-LPAZ suggesting a reduction in MSW, although the proportions of *Nothofagus dombeyi* type (~60% of TLP) continue relatively unchanged.

3*.3.5. LPAZ CB-5 (268 – 170 cm; c. 5610 - 3600 cal yr BP)*

At the beginning of this LPAZ there is a peak in corroded and degraded pollen and charcoal suggesting an interval of reduced MSW and increased availability of drier fuel. The trend to this drier period closely preceded the deposition of the Vn Aguilera tephra layer. Following this dry event there was an increase in normally preserved pollen and an increase in *Nothofagus dombeyi* type leading to the virtual exclusion of all other taxa, apart from Poaceae and Sub. Asteroideae. *Acaena* and *Empetrum rubrum*, which have been consistently present in all LPAZs from the beginning of the record are reduced to intermittent trace amounts from LPAZ CB-5 to the present surface. However, the forest canopy was still relatively open to allow *Misodendrum* to thrive during this LPAZ. The proportions of *Nothofagus dombeyi* type increased to ~90% at *c*. 4360 cal yr BP. This suggests a relative increase in humidity enabling woodland expansion and this is also indicated by the trace amounts of *Pediastrum,* which indicates the return of pools of standing water on the mire surface between *c*. 4850 and 4000 cal yr BP. The increase in MSW also appears to have driven the exclusion of Cyperaceae. Following this short wetter period there is a decline in pollen preservation between *c*. 4000 and 3150 cal yr BP (normal ~15% of TLP) suggesting a return to drier conditions and Cyperaceae recovers. However, this period of reduced MSW is more clearly defined in the pollen preservation record rather than in the percentage pollen data.

3.*3.6. LPAZ CB-6 (170 – 36 cm; c. 3600 – 710 cal yr BP)*

Following a brief peak in normal pollen at *c*. 3050 cal yr BP the trend of declining pollen preservation continues into this LPAZ and at *c*. 1160 cal yr BP the proportion of normal pollen reached its nadir of the whole record (~8% of TLP). During this LPAZ there is a small decline in *Nothofagus dombeyi* type to ~60% of TLP and a corresponding increase in Poaceae along with a general increase in taxonomic diversity, including the persistent presence of *Podocarpus*.

3.*3.7. LPAZ CB-7 (36 – 0 cm; c. 710 cal yr BP – present)*

At *c*. 710 cal yr BP there was a rapid rise in *Nothofagus dombeyi* type to ~90% of TLP leading to the virtual exclusion of all other taxa, including *Misodendrum*, and there was a corresponding peak in well-preserved pollen (normal ~70% of TLP) and TLP influx (~3000 grains cm^2 a^{-1}). This suggests an increase in humidity leading to the formation of closed *Nothofagus* forest, limiting light for *Misodendrum* to thrive, and increased MSW. There was a small reduction in *Nothofagus dombeyi* type, a corresponding increase in Poaceae and significant reduction in pollen diversity in the last ~100 years of the record which probably reflects the increased human impact following European colonisation of the region and expansion of grazing animal husbandry.

4. Landscape change at Cerro Benítez

4.1 Late glacial landscape

During the Last Glacial Maximum (LGM) it is probable that the south-eastern outlet glaciers of the present South Patagonian ice field coalesced, forming the Última Esperanza piedmont lobe, and advanced over Cerro Benítez which has a smoothed bedrock topography (Sagredo et al., 2011, Todisco et al., 2018). The present fen-peat bog at Cerro Benítez lies in a bedrock basin likely scoured by the overriding glacier. Cosmogenic surface exposure dating suggests the glacier lobe advanced to the Dos Lagunas moraine limit at *c*. 37.1-38.7 ka (Fig. 1b). Therefore, our basal age of *c*. 18,000 cal yr BP is likely to be a minimum age for deglaciation that is not necessarily close but similar in range to other radiocarbon minimum ages for retreat of the Última Esperanza glacier lobe (Sagredo et al., 2011). The initial environment at Cerro Benítez (LPAZ CB-1) indicates an isolated lake surrounded by cold tolerant grass-heath steppe vegetation and a high level of diversity in the herbaceous taxa. The littoral margins of the lake were colonised by shallow rooting *Myriophyllum* and the freshwater algae *Pediastrum* which suggests a shift to more eutrophic conditions.

The eruption of Vn Reclus at *c*. 15,000 cal BP produced the thick airfall deposit of tephra which was followed by the continued mass movement of slope material into the lake leading to a rapid expansion of the shallow littoral margins reflected in the large peak in *Myriophyllum*. However, this phase was brief and at *c*. 14,820 cal yr BP *Myriophyllum* rapidly declines and there appears to have been a general reduction in plant diversity. At this time *Nothofagus dombeyi* type (southern beech, hereafter simply referred to as *Nothofagus*) maintains a low but steady presence, likely reflecting small stands of trees in a largely open landscape. LPAZ CB-2 overlaps with the timing of the Antarctic Cold Reversal (ACR). However, as found in many pollen records from the region (Markgraf and Huber, 2010; Mansilla et al., 2016, 2018; McCulloch et al., 2019, 2020), there is no unambiguous signal for cooler temperatures between *c*. 14,440 and 12,740 cal yr BP (Gest et al., 2017). However, the virtual disappearance of *Myriophyllum* during the ACR appears to be a consistent pattern that may suggest slightly cooler temperatures in the southern sector of Patagonia (McCulloch et al., 2020). For the brief period between *c*. 13,870 and 13,550 cal yr BP there was an expansion of *Nothofagus* which seems at odds with the general picture of cooler Late glacial environments. The increase in *Nothofagus* proportions to ~30% of TLP is indicative of the presence of *parque* woodland (*sensu* Burry et al., 2006). This is also supported by the small increase in *Nothofagus* pollen influx during LPAZ CB-2b. An alternative explanation may be offered; that cooler temperatures and / or increased precipitation led to a raising of lake level leading to the virtual exclusion of *Myriophyllum.* A rise in lake level due to an increase in precipitation has also been inferred from the decline in macrophytes between c. 14,600 and 13,600 cal yr BP at Pantano Dumestre (Moreno et al., 2012). A rise in lake level at Cerro Benítez would have led to a reduction of input from the surrounding herbaceous pollen taxa leading to an over representation of *Nothofagus,* a prolific producer of pollen (Bianchi and Olabuenaga, 2006). This is consistent with the rapid expansion of *Myriophyllum* at the end of the ACR suggesting lake level lowering and an expansion of the shallow littoral zone. This amplification of the *Nothofagus* signal related to site water levels has been identified elsewhere (McCulloch et al., 2019).

The cooler climate and more open steppe-scrub vegetation of the Late glacial landscape was transformed at *c*. 12,050 cal yr BP, with the rapid expansion of *Nothofagus* forest facilitated by the onset of warmer climatic conditions (onset of the southern hemisphere Holocene, some ~400 years earlier than the Greenlandian GSSP, Walker et al., 2019). The water level at the site continued to drop to the exclusion of *Myriophyllum* and eventually also *Pediastrum* and enabled the expansion of Cyperaceae across the emergent mire surface (LPAZ CB-3b) at c. 11,540 cal yr BP. The nearby Pantano Dumestre also transitioned to a Cyperaceae-*Sphagnum* peat at c. 11,500 cal yr BP (Moreno et al., 2012) suggesting a more regional shift to drier climatic conditions. The well-preserved nature of the pollen at this time likely reflects the wetland environment during the hydroseral succession as the site transitioned from lake to a fen peat but this is relatively short-lived. Between c. 11,540 and 10,780 cal yr BP the trend to drier conditions leads to an increase in grasses across the site, probably a wet meadow. There is a corresponding decrease in the proportions of *Nothofagus* and this is supported by a small decrease in the influx of *Nothofagus*.

4.2 Early to mid-Holocene landscape

From *c*. 10,780 cal yr BP *Nothofagus* is consistently ~60% of TLP which suggests open woodland. The presence of *Nothofagus* is also indicated by the small but persistent presence of *Misodendrum*. The open nature of the woodland is also reflected in the lower proportions of grasses, *Empetrum* heath and the diverse range of herbaceous taxa. The pollen preservation data indicates sub-millenial scale fluctuations in MSW. However, the overall trend to drier conditions at the mire surface continued, reaching a low in MSW and extreme dry climatic conditions between *c*. 8720 and 7170 cal yr BP (LPAZ CB-4b). This period of reduced precipitation led to a step-reduction in *Nothofagus* forest and concomitant loss of *Misodendrum* and a corresponding expansion of grasses and loss of taxa diversity.

The onset of the early to mid-Holocene dry period at Cerro Benítez has been identified from lower lake levels recorded at Lago Eberhard (Moreno et al., 2012) and Potrok Aike (Zolitschka et al.,2013) at *c*. 10,600 and 9700 cal yr BP respectively. The development of a more variable precipitation regime has been identified at 10,800 cal yr BP from Vega Ñandú and Lago Cipreses (Villa-Martinez and Moreno, 2007; Moreno et al., 2018). Higher fire activity in the region has also been attributed to greater climatic variability and extended periods of summer drought from *c*. 11,000 cal yr BP (Markgraf and Huber, 2010). This regional pattern of warmer / drier conditions has been attributed to a weakening of the SWWs at ~51°-52°S as they migrated poleward (Zolitschka et al., 2013; McCulloch et al., 2020) or declined to a minimum in intensity (Moreno et al., 2021).

At *c*. 7170 cal yr BP there was a re-expansion of *Nothofagus* forest at Cerro Benítez, although the improvement in pollen preservation indicating increased MSW started some ~100 years earlier. Similar to the decline in forest at the start of LPAZ CB-4b, the gradual shift to wetter conditions resulted in a step-increase in *Nothofagus* forest at the start of LPAZ CB-4c suggesting threshold responses of *Nothofagus* to climatic changes. The proportion of *Nothofagus* after *c*. 7170 cal yr BP returns to ~60% of TLP and the open woodland almost shares the same characteristics as that which preceded the extreme dry phase, with the return of *Embothrium* and increased proportions of subf. Asteroideae. However, *Misodendrum* is only present intermittently and in trace amounts which may suggest a slightly more closed canopy.

The timing of the end of the early to mid-Holocene dry period is more variable within the extant palaeorecords. The warmer / drier conditions persisted at Lago Cipreses until *c*. 7500 cal yr BP (Moreno et al., 2018) followed by a shift to more humid conditions attributed to the renewed influence of the SWWs in the mid-latitudes after c. 7500 cal yr BP (Moreno et al., 2021). However, increased fire activity facilitated by the extreme climatic variability is thought to have persisted until *c*. 5500 cal yr BP (Markgraf and Huber, 2010). This may be an artefact of the differences in sensitivity and completeness of records in the region limiting the identification of the more subtle fluctuations in climate between *c*. 7500 and 5500 cal yr BP.

4.3 *Mid- to late Holocene landscape*

After *c*. 5630 cal yr BP the overall trend to drier MSW at Cerro Benítez continues until *c*. 710 cal yr BP and the *Nothofagus* forest develops a more open canopy allowing *Misodendrum* to thrive. However, there continues to be sub-millennial scale fluctuations suggesting periods of wetter conditions at *c*. 4690 – 4140 cal yr BP and *c*. 3250 – 2960 cal yr BP. During the first wetter period *Nothofagus* almost reaches 80% of TLP suggesting a more closed canopy, *Misodendrum* correspondingly declines, and there is a general reduction in the diversity of herbaceous taxa. During this period trace amounts of *Pediastrum* appear which provide more categorical evidence for an increase in humidity. The intervening drier periods are marked by peaks in fire activity at Cerro Benítez and are broadly contemporary with periods of rapid climate change leading to drier conditions at *c*. 5350-4750, 4300-3300, 2600-1850 and 1350-1100 cal yr BP inferred from a synthesis of palaeoenvironmental evidence across a latitudinal range (McCulloch et al., 2020).

However, the evidence for the continued trend to drier MSW at Cerro Benítez is in contrast to the widespread evidence for a shift to cooler and wetter conditions in the region after *c*. 5500 - 5700 cal yr BP (Villa-Martinez and Moreno 2007; Markgraf and Huber, 2010; McCulloch et al., 2020). The Cerro Benítez mire lies within a closed basin and there is no evidence for any changes in the site drainage. At present we can only suggest (unsatisfactorily) that complex topographical configuration along the southern Andes and the greater regional-seasonal variability in the proximity and intensity of the SWWs can change the balance between precipitation and evaporation along the east-west precipitation gradient. These changes will be mediated by the varying sensitivities of lake and peat bog systems and expressed as differing responses across relatively short spatial scales.

The persistent trend to drier MSW during the late Holocene at Cerro Benítez ended abruptly at *c*. 710 cal yr BP with a rapid shift to wetter conditions, the expansion of *Nothofagus* (>80% of TLP) indicative of closed forest, and the virtual absence of fire activity. This clear signal towards wetter conditions is c. 1000 years later than the rapid shift to wetter conditions in the southern Estrecho de Magallanes (Mansilla et al., 2016). However, it is broadly consistent with an increase in humidity after the Medieval Climate Anomaly recorded at Lagos Cipreses and Guanaco (Moreno et al. 2014) and the inference that the SWWs migrated equatorward during a cooler Little Ice Age (LIA) leading to glacier advances across Torres del Paine (Kaplan et al., 2016). The topmost pollen assemblage has reduced *Nothofagus,* increased grasses, and diversity of herbaceous taxa probably due to woodland clearance for grazing. The site is presently ringed by many dead trees and regeneration scrub vegetation (Fig. 2b).

5. Implications for the archaeological history of Cerro Benítez

A systematic campaign of re-excavating, evaluating, and dating faunal remains from Cueva (cave) del Medio as well as excavating and dating faunal remains from several other sites at Cerro Benítez has been pursued since 2010 (Martin et al., 2013, 2015, 2019). The results of these efforts provide a framework in which to place our record of landscape change from Cerro Benítez and to consider the relationship between the landscape events, the story of human occupation and the faunal remains.

The arrival of fauna to Cerro Benítez began after the retreat of the ice sometime before *c*. 17,500 cal yr BP and during the lowering of proglacial Lago Puerto Consuelo, reaching ~120 m asl at *c*. 16,200 cal yr BP (Sagredo et al., 2011) (Fig. 7). Large herbivores would have thrived in the open steppe vegetation surrounding Cerro Benítez after deglaciation, as evidenced by the dominance of Poaceae pollen in *Mylodon darwini* (giant ground sloth) dung older than *c*. 14,000 cal yr BP in the Cueva del Milodón (Markgraf, 1985). The fauna may also have been particularly attracted by the existence of a freshwater lake at the site. *Mylodon darwini*, *Lama gracilis* (a camelid) and other animals began to arrive at Cerro Benítez at this time (Martin et al., 2013; Metcalf et al., 2016). The oldest evidence for the presence of fauna at Cerro Benítez was found at Cueva Chica, with a *Lama gracilis* astragalus dated to *c*. 18,160 BP cal yr BP (Martin et al., 2013). Other dates from another six caves at Cerro Benítez range slightly later between *c*. 16,940 and 16,740 cal yr BP obtained from extinct faunal remains of *Hippidion saldiasi* (a small stocky horse), Camelidae and Mylodontinae (ground sloths) (Todisco et al., 2018). *Arctotherium* (bear) was present at Cueva del Milodón and dated to *c*. 15,880 cal yr BP (Table 2) (Martin et al., 2015). This group of ages bracket the period within which Cerro Benítez was populated by megafauna (*sensu* Martin, 1967) and the development of a flora and fauna in the region that could have supported humans.

It is not clear if the eruption of Vn Reclus at *c*. 15,000 cal yr BP had an impact on the fauna, although one has been suggested on the basis of a hiatus in the available radiocarbon dates for *Mylodon* (Borrero 1999: 61). It is likely that the ~23 cm thick airfall deposit of tephra on Cerro Benítez had some effect on the vegetation. However, the degree of impact on the vegetation and fauna would have depended on the season in which the eruption took place and the ability of herbivores to continue grazing. Fluorosis may have affected the grazing fauna, but within the several excavated cave deposits there are no mass dying events associated with the Vn Reclus R1 tephra layer. Several Mylodontinae bones were found embedded within the R1 tephra layer at Dos Herraduras rock shelter, some 500 m from Cueva del Milodón (Borrero and Massone 1994). However, a Mylodontinae rib provided an age of *c*. 15,270 cal yr BP which suggests it likely predated the volcanic eruption. Regardless of potential impacts of the Vn Reclus eruption and Late glacial climate changes on the fauna of Cerro Benítez, the evidence from the caves and rock shelters in the area show the continued presence of *Mylodon* and other extinct animals until *c*. 12,720 cal yr BP.

From *c*. 14,780 cal yr BP small stands of *Nothofagus* woodland arrived in the area but an open landscape likely persisted, adequate for large grazers (Fig. 7). The continued productivity / attractiveness of the landscape around Cerro Benítez is supported by the presence of a variety of fauna, including several herbivores and at least two hyper-carnivores, which overlaps with the Antarctic Cold Reversal (and a brief expansion of *Nothofagus* woodland between *c*. 13,900 and 13,580 cal yr BP), indicating a cold but productive environment. Throughout this time *Mylodon*, *Hippidion saldiasi*, *Panthera onca mesembrina* (jaguar), and Camelidae, including *Lama gracilis* and the extinct clade of guanaco, were present at many of the local bone assemblage sites. *Smilodon* (saber-toothed cat) is only represented at three sites between *c*. 13,260 and 13,000 cal yr BP (Barnett et al., 2005; Prieto et al., 2010). Evidence from Cueva del Medio in the form of a *Mylodon* scapula with tooth puncture marks dated to *c*. 13,660 cal yr BP indicates the predation of grazing animals by carnivores (Martin et al., 2015) (Table 2). Predation is also abundantly represented at Cueva del Milodón (Martin, 2018) and at two excavated carnivore dens (Borrero et al., 1997; Martin, 2013).

From c. 15,000 cal yr BP there is evidence for human occupation in different regions of Southern South America, such as Central Chile (41°S) (Dillehay et al., 2015) and the Pampas (38°S) (Politis, 2014) (Fig. 1a). However, there is still no evidence of such early presence in

Table 2: Conventional radiocarbon ages and calibrated age ranges for archaeofaunal and archaeological material referred to in the text. The SHCal20 calibration curve was applied (Hogg et al. 2020) using Calib 8.2 (Stuiver and Reimer, 1993).

No.	Sample	Lab. code	^{14}C yr BP	cal yr BP (median) 2σ$^{\#}$
1	*Lama gracilis* astragalus	Beta-288231	14,870±70	17,942-(18,159)-18,267
2	*Hippidion saldiasi* tibiae	AA-100230	13,990±150	16,497-(16,937)-17,365
3	Mylodontinae bone fragment	Beta-371882	13,980±50	16,716-(16,964)-17,090
4	*Hippidion saldiasi* lunatum	Beta-310944	13,890±60	16,598-(16,828)-17,026
5	Camelidae cf. *Lama gracilis*	AA-110238	13,840±150	16,246-(16,735)-17,121
6	Mylodontinae osteoderm	Beta-341902	13,790±60	16,428-(16,673)-16,938
7	*Arctotherium* bone fragment	WK20234	13,257±147	15,424-(15,881)-16,316
8	Mylodontinae rib	AA-12574	12,825±110	14,949-(15,269)-15,626
9	Vn Reclús tephra	n/a	12,627±48	14,578-(14,995)-15,181
10	Mylodontinae scapula	AA 100228	11,830±130	13,411-(13,663)-14,021
11	*Smilodon* radius	OXA-14457	11,420±50	13,167-(13,265)-13,400
12	*Smilodon* bone fragment	OXA-22142	11,095±50	12,849-(13,001)-13,095
13	*Hippidion saldiasi* astragalus	AA 100235	10,860±110	12,619-(12,793)-13,068
14	Mylodontinae vertebrae	Beta-288227	10,780±50	12,633-(12,724)-12,762
15	Charcoal	Beta 319538	10,410±50	11,975-(12,247)-12,475
16	*Lycalopex culpaeus* mandible	OxA-9505	10,140±120	11,241-(11,664)-12,422
17	*Artiodactyl* bone	Erl-9043	8109±64	8650-(8979)-9262
18	Guanaco bone	AA-100229	7223±75	7849-(8002)-8177
19	Charcoal	Ua-35652	6920±50	7607-(7720)-7841
20	Charcoal	BM-1204a	5684±52	6301-(6429)-6597
21	Charcoal	Pitt-0526	3950±60	4152-(4339)-4521
22	Camelidae rib	Beta-344432	3830±30	3995-(4179)-4352
23	Charcoal	A-7235	2915±105	2769-(3022)-3328
24	Charcoal	LP-386	2530±70	2364-(2565)-2737

Sample numbers refer to the posterior probability distribution plot numbers on Figure 6. Sources: Borrero and Massone, 1994: 8; Massone and Prieto, 2004: 16; Barnett et al., 2005: 11, 12; Martin et al., 2013: 1, 14; Martin et al., 2015: 6, 10, 13, 15; Metcalf et al., 2016: 7; Martin and Borrero, 2017: 2, 4; Borrero and Martin, 2018: 17-24; Todisco et al., 2018: dates 3, 5.

the far south of Patagonia. Evidence for human activity at Cerro Benítez is limited to ephemeral occupations although an abundant fauna, comprising all the above-mentioned mammals plus *Puma concolor* (puma), *Macrauchenia* (a robust litoptern, a large mammal with a long neck and elongated snout) and a Canidae (fox-like mammals), populated the area and would have made it an attractive patch for hunter-gatherers. Evidence for periods of human occupation has been obtained from Cueva del Medio, Cueva del Milodón and Cueva Lago Sofía 1, immediately north of Cerro Benítez. The timing of the earliest human occupation comes from Cueva del Medio with an *Hippidion saldiasi* astragalus with cut-marks dated to *c*. 12,790 cal yr BP, and charcoal from a hearth dated to *c*. 12,250 cal yr BP (Nami and Nakamura, 1995; Martin et al., 2015, 2019). The earliest human occupation at Cueva Lago Sofía 1 represents a similar time span (Prieto, 1991). The evidence from Cueva del Milodón only consists of *Hippidion* bones with cut-marks (Martin, 2013). The evidence recovered at these sites points to the logistical exploitation of the fauna of Cerro Benítez probably during fleeting visits. Studies of the hearths, lithics and broken bones, some with cut-marks, support their likely attribution to a stage of human exploration of the region (Borrero and Franco, 1997), which appears to reflect a relatively incomplete knowledge of the local geography and its resources. During this exploratory phase there are only three other areas with early human occupation in Southern Patagonia; the Deseado Massif, the Pali Aike lava field and Cerro de los Onas on Tierra del Fuego (Bird, 1988; Miotti et al., 2003; Massone, 2004; Steele and Politis, 2009; Martin 2013, 2021; Paunero et al., 2017; Waters et al., 2015) (Fig. 1a). All the sites in these four areas, which includes Cerro Benítez, present evidence for human activity tightly constrained between c. 12,800 and 11,600 cal yr BP, and share similar sets of tools, hearths and prey (Massone and Prieto, 2004; Flegenheimer and Cattáneo, 2013; Borrero and Martin, 2020).

The archaeofaunal evidence suggests that the giant ground sloths and many of the now extinct fauna started disappearing from the Cerro Benítez faunal record from *c*. 12,700 cal yr BP, some ~700 years before the rapid expansion of the *Nothofagus* forest and significant loss of their grazing habitat at *c*. 12,050 cal yr BP (Fig. 7). The loss of grazing habitat is evidenced in the change in diet identified from pollen analysis of *Mylodon darwini* dung from the Cueva del Milodón, which suggests the megafauna shifted their grazing from a species-rich grassland to vegetation dominated by *Empetrum* (Markgraf, 1985; Heusser et al., 1992). This probably suggests that the ground sloths were utilising the Cerro Benítez mire and similar open heathland spaces as the expansion of forest denied them their former habitat.

The coincidence between the arrival of humans to Cerro Benítez at *c*. 12,790 cal yr BP and the onset of the decline of the now extinct Late Pleistocene megafauna, is persuasive of a link between hunting and faunal extinctions and it has been proposed that humans ‘caused’ the mega-carnivore extinctions (Villavicencio et al., 2015). However, the human occupations at Cerro Benítez were marginal, as indicated by the low intensity and discontinuous use of these sites. None of the bone assemblages indicate a focus on the larger mammals, such as *Mylodon* and *Macrauchenia*. Instead, human predation was concentrated mainly on the extinct clade of guanacos and large mammals such as *Hippidion*. It has been suggested that *Mylodon* presence was contemporaneous with humans and perhaps hunted at Cueva del Medio (Nami, 1994). However, it must be stressed that no valid behavioural association between humans and *Mylodon* has been found at Cerro Benítez, even when these animals were living in the same area during the time of human occupation (Martin et al., 2015). This view of human-megafauna interactions, or lack of, is similar to that recorded at the other Late Pleistocene occupations in Southern Patagonia, excepting Cueva Fell in the Pali Aike Lava Field and Piedra Museo in the Deseado Massif, where cut-marks were identified on *Mylodon* bones indicating some kind of interaction (Marchionni and Vázquez, 2012; Martin, 2021). Cueva Fell is also the only site in Southern Patagonia where the archaeofauna are dominated by *Hippidion saldiasi*, an extinct mammal (Alberdi and Prieto, 2000; Martin, 2021).

There is no evidence of occupational continuity in the Cerro Benítez area after *c*. 12,250 cal yr BP at Cueva del Medio, and *c*. 11, 660 cal yr BP at Cueva Lago Sofia 1, and the area was only revisited towards the end of the early Holocene *c*. 8980 cal yr BP. Despite the systematic campaign of excavations of the caves and rock shelters at Cerro Benítez, presently no archaeological evidence for human occupation from the period between *c*. 11,660 cal yr BP and *c*. 8980 cal yr BP has been found (Borrero and Martin 2018). The reasons for the discontinuation of human visits to Cerro Benítez are unclear, but perhaps the decline of the fauna and sustained dominance of *Nothofagus* forest after *c*. 12,050 cal yr BP made it a more challenging environment for hunting. It is also probable that the Holocene dry period at Cerro Benítez, between *c*. 10,900 and *c*. 7200 cal yr BP, reduced the availability of surface freshwater resources, thus rendering the area less attractive for sustained human incursions.

The return of human activity during the mid-Holocene at Cerro Benítez started at Alero (rock shelter) Pedro Cárdenas at *c*. 8980 cal yr BP (Legoupil and Bertran 2006) and it may reflect early and ephemeral visits by hunter-gatherers. Other sites at Cerro Benítez began to be occupied later, such as Cueva Ciro *c*. 8000 cal yr BP (Borrero and Martin 2018) and Alero Quemado *c*. 7720 cal yr BP (Sierpe et al., 2009). The timings of these visits are coincident with the minima in Holocene *Nothofagus* forest cover between *c*. 8720 and 7170 cal yr BP and may suggest easier hunting conditions across a more open landscape.

The mid-Holocene occupations are located at new places within Cerro Benítez and the archaeofaunal evidence suggests that these hunter-gatherers had acquired a good knowledge of their more wooded environment. In comparison with the Late Pleistocene groups, the mid-Holocene groups hunted a different fauna, namely guanaco. They were also limited in their use of other terrestrial resources, such as *Hippocamelus bisulcus* (mid-sized deer) and perhaps *Lycalopex* (fox). There is evidence for the consumption of marine resources, such as gastropods (snails), *Leukoma antiqua*, *Aulacomya atra*, *Mytilus* (bivalve molluscs), fish, and even pinnipeds (seals) recorded at Alero del Diablo (García Huidobro Mery, 2015). The early record of *Hippocamelus bisulcus* at Alero Pedro Cárdenas and its presence in the upper layers of Alero Quemado, Cueva del Milodón, Cueva Lago Sofía 1, Cueva Ciro and Dos Herraduras likely reflects the gradual incorporation of a local forest resource. The products of the sea do not appear to have been regularly used, but they show an amplification of the diet including resources from the Golfo Almirante Montt. These hunter-gatherers also used a variety of stone tools made from diverse raw materials, some of them obtained at a distance from Cerro Benítez, which exemplifies the increasing connection between humans and their landscape as they adapted to the changing environment.

During the mid-Holocene there is further evidence that hunter-gatherers revisited the area at *c*. 6430 cal yr BP (Cueva del Milodón), at *c*. 4330 cal yr BP (Cueva Lago Sofía 1), and at *c*. 4130 cal yr BP (Cueva del Medio) (Saxon 1979; Prieto 1991; Martin et al., 2015). The archaeofaunal evidence suggests that these hunter-gatherers continued to be more focused on the consumption of guanaco, complemented with deer and sea molluscs. Evidence from the rock shelters, such as Alero Quemado and Alero del Diablo indicates that these sites continued to be used and exhibited the same pattern of wider use of the locally available resources. It is noteworthy that these mid-Holocene visits occur during a time of more humid conditions and increased *Nothofagus* cover.

During the late Holocene, more sites began to be used in different places at Cerro Benítez and neighbouring areas like Cerro Torta and Península Varas. Most notable is the evidence for semi contemporaneous occupations at the three Dos Herraduras rock shelters, between *c*. 3020 and 2560 cal yr BP, but most of the already known sites continued to be used at this time. Maritime resources appear to have been slightly more important at some sites located closer to the coast or in the islands of Golfo Almirante Montt (San Román, 2016; Borrero and Martin, 2018). It is tempting to relate the smaller mid- to late Holocene gaps in occupation to the later changes in climate and it is likely that the expansion of *Nothofagus* forest *c*. 710 cal yr BP rendered the area less attractive for human activity. However, at present the upper sediments within the caves and rock shelters at Cerro Benítez are insufficiently dated.

6. Conclusion

The Cerro Benítez record provides valuable insights into the nature and timing of landscape changes at the eastern margins of the forest-steppe boundary at ~52°S. Our pollen inferred vegetation record is supported by pollen preservation data to reconstruct shifts in humidity. After deglaciation, between *c*. 18.0 and 15.0 ka, the Cerro Benítez landscape was characterised by a treeless tundra / steppe vegetation favoured by the mega-herbivores (e.g. ground sloths, camelids, litopterns) adapted to grazing open grassland vegetation. The grazing fauna were in turn predated by mega-carnivores (e.g. sabre-toothed cats). At *c*. 15.0 ka there was the development of patchy *Nothofagus* trees, but this is unlikely to have significantly altered the resources available to the fauna. There is no unambiguous evidence of impacts on the landscape coeval with the Antarctic Cold Reversal. At *c*. 12.7 ka there is evidence for incursions by hunter-gatherers and the beginning of the decline of megafauna. This is followed ~700 years later by a rapid expansion of *Nothofagus* forest and the onset of Holocene-like conditions at *c*. 12.1 ka. This suggests that loss of habitat due to climate change is unlikely to have been one of the initial drivers for megafaunal extinction, at least at Cerro Benítez. However, the limited evidence for sustained human–megafauna interactions during a short period at Cerro Benítez does not unambiguously implicate human activity for the demise of the largest species of megafauna. This evidence is restricted to camelids and horses. It is likely that the expansion of forest led to the area being both unattractive to hunters and the remaining prey alike. During the Holocene, human utilization of Cerro Benítez and nearby areas was not intensive at any time and the archaeology continues to be characterized by sites of fleeting occupation. However, it is probable that the sustained early Holocene drier period between *c*. 11.0 and 7.2 ka led to a contraction of the forest and an opening of the landscape for hunter and prey alike. Only during the Late Holocene is there some evidence for periods of more intensive occupation and redundant use of places. Increasing use of the local resources, particularly from the sea, accompanies this process and may be associated with short visits by maritime foragers to the coasts of the Golfo Almirante Montt.

Author contributions

R. McCulloch: Conceptualization, Funding acquisition, Methodology, Data collection, analysis and interpretation; C. Mansilla: Data collection, analysis and interpretation; F. Martin: Conceptualization, Funding acquisition, Data collection, analysis and interpretation; L. Borrero: Data collection, analysis and interpretation; R. Staff: Data analysis and Interpretation; E. Tisdall: Interpretation. All authors contributed to the Drafting and Critical revision of the article.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability.

All pollen data will be lodged with Neotoma upon publication. Tephra glass major element geochemistry is available as supplementary material.

Acknowledgements

This research was supported by the Chilean National Agency for Research and Development (Agencia Nacional de Investigación y Desarrollo de Chile (ANID)): FONDECYT 1150845 and FONDECYT 1180272. RMcC is supported by ANID R20F0002 (PATSER) and R17A10002 (Lab. Eco Climatico) and CAM is supported by ANID SIA/PAI 77180002 ANID. The University of Stirling provided additional support for the preparation of pollen samples and tephra samples for the Electron Microprobe analyses by RMcC. We are grateful to Dr Chris Hayward for assistance in the use of the Cameca SX100 Electron Microprobe in the School of GeoSciences, The University of Edinburgh. We are grateful to Dr Mary McCulloch and the reviewers for their constructive comments on earlier versions of the manuscript.

References

Alberdi, M.T., A. Prieto. 2000. Hippidion (Mammalia, Perissodactyla) de las cuevas de las provincias de Magallanes y Tierra del Fuego. Anales del Instituto de la Patagonia, 28:147-171.

Barnett, R., Phillips, M.J., Martin, L.D., Harington, C.R., Leonard, J.A., Cooper, A. 2005. Evolution of the extinct sabre-tooths and the American cheetah-like cat. Current Biology, 15: R589-590.

Berglund, B.E., Ralska-Jasiewiczowa, M. 1986. *Pollen analysis and pollen diagrams*. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. Chichester: Wiley, pp. 455-484.

Bianchi, M.M., Olabuenaga, S.E. 2006. A 3-year airborne pollen and fungal spores record in San Carlos de Bariloche, Patagonia, Argentina. Aerobiologia, 22: 247–257.

Bird, J.B. 1988. Travels and archaeology in South Chile. In: Hyslop, J. (Ed.). Iowa City: University of Iowa Press.

Borrero, L.A. 1999. The faunas of the Pleistocene/Holocene Boundary in the Seno de la Última Esperanza, Chile. In: Driver, J. Zooarchaeology of the Pleistocene/Holocene Boundary Oxford, England: BAR International Series 800, pp. 59-62.

Borrero, L.A., Lanata, J.L., Cárdenas, P. 1991. Reestudiando Cuevas: nuevas excavaciones en Última Esperanza, Magallanes. Anales del Instituto de la Patagonia, 20: 101-110.

Borrero, L.A., Massone, M. 1994. Arqueología de los aleros de Dos Herraduras, Última Esperanza. Revista del Museo Historia Natural San Rafael, 14(1/4): 288-289.

Borrero, L.A., Franco, N.V. 1997. Early Patagonian Hunter-Gatherers: Subsistence and Technology. Journal of Anthropological Research, 53: 219-239.

Borrero, L.A., Martin, F.M., Prieto, A. 1997. La Cueva Lago Sofía 4, Última Esperanza: una madriguera de felino del Pleistoceno tardío. Anales del Instituto de la Patagonia, 25: 103-122.

Borrero, L.A., Martin, F.M. 2018. Archaeological discontinuity in Última Esperanza: A supra-regional overview. Quaternary International, 473B: 290-305.

Borrero, L.A., Martin, F.M. 2020. Pioneer population nodes in southern patagonian lands. South American Contributions to World Archaeology. In: Bonomo, M., Archila, S. (Eds). One World Archaeology Series, New York: Springer, in press.

Bronk Ramsey, C. 2008. Deposition models for chronological records. Quaternary Science Reviews, 27(1-2): 42-60.

Bronk Ramsey, C. 2009. Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1): 337-360.

Bronk Ramsey, C., Dee, M., Lee, S., Nakagawa, T., Staff, R. 2010. Developments in the Calibration and Modeling of Radiocarbon Dates. Radiocarbon, 52(3): 953-961.

Bronk Ramsey, C., Lee, S. 2013. Recent and planned developments of the program OxCal. Radiocarbon, 55 (2-3): 720-730.

Burry, L.S., Trivi de Mandri, M., D'Antoni, H.L. 2006. Paleocomunidades vegetales del centro de Tierra del Fuego durante el Holoceno temprano y tardío. Revista del Museo Argentino de Ciencias Naturales, 8: 127–133.

Davies, B.J., Darvill, C.M., Lovell, H., Bendle, J.M., Dowdeswell, J.A., Fabel, D., García, J-L., Geiger, A., Glasser, N.F., Gheorghiu, D.M., Harrison, S., Hein, A.S., Kaplan, M.R., Martin, J.R. V., Mendelova, M., Palmer, A., Pelto, M., Rodés, Á., Sagredo, E.S., Smedley, R.K., Smellie, J.L., Thorndycraft, V.R. 2020. The evolution of the Patagonian Ice Sheet from 35 ka to the present day (PATICE). Earth-Science Reviews, 204: 103152.

Dillehay, T.D., Ocampo, C., Saavedra, J., Oliveira Sawakuchi, A., Vega, R.M., Pino, M., Collins, M.B., Scott Cummings, L., Arregui, I., Villagran, X.S., Hartmann, G.A., Mella, M., González, A., Dix, G. 2015. New archaeological evidence for an early human presence at Monte Verde, Chile. Plos One 10(11): e0141923 (Erratum in: PLoS One. 2015;10(12):e0145471.

Dugmore, A.J., Newton, A.J., Sugden, D.E. 1992. Geochemical stability of fine-grained silicic Holocene tephra in Iceland and Scotland. Journal of Quaternary Science**,** 7(2): 173-183.

Emperaire, J., Laming, A. 1954. La grotte du Mylodon (Patagonie Occidentale). Journal de la Société des Américanistes, Nouvelle Série XLIII: 173-205.

Flegenheimer, N., Cattaneo, R. 2013. Análisis comparativo de desechos de talla en contextos del Pleistoceno final/Holoceno temprano de Chile y Argentina. Magallania, 41(1): 171-192.

García Huidobro Mery, V. 2015. Interacción entre fauna y ser humano durante el Holoceno en Cerro Benítez (Última Esperanza, Patagonia chilena): Aproximaciones desde los sitios Alero Pedro Cárdenas, Alero del Diablo, Cueva del Milodón y Cueva Ciro. Unpublished thesis, Universidad SEK, Santiago, Chile.

Garreaud, R.D., Lopez, P., Minvielle, M., Rojas, M. 2013. Large-Scale Control on the Patagonian Climate. Journal of Climate**,** 26(1): 215-230.

Gest, L., Parrenin, F., Chowdhry Beeman, J., Raynaud, D., Fudge, T.J., Buizert, C., Brook, E.J. 2017. Leads and lags between Antarctic temperature and carbon dioxide during the last deglaciation. Climate of the Past Discussions, doi:10.5194/cp-2017-71.

Grimm, E.C. 1987. CONISS: A Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences, 13: 13–35.

Grimm, E.C. 2011. Tilia software v. 2.1.1. Illinois, Illinois State Museum.

Hauthal, R., 1899. Reseña de los hallazgos en las cavernas de Última Esperanza (Patagonia austral). Revista del Museo de La Plata, IX: 411-420.

Hayward, C. 2012. High spatial resolution electron probe microanalysis of tephras and melt inclusions without beam induced chemical modification. The Holocene, 22: 119-125.

Heusser, C.J. 1971. Pollen and Spores of Chile. Tucson: The University of Arizona Press.

Heusser, C.J. 1995. Three late Quaternary pollen diagrams from southern Patagonia and their palaeoecological implications. Palaeogeography, Palaeoclimatology and Palaeoecology 118: 1–24.

Heusser, C.J., Borrero, L.A., Lanata, J.A. 1992. Late glacial vegetation at Cueva del Mylodon. Anales del Instituto de la Patagonia, 21: 97-102.

Hogg, A. G., Heaton, T. J., Hua, Q., Palmer, J. G., Turney, C. S. M., Southon, J., Bayliss, A., Blackwell, P. G., Boswijk, G., Bronk Ramsey, C., Pearson, C., Petchey, F., Reimer, P., Reimer, R., Wacker, L. 2020. SHCal20 Southern Hemisphere Calibration, 0-55,000 Years cal BP. Radiocarbon, 62(4): 759-778.

Hunt, J.B, Hill, P.G. 1993. Tephra geochemistry: A discussion of some persistent analytical problems. The Holocene, 3: 271–278.

Jowsey, P.C. 1966. An improved peat sampler. New Phytologist, 65: 245–248.

Kaplan, M.R., Schaefer, J.M., Strelin, J.A., Denton, G.H., Anderson, R.F., Vandergoes, M.J., Finkel, R.C., Schwartz, R., Travis, S.G., Garcia, J.L., Martini, M.A., Nielsen, S.H.H. 2016. Patagonian and southern South Atlantic view of Holocene climate. Quaternary Science Reviews, 141: 112-125.

Komárek, J., Jankovská, V. 2001. Review of the green algal genus Pediastrum; implications for pollen analytical research. Bibliotheca Psychologica, 108: pp.127.

Legoupil, D., Bertran, P., 2006. L’abri de Pedro Cárdenas et l’abri de Cerro Castillo. Rapport de Mission 2006. CNRS, Paris.

Lowe, J.J. 1982. Three Flandrian pollen profiles from the Teith valley, Scotland. II. Analysis of deteriorated pollen. New Phytologist, 90: 371-385.

Mansilla, C.A., McCulloch, R.D., Morello, F. 2016. Palaeoenvironmental change in Southern Patagonia during the Late glacial and Holocene: Implications for forest refugia and climate reconstructions. Palaeogeography, Palaeoclimatology, Palaeoecology, 447: 1-11.

Mansilla, C.A., McCulloch, R.D., Morello, F. 2018. The vulnerability of the Nothofagus forest-steppe ecotone to climate change: Palaeoecological evidence from Tierra del Fuego (53°S). Palaegeography, Palaeoclimatology, Palaeoecology, 508: 59-70.

Marchionni, L., Vázquez, M. 2012. New Data on Exploited Pleistocene Fauna at Piedra Museo (Central Plateau of Santa Cruz Province, Argentina). In: Miotti, L., Salemme, M., Flegenheimer, N., Goebel, T. (Eds), Southbound: Late Pleistocene Peopling of Latin America, Center for the Study of the First Americans. College Station: Texas A&M University, pp. 139-142.

Markgraf, V. 1985. Late Pleistocene Faunal Extinctions in Southern Patagonia. Science, 228: 1110-1112.

Markgraf, V., Whitlock, C., Haberle, S. 2007. Vegetation and fire history during the last 18,000 cal yr B.P. in Southern Patagonia: Mallín Pollux, Coyhaique, Province Aisén (45°41’30” S, 71°50’30” W, 640 m elevation). Palaeogeography, Palaeoclimatology, Palaeoecology, 254: 492-507.

Markgraf, V, Huber, U.M. 2010. Late and postglacial vegetation and fire history in Southern Patagonia and Tierra del Fuego. Palaeogeography, Palaeoclimatology, Palaeoecology**,** 297: 351–366.

Martin, F.M., 2013. Tafonomía de la Transición Pleistoceno-Holoceno en Fuego-Patagonia. Interacción entre humanos y carnívoros y su importancia como agentes en la formación del registro fósil. Punta Arenas: Ediciones de la Universidad de Magallanes.

Martin, F.M. 2018. Cueva del Milodón. The hunting grounds of the Patagonian panther. Quaternary International, 466: 212-222.

Martin, F.M. 2021. Fell Cave Reinterpreted. Chungara: Revista de Antropología Chilena, in press.

Martin, F.M., San Román, M., Morello, F., Todisco, D., Prevosti, F.J., Borrero, L.A. 2013. Land of the ground sloths: recent research at Cueva Chica, Última Esperanza, Chile. Quaternary International, 305: 56-66.

Martin, F., Todisco, D., Rodet, J., San Román, M., Morello, F., Prevosti, F., Stern, C., Borrero, L. 2015. Nuevas excavaciones en Cueva del Medio. Avances en los estudios de interacción entre cazadores recolectores y fauna extinta (Pleistoceno final, Patagonia meridional). Magallania, 43(1): 165-189.

Martin, F.M., Borrero, L.A. 2017. Climate change, availability of territory, and Late Pleistocene human exploration of Última Esperanza, South Chile. Quaternary International, 428: 86-95.

Martin, F., Todisco, D., Rodet, J., Prevosti, F.J., San Román, M., Morello, F., Stern, C., Borrero, L.A. 2019. The Cave at the End of the World, Cueva del Medio and the Early Colonization of Southern South America. In: Suárez, R., Ardelean, C. (Eds.), People & Culture in Ice Age Americas. New Dimensions in Paleoamerican Archaeology. Salt Lake City: University of Utah Press, pp. 1-12.

Martin, P.S. 1967. Prehistoric overkill. In: Martin P.S., Wright H.E. (Eds.), Pleistocene extinctions. New Haven: Yale University Press, pp. 75–120.

Massone, M., Prieto, A. 2004. Evaluación de la modalidad cultural Fell 1 en Magallanes. Chungara: Revista de Antropología Chilena, Volumen Especial, pp. 303–315.

Massone, M. 2004. Los cazadores después del hielo. Santiago, Chile: Ediciones de la Dirección de Bibliotecas, Archivos y Museos.

McCulloch, R.D., Bentley, M.J. 1998. Late glacial ice advances in the Strait of Magellan, southern Chile. Quaternary Science Reviews, 17: 775-787.

McCulloch, R.D., Bentley, M.J., Purves, R.S., Sugden, D.E., Clapperton, C.M. 2000. Climatic inferences from glacial and palaeoecological evidence at the last glacial termination, southern South America. Journal of Quaternary Science, 15: 409-417.

McCulloch, R., Fogwill, C., Sugden, D.E., Bentley, M., Kubik, P. 2005. Chronology of the last glaciation in central Strait of Magellan and Bahía Inútil, southernmost South America. Geografiska Annaler, Ser. B 87(2): 289–312.

McCulloch, R.D., Mansilla, C.A., Morello, F., De Pol-Holz, R., San Román, M., Tisdall, E., Torres, J. 2019. Late glacial and Holocene landscape change and rapid climate and coastal impacts in the Canal Beagle, southernmost Patagonia. Journal of Quaternary Science, 34(8): 674-684.

McCulloch, R.D., Blaikie, J., Jacob, B., Mansilla, C.A., Morello, F., De Pol-Holz, R., San Román, M., Tisdall, E., Torres, J. 2020. Late glacial and Holocene climate variability, southernmost Patagonia. Quaternary Science Reviews, 229, 106131.

Metcalf, J.L., Turney, C., Barnett, R., Martin, F.M., Bray, S.C., Vilstrup, J.T., Orlando, L., Salas-Gismondi, R., Loponte, D., Medina, M., De Nigris, M., Civalero, T., Fernández, P.M., Gasco, A., Duran, V., Seymour, K.L., Otaola, C., Gil, A., Paunero, R., Prevosti, F.J., Bradshaw, C.J.A., Wheeler, J.C., Borrero, L.A., Austin, J.J., Cooper, A. 2016. Synergistic roles of climate warming and human occupation in Patagonian megafaunal extinctions during the Last Deglaciation. Science Advances 2: e1501682.

Miotti, L., Salemme, M., Rabassa, J., 2003. Radiocarbon chronology at Piedra Museo Locality. In: Miotti, L., Salemme, M., Flegenheimer, N. (Eds.), Ancient Evidence for Paleo South Americans: from Where the South Winds Blow. Center for the Study of the First Americans. College Station: Texas A&M University, pp. 99-104.

Moore, P.D., Webb, J.A., Collinson, M.E. 1991. Pollen Analysis. London: Blackwell Scientific.

Moreno, P.I. 2004. Millennial-scale climate variability in northwest Patagonia over the last 15 000 yr. Journal of Quaternary Science, 19(1): 35–47.

Moreno, P.I., Villa-Martinez, R., Cardenas, M.L., Sagredo, E.A. 2012. Deglacial changes of the margin of the southern westerly winds revealed by terrestrial records from SW Patagonia (52°S). Quaternary Science Reviews, 41: 1–21.

Moreno, P., Vilanova, I., Villa-Martínez, R. Garreaud, R.D., Rojas, M., De Pol-Holz, R. 2014. Southern Annular Mode-like changes in southwestern Patagonia at centennial timescales over the last three millennia. Nature Communications, 5:4375.

Moreno, P.I., Vilanova, I., Villa-Martínez, R.P., Francois, J.P. 2018. Modulation of fire regimes by vegetation and site type in southwestern Patagonia since 13 ka. Frontiers in Ecology and Evolution, 6:34.

Moreno, P.I, Henríquez, W.I., Pesce, O.H., Henríquez, C.A., Fletcher, M.S., Garreaud, Villa-Martínez, R.D. 2021. An early Holocene westerly minimum in the southern mid-latitudes. Quaternary Science Reviews, 251: 106730.

Moy, C.M., Dunbar, R.B., Moreno, P.I., Francois, J.P., Villa-Martinez, R., Mucciarone, D.M., Guilderson, T.P., Garreaud, R.D. 2008. Isotopic evidence for hydrologic change related to the westerlies in SW Patagonia, Chile, during the last millennium. Quaternary Science Reviews, 27: 1335-1349.

Nami, H. G. 1994. Reseña sobre los avances de la arqueología finipleistocénica del extremo sur de Sudamérica. Chungara: Revista de Antropología Chilena, 26: 145-163.

Nami, H.G., Nakamura, T. 1995. Cronología radiocarbónica con AMS sobre muestras de huesos procedentes del sitio cueva del Medio. Anales del Instituto de la Patagonia. 32: 125-133.

Nordenskjöld, E., 1996 [1900]. Observaciones y relevamientos en cuevas de Última Esperanza en Patagonia occidental. Anales del Instituto de la Patagonia, 24: 99-124.

Paunero, R., Valiza Davis, C., Rindel, D., Tessone, A. 2017. La fauna pleistocénica: evidencias zooarqueológicas en la meseta central de Santa Cruz, los sitios de La María. Magallania, 45(2): 181-198.

Politis, G. 2014. Discusión y consideraciones finales. In: Politis, G., Gutiérrez, M.A., Scabuzzo, C. (Eds.), Estado actual de las investigaciones en el sitio arqueológico Arroyo Seco 2. Olavarría: INCUAPA-CONICET-UNICEN, pp. 439-459.

Prieto, A. 1991. Cazadores Tempranos y Tardíos en la Cueva 1 Lago Sofía. Anales del Instituto de la Patagonia, 20: 75-99.

Prieto, A., R. Labarca and V. Sierpe. 2010. New evidence of the sabertooth cat Smilodon (Carnivora: Machairodontinae) in the late Pleistocene of southern Chilean Patagonia. Revista Chilena de Historia Natural, 83: 299-307.

Romans, B.W., Fildani, A., Hubbard, S.M., Covault, J.A., Fosdick, J.C., Graham, S.A. 2011. Evolution of deepwater stratigraphic architecture, Magallanes Basin, Chile. Marine and Petroleum Geology, 28: 612–628.

Sagredo, E.A., Moreno, P.I., Villa-Martínez, R., Kaplan, M.R., Kubik, P.W., Stern, C.R. 2011. Fluctuations of the Última Esperanza ice lobe (52°S), Chilean Patagonia, during the last glacial maximum and termination 1. Geomorphology, 125: 92-108.

Salmi, M. 1955. Additional information on the findings in the Mylodon Cave at Última Esperanza. Acta Geographica Helsinki, 14(19): 314-333.

San Román, M. 2016. Stratégies économiques et sociales des chasseurs marins de Patagonie: Archéozoologie des sites anciens du détroit de Magellan et des mers intérieures. L'Université de Paris I Panthéon-Sorbonne, Paris.

Saxon, E. 1979. Natural prehistory: the archaeology of fuego-patagonian ecology. Quaternaria XXI, 329-356.

Sierpe, V., Prieto, A., Huidobro, C., Stern, C.R. 2009. Excavaciones arqueológicas en el sitio 'Alero Quemado' (Última Esperanza, Magallanes, Chile). Magallania, 37(2): 177-189.

Steele, J., Politis, G. 2009. AMS ^{14}C dating of early human occupation of southern South America. Journal of Archaeological Science, 36(2): 419–429.

Stern, C.R., Moreno, P.I., Villa-Martinez, R., Sagredo, E.A., Prieto, A., Labarca, R. 2011. Evolution of ice-dammed proglacial lakes in Última Esperanza, Chile: implications from the late-glacial R1 eruption of Reclus volcano, Andean Austral Volcanic Zone. Andean Geology, 38: 82-97.

Stockmarr, J. 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores, 13: 615–621.

Stuiver, M., Reimer, P.J. 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon, 35: 215-230.

Tipping, R.M. 1987. The origins of corroded pollen grains at 5 early post glacial pollen sites in western Scotland. Review of Palaeobotany and Palynology**,** 53: 151-161.

Tipping, R. 2000. Pollen preservation analysis as a necessity in Holocene pollen analysis. In: Huntley, J., Stallibrass, S. (Eds.) Taphonomy and Interpretation. Symposia of the Association for Environmental Archaeology, 14. Oxford: Oxbow Books, pp. 23-34.

Tipping, R., Davies, A., McCulloch, R., Tisdall, E. 2008. Response to late Bronze Age climate change of farming communities in north east Scotland. Journal of Archaeological Science, 35: 2379-2386.

Todisco, D. Rodet, J., Nehme, C., Martin, F., Borrero, L.A. 2018. Les cavités du Cerro Benítez (Patagonie, Chili) Hypothèses génétiques glacio-karstiques. Karstologia, 67: 31-42.

Tweddle, J.C., Edwards, K.J. 2010. Pollen preservation zones as an interpretative tool in Holocene palynology. Review of Palaeobotany and Palynology, 161: 59-76.

Villa-Martínez, R., Moreno, P.I. 2007. Pollen evidence for variations in the southern margin of the westerly winds in SW Patagonia over the last 12,600 years. Quaternary Research 68, 400-409.

Villagrán, C. 1980. Vegetationsgeschichtliche und pflanzensoziologische Untersuchungen im Vicente Pérez Rosales Nationalpark (Chile). Vaduz: Cramer.

Villavicencio, N.A., Lindsey, E.L., Martin, F.M., Borrero, L.A., Moreno, P.I., Marshall, C.R., Barnosky, A.D. 2015. Combination of humans, climate, and vegetation change triggered Late Quaternary megafauna extinction in the Última Esperanza region, southern Patagonia, Chile. Ecography 38: 001–016.

Walker, M., Head, M.J., Lowe, J., Berkelhammer, M., BjÖrck, S., Cheng, H., Cwynar, L.C., Fisher, D., Gkinis, V., Long, A., Newnham, R., Rasmussen, S.O., Weiss, H. 2019. Subdividing the Holocene Series/Epoch: formalization of stages/ages and subseries/subepochs, and designation of GSSPs and auxiliary stratotypes. Journal of Quaternary Science, 34(3): 173-186.

Waters, M., Amorosi, T., Stafford Jr., T.W. 2015. Redating Fell's cave, Chile and the chronological placement of the fishtail projectile point. American Antiquity, 80(2): 376-386.

Whitlock, C., Larsen, C. 2001. Charcoal as a fire proxy. In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments Terrestrial, Algal and Siliceous Indicators vol. 3. Dordrecht: Kluwer Academic Publishers.

Wingenroth, M., Heusser, C.J. 1984. Pollen of the High Andean Flora. Quebrada Benjamin Matienzo, Province of Mendoza Argentina. Mendoza: Instituto Argentino de Nivologia y Glaciologia.

Whittington, G., Edwards, K.J. 1994. Palynology as a predictive tool in archaeology.

Proceedings of the Society of Antiquaries of Scotland, 124: 55–65.

Zolitschka, B., Anselmetti, F., Ariztegui, D., Corbella, H., Francus, P., Lücke, A., Maidana, N.I., Ohlendorf, C., Schäbitz, F., Wastegård, S. 2013. Environment and climate of the last 51,000 years – new insights from the Potrok Aike maar lake Sediment Archive Drilling prOject (PASADO). Quaternary Science Reviews, 71: 1-12.

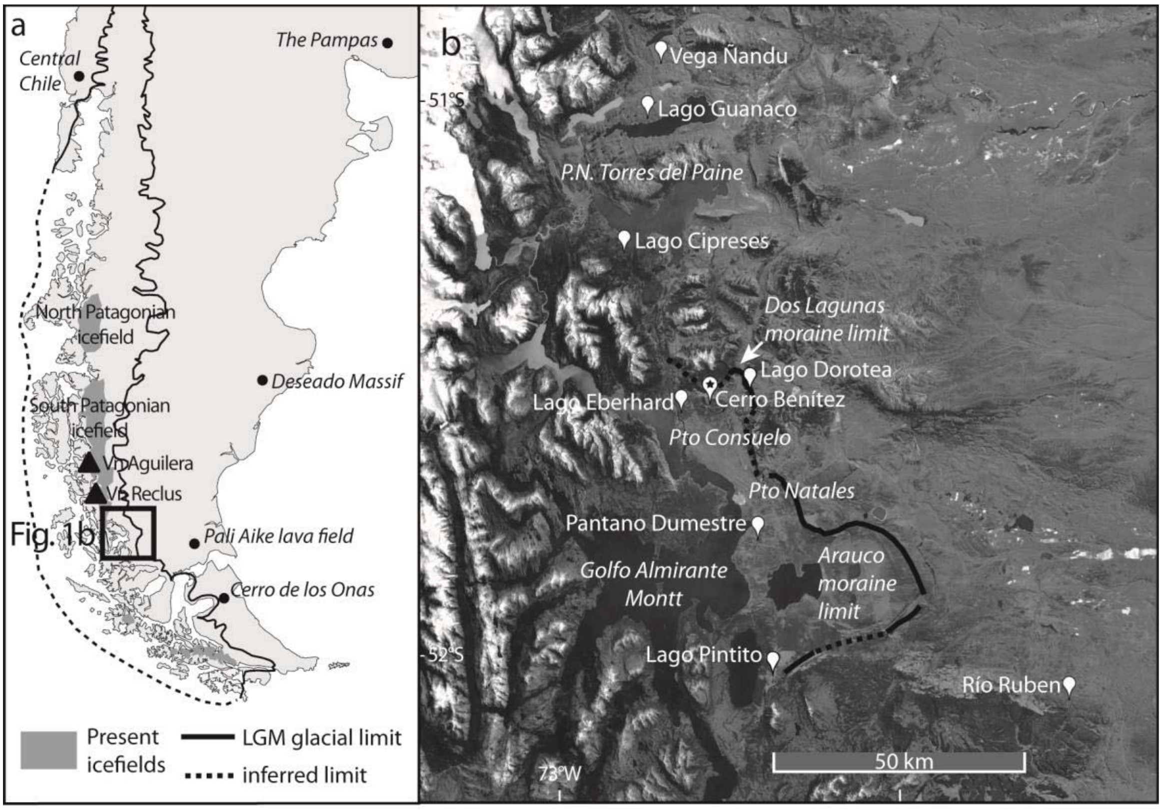

Figure 1: a) Southern South America and estimation of the coterminous Patagonian ice cap during the LGM (from McCulloch et al., 2000). The broad location of archaeological areas (Central Chile, The Pampas, Deseado Massif, Pali Aike lava field and Cerro de los Onas) are also indicated; b) the Seno Última Esperanza area and locations of palaeoenvironmental sites mentioned in the text (base image from Google Earth).

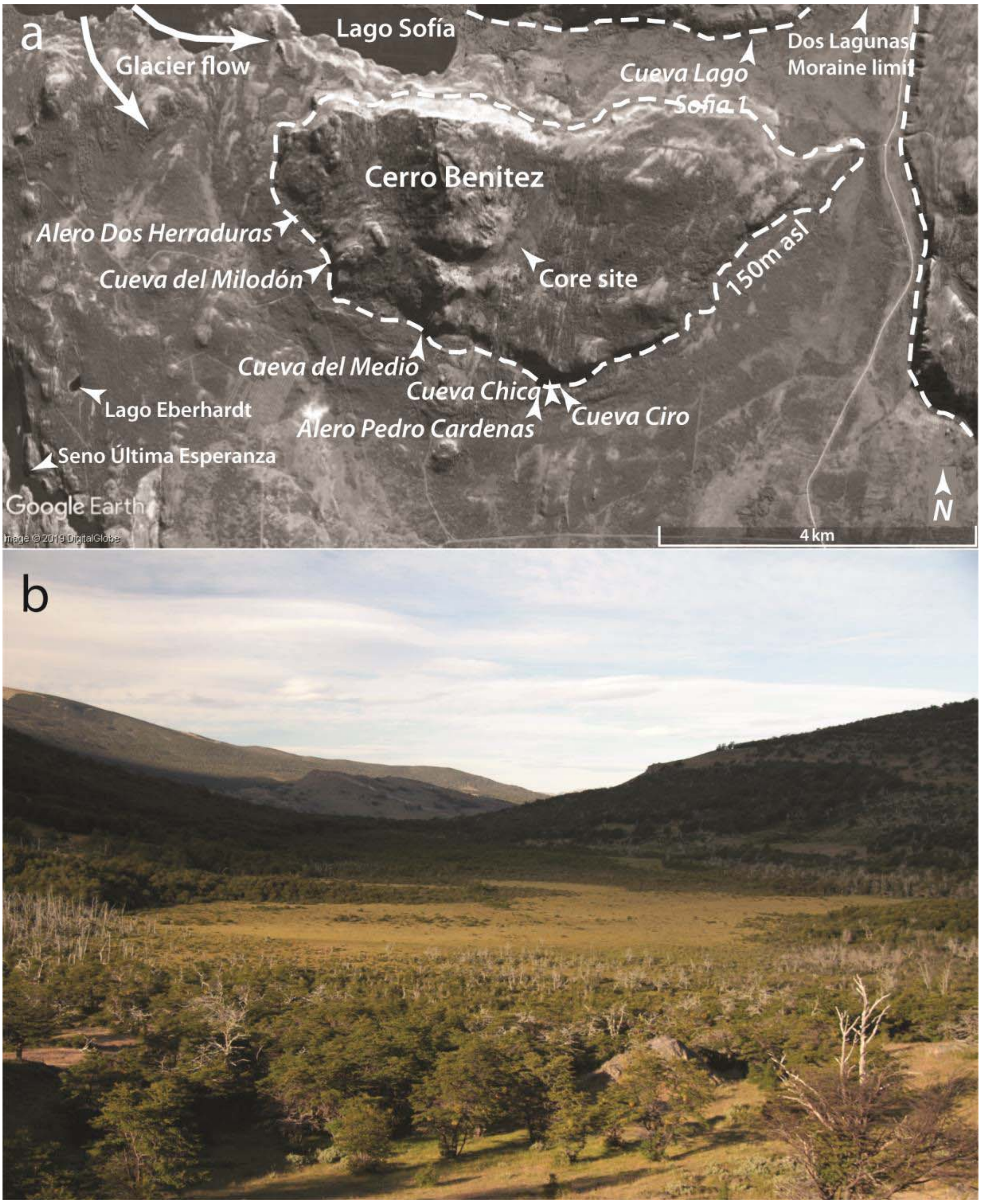

Figure 2: a) Cerro Benítez and the location of the caves and aleros, mentioned in the text, along the 150m asl proglacial Lago Puerto Consuelo palaeoshoreline (white dashed line) (Sagredo et al., 2011; Stern et al., 2011) (base image from Google Earth); b) the fen-peat bog encircled by *Nothofagus* woodland at Cerro Benítez (view looking north) (Photograph: R. McCulloch).

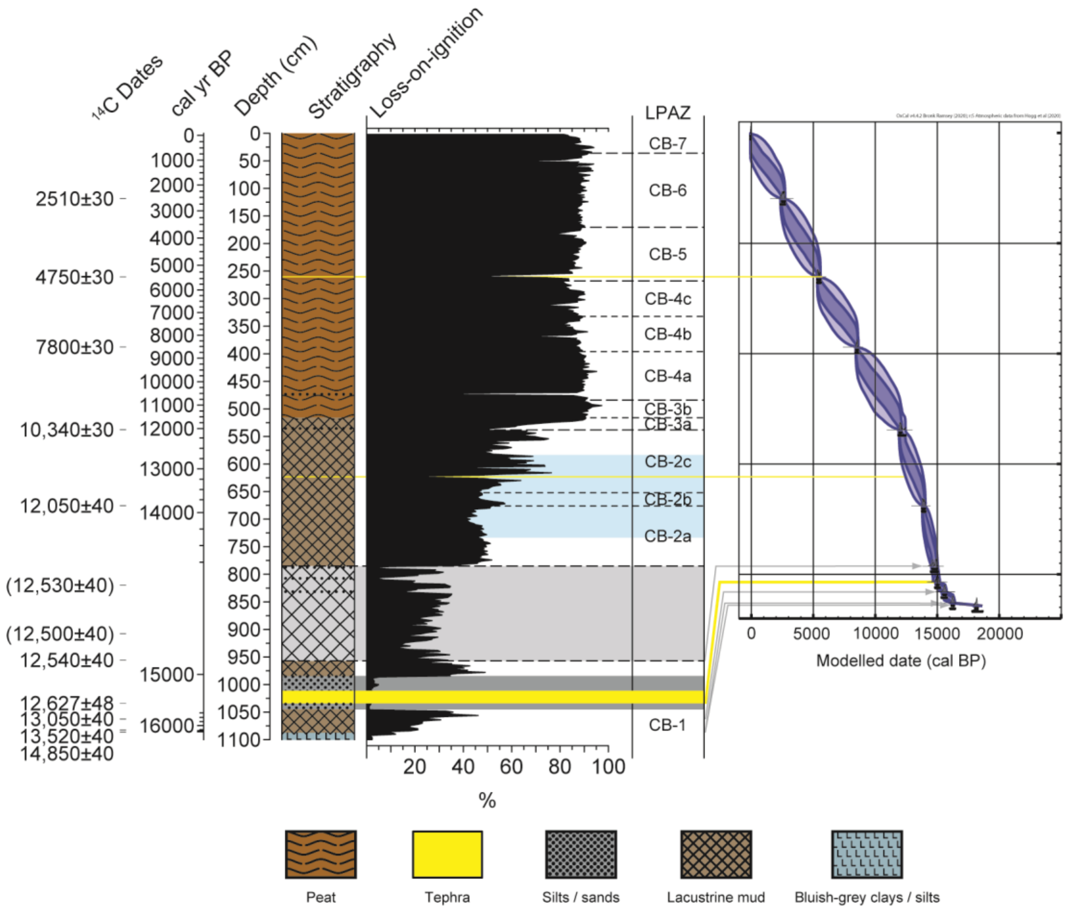

Figure 3: Stratigraphy of the Cerro Benítez core and age-depth model from OxCal (Bronk Ramsay, 2009; Bronk Ramsey and Lee, 2013). The grey shaded bar between LPAZs CB-1 and CB-2a represents the near-instantaneous accumulation of sediments at *c.* 12,500 cal a BP which, along with mineral inwash and tephra layers, have been removed from the age-depth model. The blue shaded bar in Figures 3 to 6 indicates the timing of the ACR (Gest et al., 2017).

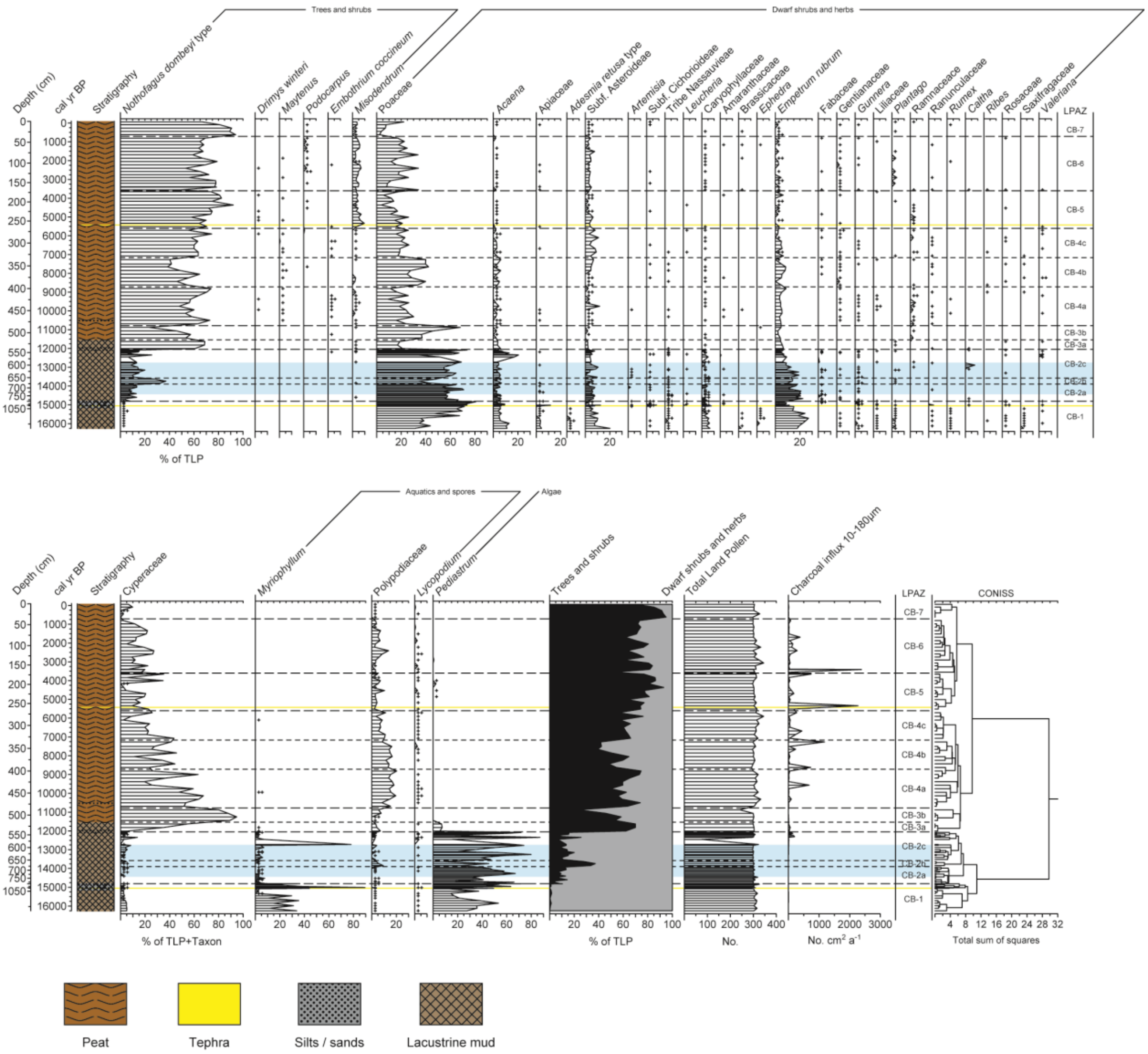

Figure 4: Percentage pollen and spore diagram for selected taxa from Cerro Benítez. The LPAZs were determined using CONISS (Grimm, 1987) and also applied to Figures 5, 6 and 7 to aid comparison.

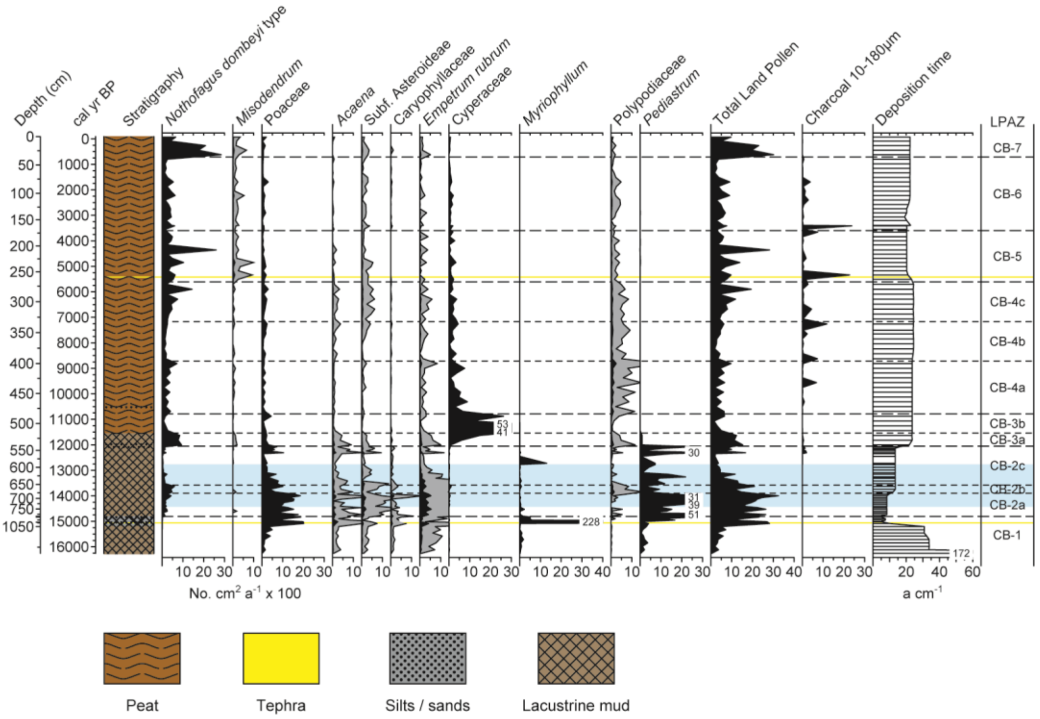

Figure 5: Influx (grains cm^2 a^{-1}) diagram for selected taxa from Cerro Benítez.

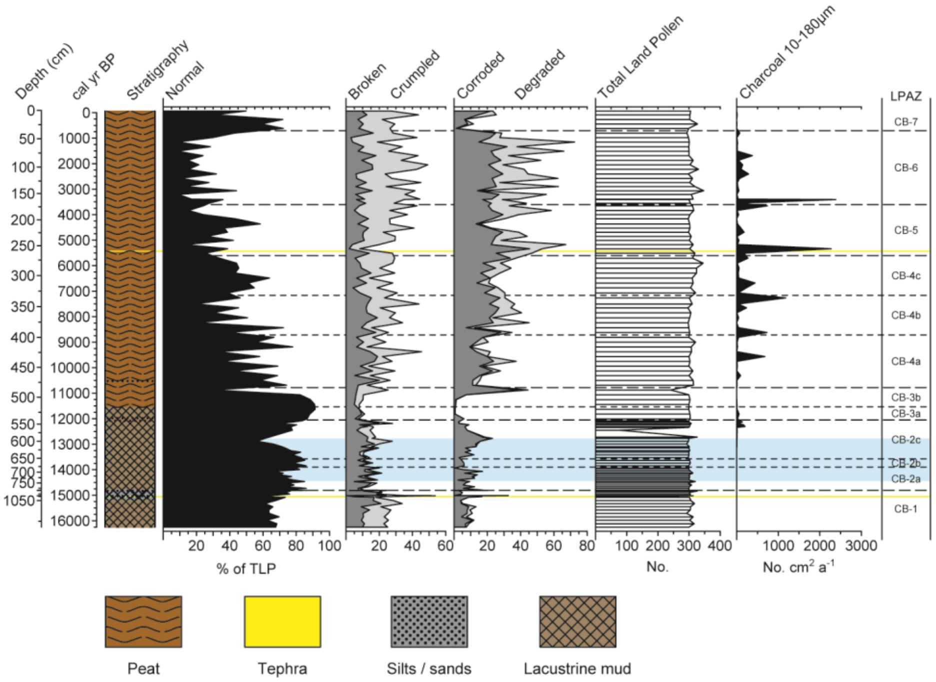

Figure 6: Percentage land pollen preservation diagram from Cerro Benítez.

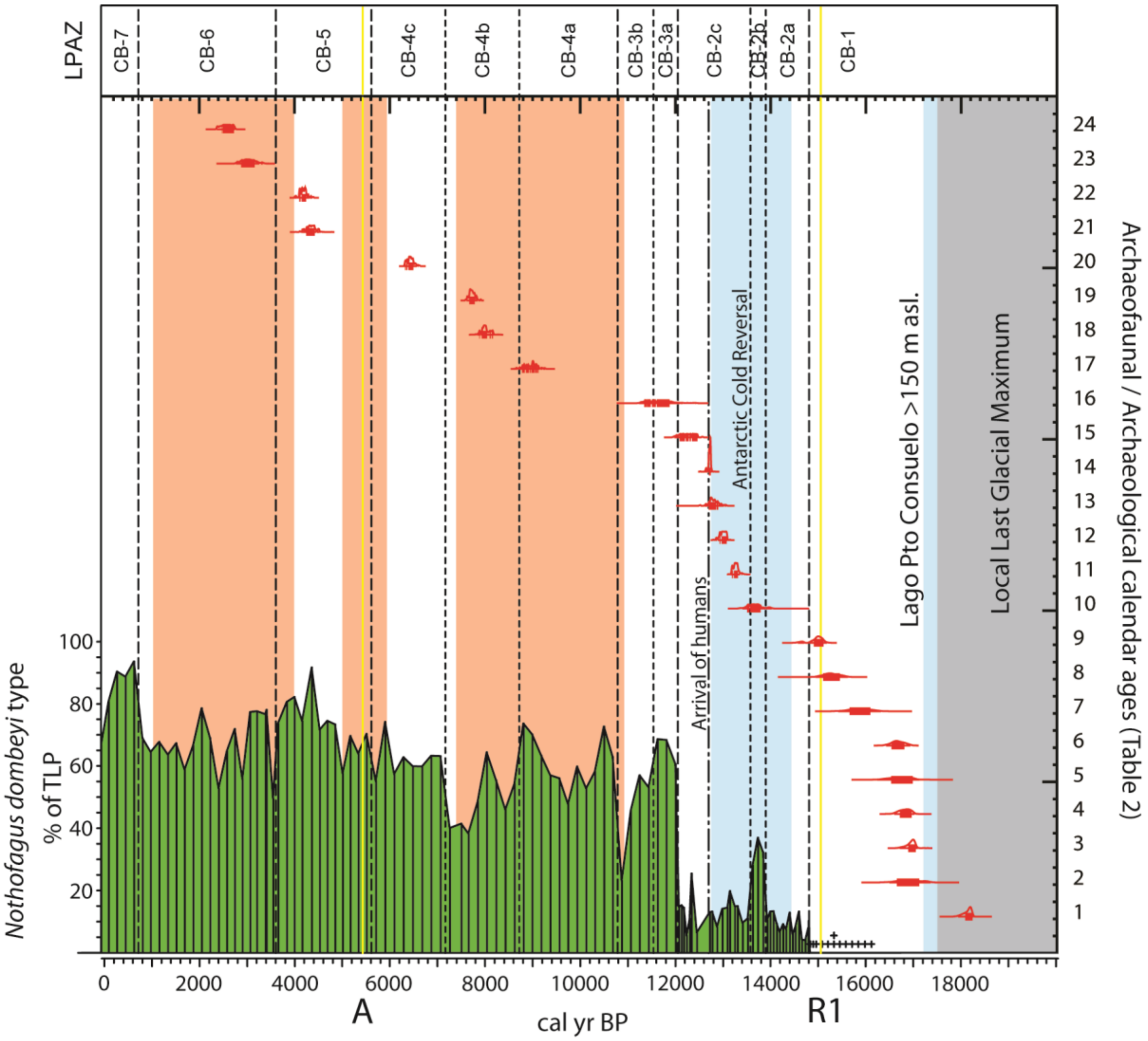

Figure 7: A synthesis of the palaeoenvironmental and archaeofaunal-archaeological evidence from Cerro Benítez. The calibrated age ranges of the archaeofaunal and archaeological samples given in Section 5 of this paper. The posterior probability distribution plots (in red) were produced using Calib 8.2 (Stuiver and Reimer, 1993) and the SHCal20 calibration curve (Hogg et al. 2020). The number of each plot refers to the sample information in Table 2. The periods of the raised (>150m asl) pro-glacial lake level of Lago Puerto Consuelo and the Antarctic Cold Reversal are indicated by blue shaded bars. The percentage *Nothofagus dombeyi* type pollen curve and LPAZs are plotted as an indicator of changes in habitat. The pink shaded bars indicate relatively drier periods as evidenced by the pollen preservation data (Fig. 6).