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Late glacial and Holocene landscape change and rapid climate and coastal impacts in the Canal Beagle, southernmost Patagonia.

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Abstract

Palaeoenvironmental data for the Late glacial and Holocene is provided from Caleta Eugenia, in the eastern sector of Canal Beagle, southernmost Patagonia. The record commences at c. 16,200 cal a BP following glacier retreat in response to climatic warming. However, cooler conditions persisted during the Late glacial period. The onset of more temperate conditions after c. 12,390 cal a BP is indicated by the arrival of southern beech forest and later establishment at c. 10,640 cal a BP, but the woodland growth was restricted by lower levels of effective moisture. The climate signal is then truncated by a rapid marine incursion at c. 8640 cal a BP which lasted until a more gradual emergence of the coast at c. 6600 cal a BP. During this period the pollen record appears to be dominated by the southern beech woodland. A punctuated hydrosere succession follows the isolation of the site from the sea leading to the re-establishment of a peat bog. Between c. 5770 cal a BP and the present there were several periods of short rapid climatic change leading to drier conditions, probably as a result of late Holocene periods of climatic warming.

25
26 Keywords: Pollen analysis, Tephrochronology, Sea-level change, Pollen preservation, Southern westerly
27 winds.

29 1. Introduction

31 Climate of the south-eastern part of the Fuegian archipelago, southernmost Patagonia, is strongly
32 influenced by the westerly atmospheric circulation, the southern westerly winds (SWWs). The intensity
33 and location of the westerlies reflect the extent of Antarctic sea ice, the movements in the circumpolar
34 oceanic Antarctic Convergence and the strength of sub-tropical anticyclonic cells over the Atlantic and
35 Pacific Oceans (Moy et al., 2008). The steep climatic gradients and Andean topography of the Fuegian
36 archipelago results in a complex mosaic of environments which range from maritime to alpine to
37 continental conditions within tens of kilometres. Topography (highest point 2405 m a.s.l.) and climate
38 combine to support extant ice fields on the Cordillera Darwin. The present vegetation of the region
39 closely reflects the steep precipitation gradient from the hyper humid Magellanic moorland and
40 evergreen forests in the west (mean annual precipitation ~ 3000 - 2000 mm a⁻¹) to the deciduous forests
41 and steppe vegetation (mean annual precipitation ~ 500 - 300 mm a⁻¹) in the east (Fig. 1). The core of the
42 present SWWs migrates seasonally but also probably migrated $\sim 5^\circ$ of latitude northwards during the
43 Last Glacial Maximum (Hulton et al., 2002). Shifts in the latitudinal position of the SWWs during the Late
44 glacial and Holocene would have driven shorter term regional changes in precipitation, generating
45 complex vegetation and landscape responses. A chronologically well constrained palaeoenvironmental
46 record of these landscape and vegetation dynamics can provide regional evidence for shifts in the
47 position of the SWWs.

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2
3 49 The Canal Beagle (54°54'S) is a west-east trending trough at the boundary between the South America
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5 50 and Scotia tectonic plates (Bujaleski 2011) (Fig. 1). The canal lies to the east of the Cordillera Darwin and
6
7 51 has been repeatedly scoured by glacier advances draining the eastern ice divide of the cordillera during
8
9 52 successive glacial cycles. During the Last Glacial Maximum (LGM) the Canal Beagle glacier likely
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11 53 advanced as far as Pta. Moat-Isla Picton (Rabassa et al., 2000) (Fig. 1). The timing of ice retreat of the
12
13 54 Cordillera Darwin glaciers after the LGM is uncertain but there is evidence to suggest widespread retreat
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15 55 after c. 17,500 cal a BP (Rabassa et al., 2000; McCulloch et al., 2005; Hall et al., 2018) in response to
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17 56 regional warming reflected in the Antarctic ice cores (Jouzel et al., 2007). The isostatic legacy of the last
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19 57 glaciation is also evidenced by raised palaeoshorelines associated with ice dammed proglacial lakes and
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21 58 a raised Holocene marine shoreline (Borromei and Quattrocchio, 2007).
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27 60 However, our ability to describe how such a heterogenous landscape responded to climate change, and
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29 61 in particular shifts in the SWWs, is limited by the geographic and temporal paucity of
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31 62 palaeoenvironmental records from the region. There are a number of Holocene palaeoecological
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33 63 records from the north of the Canal Beagle (Valle Andorra: Borromei, 1995; Punta (Pta.) Moat: Borromei
34
35 64 et al., 2014) and a few that span the Late glacial - Holocene (Puerto (Pto.) Harberton: Markgraf and
36
37 65 Huber, 2010; Ushuaia I, II and III: Heusser, 1998; Cañadón del Toro: Borromei et al., 2016; Terra
38
39 66 Australis: Mussoto et al., 2017). Together these sites suggest a landscape that was treeless during the
40
41 67 Late glacial and was generally colonised by *Nothofagus* (southern beech) woodland between c.10,500
42
43 68 and 10,300 cal a BP (see Mansilla et al., 2016 for a more comprehensive review). There is only one
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45 69 palaeoecological record from the south of the Canal Beagle (Caleta (Cta.) Robalo (aka Pto. Williams:
46
47 70 Heusser, 1989) and one to the east on Isla de los Estados (Cta. Lacroix: Ponce and Fernandez, 2014).
48
49 71 These records suggest that the position of the SWWs has shifted latitudinally during the Late glacial and
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51 72 Holocene but there remains a lack of spatial definition of poleward shifts as well as poor temporal
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73 resolution. Here we present palaeoenvironmental evidence from a mire within an isolation basin
74 located at the eastern end of the north shore of Isla Navarino (Canal Beagle), part of the Fuegian
75 archipelago. Such sites are relatively rare, and the record will provide a climate sensitive, multi proxy
76 record of environmental change and provide valuable insights into the evolution of the coastal margin in
77 a post-glaciated area.

78
79 Several studies in the Canal Beagle have focused on Holocene marine transgression sites on the north
80 side of the canal (Lapataia 1 and 2: Heusser, 1998; Borrromei and Quattrocchio, 2007; Albufera
81 Lanushuaia: Candela et al., 2011 and Rio Varela: Grill et al., 2002). The timing of the marine incursion is
82 broadly c. 8800 to 6800 cal a BP. However, extent and duration of the mid-Holocene marine incursion
83 and the potential disruptive effects of neotectonics movements remains uncertain (Borrromei and
84 Quattrocchio, 2007). A clearer definition of the mid-Holocene marine incursion is required as it is central
85 to any interpretation of human colonisation and occupation of the region.

86
87 The human occupation of Tierra del Fuego dates from the Late glacial-Holocene transition and the
88 earliest archaeological record is from Cueva Tres Arroyos 1, northern Tierra del Fuego, which indicates
89 that humans had arrived by c. 12,000 cal a BP (Massone, 2004). Human activity was strongly related to
90 terrestrial resources, mainly guanaco (*Lama guanicoe*) and the minor use of now extinct taxa (Martin,
91 2006). Along the southern coast of Tierra del Fuego, along the Canal Beagle, the earliest evidence for
92 human occupation ranges between c. 8700 and 7300 cal a BP (lower layers of archaeological sites Túnel
93 1, Imiwaia and Binushmuka I (Bahía Cambaceres): Orquera and Piana 2009; Zangrando et al., 2019) (Fig.
94 1). Archaeological evidence from Isla Navarino suggests the coastal margins were colonized by early
95 marine hunter-gatherer groups at c. 7000 cal a BP and this nomadic lifestyle persisted till the beginning
96 of the twentieth century (Legoupil et al., 1993; Ocampo and Rivas, 2000; San Roman et al., 2017). Thus,

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3 97 understanding the environment-human dynamics along the coastal margins are key to understanding
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5 98 the nomadic peopling of the sub Antarctic region during the Holocene (McCulloch and Morello, 2009;
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7 99 Rozzi, 2012). The narrow strip of land that forms the coastal zone, including the near-shore highly
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10 100 productive ecosystems of kelp forests and diverse hotspots for marine resources (Cádenas and Montiel,
11
12 101 2016), was an important geographical space for accessing marine and terrestrial resources (e.g.
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14 102 materials for diet, fuel, tools and shelter). The littoral setting is directly related to all past socio-cultural
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16 103 activity of the Canal Beagle inhabitants (San Roman, 2018). Thus, the palaeoenvironmental record from
17
18 104 Cta. Eugenia may help us better understand the interactions between humans and their changing
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21 105 landscape ecosystems at the land-marine interface along the Canal Beagle channel during the Holocene
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25 107 **2. Material and methods**
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30 109 2.1. Study area
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34 111 The site is a mire within a small depression near Cta. Eugenia (54°55'44.7"S, 67°20'44.5"W, altitude 3.7
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36 112 m a.s.l.; Fig. 1). The surrounding landforms comprise glacial drift and were probably formed during the
37
38 113 Last Glacial Maximum, when the glaciers expanded from the Cordillera Darwin and flowed eastwards
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40 114 along the Canal Beagle (Rabassa et al., 2000). The mire site is located between the open coastal
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43 115 landscape, including a series of storm beach ridges (the highest ridge reaches ~4.0 m a.s.l.), and dense
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45 116 forest (Fig. 2). There is an ephemeral linear pool of water that lies inland of the storm beach ridges and
46
47 117 bounds the raised mire. The present vegetation suggests reduced mire surface wetness with *Empetrum*
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49 118 *rubrum* and *Chilotrachium diffusum* scrub and *Nothofagus betuloides* and *Nothofagus antarctica*
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51
52 119 colonising the mire surface. Smaller wetter areas are dominated by hummocky *Sphagnum*
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54
55 120 *magellanicum*. The surrounding landscape is covered by *Festuca* - *Chilotrachium* grass-scrub along the
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121 coastal margin and inland there is dense primary and secondary southern beech deciduous forest
122 (*Nothofagus pumilio* and *Nothofagus antarctica*). The climate of Isla Navarino lies at the boundary
123 between temperate humid with cool summers (Cfc) and Polar tundra (ET). Annual precipitation is ~500
124 mm a⁻¹ with more falling in the austral summer months, and there is a seasonal difference in
125 temperature, with a mean temperature in January (austral summer) of ~9.3°C and in July (austral
126 winter) 1.8°C (Tuhkanen et al., 1989-1990).

128 2.3. Sediment coring and laboratory methods

130 A 900 cm core was retrieved from the mire using a 50 cm long Russian corer with a 5.5 cm diameter
131 (Jowsey, 1966). Each core section was photographed and described in the field following Troels Smith
132 (1955) with simplified lithology shown in figures for ease of reproduction. Core sections were then
133 transferred to plastic guttering, sealed in polythene lay-flat tubing and stored at a constant 4°C at the
134 University of Stirling.

136 The organic content of the core was estimated by loss-on-ignition with 2 cm contiguous sub-samples
137 combusted for 4 hours at 550°C (LOI₅₅₀). Sub-samples of 1 cm³ were taken from the core at a resolution
138 of between 8 cm and 4 cm and prepared for pollen analysis using a standard methodology (Moore et al.,
139 1991). Pollen, spores and algae were identified using an Olympus BX43 light microscope, at 400x
140 magnification and a minimum of 300 total land pollen (TLP) were counted per sub-sample, the total
141 excluding Cyperaceae, aquatics and spores. Known concentrations of *Lycopodium clavatum* spores were
142 added to the samples to facilitate the estimation of the concentration of pollen, spores and algae (No.
143 grains cm⁻³) (Stockmarr, 1971). The concentration values and sediment accumulation rates (cm a⁻¹) were
144 used to calculate the total pollen accumulation rate (pollen influx, No. grains cm⁻² a⁻¹) and total charcoal

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3 145 accumulation rate (charcoal influx, No. particles cm⁻² a⁻¹). The charcoal particles were counted and
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5 146 measured alongside the pollen and were classified into two categories by size ≤100 μm (microscopic)
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7 147 and 100-180 μm (macroscopic) (Whitlock and Larsen, 2001).
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9 148
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11
12 149 Pollen and spores were identified with the aid of a pollen reference collection (held by RMcC) supported
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14 150 by photographs of pollen and spores (Heusser, 1971; Wingenroth and Heusser, 1984; Moore et al.,
15
16 151 1991). The palynological data was plotted using Tilia version 2.6.1 (Grimm, 2011). Local pollen
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18 152 assemblage zones (LPAZs) were determined using the stratigraphically constrained incremental sum-of-
19
20 153 squares cluster analysis (CONISS, Grimm, 1987).
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25 155 Additional insights into the changing environmental conditions at the site were obtained through the
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27 156 hierarchical categorization of the state of preservation of each land pollen grain: normal, broken,
28
29 157 crumpled, corroded and degraded (Tipping, 1987; McCulloch and Davies, 2001; Mansilla et al., 2018).
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31 158 Pollen grains are best preserved (i.e. normal) in wetter-acidic and anaerobic conditions found in low-
32
33 159 energy environments such as peat bogs and undisturbed lake sediments. Broken and crumpled pollen
34
35 160 may reflect a more abrasive and/or energetic environment prior to final deposition. Corroded and
36
37 161 degraded pollen are considered to have been damaged by oxidation and the actions of bacteria and
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39 162 fungi (biochemical factors) operating under more aerobic conditions.
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46 164 **3. Results**

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50 166 3.1. Sediment stratigraphy
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3 168 A simplified stratigraphy of the core from Cta. Euegnia is shown alongside the LOI₅₅₀ profile in Figure 3.
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5 169 From 900 cm to 882 cm, the basal sediments comprise compact light bluish-grey clays and silts and were
6
7 170 probably deposited under a proglacial lake following glacier retreat. Between 882 cm and 838 cm the
8
9 171 sediment gradually increases in organic content to form a rich lacustrine mud but with sub-centimetre
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11 172 bands of bluish-grey clays suggesting the warming trend was punctuated by brief reversals. At 842 cm
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13 173 the lacustrine mud is overlain by a 28 cm thick layer of soft bluish-grey clays. The clays are dissimilar in
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15 174 colour and degree of compactness in comparison to the basal clays and silts and we suggest they are
16
17 175 periglacial solifluction clays rather than a return to direct glacial inputs to the site. Overlying the clays is
18
19 176 a 10 cm layer of organic rich lacustrine mud which grades rapidly into compact well-humified peat to
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21 177 764 cm. Between 764 cm and 746 cm there is a brief increase in mineral content before returning to
22
23 178 peat. The accumulation of peat continues to 636 cm where it is truncated by a sharp contact to
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25 179 greenish-grey clays and silts with occasional fragments of mollusc shells suggesting the sediments are
26
27 180 marine in origin. The sharp contact between the peat and the overlying marine sediments may
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29 181 represent an erosive contact. However, we suggest it is unlikely as the marine sediments are clay-silts
30
31 182 indicative of a low-energy depositional environment. Relatively homogenous marine sediments continue
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33 183 to accumulate until ~431 cm when the stratigraphy becomes more banded and small peaks in organic
34
35 184 content occur. From 409 cm the stratigraphy gradually develops into an organic rich fine lacustrine mud
36
37 185 / fen peat (>80%) which continues to 360 cm above which it becomes a very pale brown, very fibrous
38
39 186 peat. Between 288 cm and the surface the peat accumulation continues with varying degrees of fibrous
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41 187 content and compactness.
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50 189 Light and polarised light microscopy analysis of the mineral residue from the LOI₅₅₀ samples identified
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52 190 two cryptotephra layers: Mount Burney (~52°S), a white silt layer at 236 cm (MB2) and Volcán Hudson
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54 191 (~46°S), a dark olive-green coarse silt layer at 612 cm (H1). The glass component of each tephra layer
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was isolated using the preparation methodology of Dugmore et al. (1992). Individual glass shards were geochemically analysed by RMCC using an SX100 Cameca Electron Microprobe at the School of GeoSciences, The University of Edinburgh (Hayward, 2011). The ages for each geochemically identified tephra layer are included in Table S1.

3.2. Chronology

The core is constrained by 8 AMS radiocarbon dates on bulk organic material and from fine plant material. The ¹⁴C minimum and maximum ages for the period of marine sedimentation were obtained from millimetre slices of peat / organic rich lacustrine mud immediately below and above the marine clays respectively. Therefore, we are confident that any marine reservoir effect will be negligible. Ages for the H1 and MB2 tephtras were also included to provide a more robust chronology (Table 1). The Bayesian modelling software BACON (Blaauw and Christen, 2011) was used to construct the age–depth model (Fig. 3). The weighted mean ages from the BACON age–depth model were used to provide the age–depth axis (cal a BP) for the pollen diagrams: percentage pollen (Fig. 4), pollen accumulation rate (influx) (Fig. 5) and percentage pollen preservation (Fig. 6).

3.3. Palaeoenvironmental results and inferences

Seven Local Pollen Assemblage Zones (LPAZs) were defined for the Cta. Eugenia pollen record using constrained cluster analysis and applied to Figs. 4, 5 and 6 to aid comparison.

3.3.1. LPAZ CE-1 (882–842 cm; 16,290 – 15,470 cal a BP)

215 The basal LPAZ is dominated by fluctuating amounts of relatively poorly preserved (Normal = ~30-40%)
216 *Gunnera* and *Empetrum rubrum*. The organic content gradually increases starting from the sterile bluish-
217 grey clays at the base and there is a small amount of Cyperaceae (~10-20%), though aquatic pollen are
218 absent. This suggests that the basin was occupied by open water ringed by sedges and the recently
219 deglaciaded terrain and development of soils surrounding the site was initially colonised by *Gunnera*
220 ground cover and *Empetrum* heath, shifting in response to small-scale changes in effective moisture.
221 Although the trend is towards more temperate conditions, climate continues to be cool and favours
222 cold-tolerant taxa. The warming trend is then interrupted at c. 15,470 cal a BP indicated by the
223 deposition of barren periglacial bluish-grey clays which continues until c. 14,530 cal a BP.

225 3.3.2. LPAZ CE-2 (814–754 cm; 14,530 – 12,390 cal a BP)

226 After the cessation of clay accumulation, the pollen assemblage dramatically changes to be dominated
227 by Poaceae with lesser amounts of *Empetrum rubrum* and *Caltha*. This suggests a shift to a drier
228 landscape largely covered by grasses surrounding the site and the water level at the site shallowing in
229 response to drier conditions leading it to be dominated by Cyperaceae (>60%) and *Caltha*. This picture is
230 reinforced by the continued poor preservation of the terrestrial pollen (Normal = ~30%), the compact
231 and dark fine-detrital sediment and the slower rate of sediment accumulation (~35 a cm⁻¹). The small
232 increase in the influx of Cyperaceae suggests the extent of open water was reduced and sedges were
233 able to spread across the site.

235 3.3.3. LPAZ CE-3 (754–632 cm; 12,390 – 8540 cal a BP)

236 This LPAZ marks the continuous deposition of *Nothofagus dombeyi* type pollen (>2%) which probably
237 reflects the dispersal of southern beech trees into the area in response to ameliorating climatic
238 conditions, although the pollen influx of *Nothofagus dombeyi* type remains very low. The establishment

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3 239 of *Nothofagus* forest (~20% TLP; ‘Parque’ *sensu* Burry et al., 2006) occurs later at c. 10,640 cal a BP and
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5 240 this is mirrored by the coeval increase in the hemiparasite *Misodendrum* that favours *Nothofagus*
6
7 241 *antarctica* and *Nothofagus pumilio*. However, the expansion of the forest was likely constrained by the
8
9 242 continued relatively drier conditions evidenced by the increase in corroded and degraded pollen
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11 243 (Normal = ~10-20%) and the proportion of *Nothofagus dombeyi* type declines towards the upper
12
13 244 boundary. This constraint is reflected in the continued dominance of steppe vegetation (Poaceae, subf.
14
15 245 Asteroideae) which replaced Cyperaceae across the drier site and the rate of sediment accumulation
16
17 246 slowed to its lowest level (~48 a cm⁻¹) of the whole record. A shift to warmer drier conditions is also
18
19 247 emphasised by the dramatic expansion in Polypod ferns (Polypodiaceae) and the increase in charcoal
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21 248 influx, probably as a result of the increase in the availability of drier fuel.
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28 250 3.3.4. LPAZ CE-4 (632–408 cm; 8540 - 6680 cal a BP)

29
30 251 This LPAZ marks the very rapid relative sea-level rise and inundation of the mire at Cta. Eugenia. The
31
32 252 stratigraphic transition occurs at c. 8640 cal a BP (636 cm) from peat to greenish-grey clays and silts
33
34 253 within <10 years. The rapid and categorical change in stratigraphy is also reflected in the increase in
35
36 254 *Nothofagus dombeyi* type pollen and improvement in pollen preservation (Normal ~65%), a
37
38 255 corresponding decrease in steppe vegetation (Poaceae, subf. Asteroideae) and the gradual decline in
39
40 256 Polypod ferns which began towards the top of LPAZ CE-3. Climatic inferences from this LPAZ are limited
41
42 257 as it is unlikely that forest expansion and increase in humidity was synchronous with the sea level rise. It
43
44 258 is probable that that the marine inundation resulted in the over-representation of *Nothofagus*, a prolific
45
46 259 producer of pollen, against a backdrop of low pollen influx. The dominance of *Nothofagus* pollen within
47
48 260 a range of ecological settings, from montane to lowland environments, is demonstrated by sampling of
49
50 261 the modern pollen rain in the region (Heusser, 1989). However, the richness of the coastal flora is still
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represented by the persistence of trace amounts of *Acaena*, subf. Asteroideae, Caryophyllaceae, *Plantago* and *Gunnera*.

3.3.5. LPAZ CE-5 (408-248 cm; 6680 - 4310 cal a BP)

LPAZ CE-5 is divided into three sub-zones that reflect the gradual emergence of the site as relative sea-level lowered. The basin morphology of the site has been maintained by the formation of a series of storm beach ridges reaching ~4.0 m a.s.l. (Fig. 2). The storm beach ridges have both protected the soft-sediments at the site from coastal erosion and enabled the development of an isolated freshwater lagoon and this is reflected in the increasing organic-rich stratigraphy and expansion of freshwater taxa during LPAZ CE-5a. The transition from marine sediments to the organic rich freshwater sediments occurs over ~420 years. However, there are two peaks in *Hippuris vulgaris* and *Myriophyllum* at c. 6600 and 5690 cal a BP separated by a peak in freshwater algae, a brief increase in mineral content and near absence of charcoal. These changes probably indicate that the initial trend to shallower water indicated by the change from *Myriophyllum* to Poaceae-*Caltha* wet meadow was interrupted by a pluvial period that led to clear still and deeper water at the site and a reduction in the availability of drier fuel.

LPAZ CE-5b (c. 5780 cal a BP) marks the restart of the hydrosere succession and the return of shallower water conditions, a brief expansion of *Hippuris vulgaris* and *Myriophyllum* and then continued drying at the surface of the site facilitating the growth of Poaceae. *Nothofagus* proportions reach their lowest values (~20%) since the Late glacial – early Holocene transition. This decline in *Nothofagus* commenced in LPAZ CE-5a and the initial decline probably reflects the changing balance of pollen inputs following the end of the marine environment. However, the continued contraction of *Nothofagus* cover during LPAZ CE-5b, also suggested by the reduction in *Nothofagus* influx, was probably a response to a shift to drier climatic conditions. This inference is reinforced by the steady increase in corroded and degraded

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3 286 pollen (Normal declines from ~80% to ~25%) and a small increase in charcoal at the same time. During
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5 287 LPAZ CE-5c there is a rapid shift to wetter conditions indicated by the reduction in Poaceae and a shift to
6
7 288 heath vegetation and a dramatic improvement in the preservation of pollen (Normal = ~60%). The
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9 289 increase in effective moisture also facilitated an expansion of *Nothofagus* woodland (~50%).
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14 291 3.3.6. LPAZ CE-6 (248-136 cm; 4310-2180 cal a BP)
15
16 292 The heath vegetation that developed during the preceding LPAZ was rapidly replaced by *Nothofagus*
17
18 293 woodland. At c. 4160 cal a BP (236 cm) the MB2 cryptotephra was deposited. A small and brief peak in
19
20 294 Poaceae occurs at the time of the deposition of the tephra layers but the expansion of *Nothofagus*, also
21
22 295 reflected in a large peak in pollen influx values, commenced ~200 years prior to the eruption. Between c.
23
24 296 4310 and 3220 cal a BP the woodland appears to be open and *Misodendrum* and Polypod ferns also
25
26 297 flourished. *Nothofagus* wood fragments can be found in the core during this period indicating the
27
28 298 expansion of *Nothofagus* over the mire surface. The evidence suggests that there was a rapid change
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30 299 from the wetter conditions of LPAZ-5c to drier climatic conditions that led to a significant reduction in
31
32 300 mire surface wetness (MSW). This sustained period of dryness led to the decline of the *Empetrum*
33
34 301 heathland and the expansion of *Nothofagus* woodland onto the mire surface between c. 4310 and 3220
35
36 302 cal a BP. This climatic inference is further supported by the dramatic increase in corroded and degraded
37
38 303 pollen (Normal = ~20%). The expansion of *Nothofagus* covering the mire increased the local input of
39
40 304 *Nothofagus dombeyi* type pollen during this LPAZ which gives the appearance of the dominance of
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42 305 woodland. However, the mire pollen input masks the pollen signal from the surrounding landscape at
43
44 306 this time. It is likely that the surrounding *Nothofagus* woodland would have been more open under such
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46 307 drier climatic conditions and that the mire formed an oasis of woodland cover.
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At c. 3220 cal a BP the forest became more closed (*Nothofagus* ~90%) and *Misodendrum* and virtually all other taxa were excluded from the record. There is also an increase in normally preserved pollen from which an increase in humidity and MSW is inferred. The trend to wetter conditions is interrupted at c. 2390 - 1830 cal a BP by a brief return to drier conditions, as evidenced by an increase in corroded and degraded pollen and a large peak of charcoal at c. 2550 cal a BP.

3.3.7. LPAZ CE-7 (136cm-surface; 2180 - present cal a BP)

During LPAZ CE-7 the general trend to wetter conditions that commenced at c. 3000 cal a BP continues leading to an increase in MSW inferred from improved pollen preservation and the return of *Empetrum* heathland. The decline of *Nothofagus* appears to be at odds with the inferred increase in humidity. However, we argue that the contraction of woodland should be viewed in the context of the preceding LPAZ CE-6 and the reduction in *Nothofagus* probably reflects the loss of trees from the wetter mire surface and a rebalancing of pollen inputs. Between c. 2180 and present *Nothofagus* proportions fluctuate around ~60% of TLP and trace amounts of *Drimys winteri* also suggest increasing plant diversity within a more open forest canopy. The site continued to experience periods of rapid climate change as the general trend to increased MSW was punctuated by short but high magnitude periods of drier climate inferred from fluctuations between heath and woodland. Reductions in normally preserved pollen and coupled with peaks in charcoal occurred at c. 1830 cal a BP, 1160 cal a BP, 500 cal a BP. The final peak in charcoal <100 years ago was probably due to woodland clearance of the coastal margin of Isla Navarino by European settlers.

4. Discussion

4.1. Climatic inferences from the Cta. Eugenia record

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5 334 The basal minimum age for deglaciation at Cta. Eugenia suggests the Canal Beagle glacier had retreated
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8 335 from its eastern LGM extent some time before c.16,200 cal a BP. Age constraints for the LGM in the
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10 336 Canal Beagle are limited but the minimum age from Cta. Eugenia is almost certainly an underestimate as
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12 337 it is likely that ice retreat began at least ~1000 years earlier but the persistence of periglacial tundra
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14 338 inhibited the growth and accumulation of dateable organic material at the site. The onset of relatively
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16 339 warmer and more humid conditions is indicated by the initial heath and *Gunnera* assemblage, however,
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18 340 the treeless landscape suggests the persistence of colder conditions in comparison to later Holocene
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20 341 interglacial conditions. This picture is similar to the nearest Late glacial record from Pto. Harberton
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22 342 which commenced at c. 16,000 cal a BP and was also initially colonised by heath and *Gunnera* vegetation
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24 343 (Markgraf, 1993). However, at Cta. Eugenia the trend to slightly warmer conditions was interrupted by
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26 344 the deposition of soliflucted clays between c. 15,470 and 14,530 cal a BP. The timing of this ‘cooling’
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28 345 event does not correlate to the onset of the Antarctic Cold Reversal (ACR, c. 14,440 – 12, 760 cal a BP)
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30 346 (Gest et al., 2017) and is not identified in any of the other records from around the Canal Beagle and so
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32 347 for the moment this event appears to be site-specific. Somewhat counter intuitively at c. 14,530 cal a BP
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34 348 the stratigraphic evidence suggests relatively warmer conditions resumed which continued during the
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36 349 ACR. However, the pollen assemblage, and in particular the poor pollen preservation, continues to
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38 350 reflect the persistence of colder and drier conditions relative to the present interglacial. The
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40 351 identification of a cooling event equivalent to the ACR in southern Patagonia is challenging as steppe-
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42 352 tundra vegetation is cold-tolerant and so not necessarily sensitive to the relatively small-scale cooling as
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44 353 indicated by Antarctic ice cores during the ACR (Jouzel et al., 2007). However, the southern Patagonian
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46 354 Late glacial vegetation is responsive to latitudinal shifts in the belt of precipitation driven by the
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48 355 southern westerly winds (SWWs). It is probable that Antarctic cooling during the ACR impeded and / or
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reversed the southerly migration of the SWWs following deglaciation after the LGM (Hulton et al., 2002; Lamy et al., 2010) leading to the drier conditions at Cta. Eugenia between c. 14,530 and 12,390 cal a BP.

The glacial-interglacial transition was a gradual process of warming indicated by the arrival of *Nothofagus* woodland in the area commencing at c. 12,390 cal a BP. This is close to the age for woodland expansion at Pto. Harborton at c. 12,200 cal a BP (Markgraf and Huber 2010). The arrival of *Nothofagus* appears to be earlier at the eastern end of Canal Beagle than at other sites in the region that suggest ages closer to c. 10,500 cal a BP (Mansilla et al., 2018). However, the difference probably reflects the closer proximity of Cta. Eugenia and Pto. Harborton to woodland refugia during the last glaciation on Peninsula Mitre (Premoli et al., 2010; Mansilla et al., 2016) and that the other sites are either more montane or closer to the Cordillera Darwin ice field and so deglaciated later. The establishment of *Nothofagus* woodland at Cta Eugenia occurred at c. 10,640 cal a BP which is closer to the timing of the regional expansion of *Nothofagus* woodland and marks the onset of warmer Holocene conditions.

The limited expansion of the *Nothofagus* woodland and indications of declining humidity as temperatures increased after c. 12,390 cal a BP contrasts with the evidence for greater humidity at ~52-53°S (McCulloch and Davies, 2001; Markgraf and Huber, 2010; Mansilla et al., 2016; 2018). This suggests that the SWWs may have been more focussed to the north of the Cordillera Darwin divide at this time. However, after c. 11,000 cal a BP there is widespread regional drier conditions leading to the westward contraction of the *Nothofagus* forest ecotone and increased fire frequency between 52° and 55°S. This period of regional dryness is contemporary with the thermal maximum of sea surface temperatures (SSTs) at ~53°S (Lamy et al., 2010). We suggest the increased temperatures and a more southerly focus of the SWWs led to drier conditions at Cta. Eugenia and increased ocean temperatures along the

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3 380 western margins of the Antarctic Peninsula and the eventual loss of ice shelves (Bentley et al., 2009).
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5 381 The period of relative dryness continues at Cta. Eugenia until the climatic record is interrupted by the
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7 382 mid-Holocene marine incursion at c. 8640 cal a BP. Previous studies of marine transgression sediments
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9 383 have suggested that the *Nothofagus* forest dominated the landscape at this time (Borromei and
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11 384 Quattrocchio, 2007). However, the *Nothofagus* influx values at Cta. Eugenia do not support the near-
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13 385 closed forest indicated by the percentage pollen data, which is more an artefact of the change of
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15 386 balance between the different pollen sources to the basin. We suggest estimations of woodland cover
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17 387 based on percentage data alone from marine or lacustrine sites should be treated with caution.
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22 389 Following relative sea-level lowering at c. 6690 cal a BP the lagoon at Cta. Eugenia followed the natural
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24 390 hydroseral process of basin infilling and vegetation development leading to the re-establishment of a
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26 391 mire. Climatic inferences from this period are limited but the interruption of the shallowing of the
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28 392 lagoon during LPAZ CE-5a suggests a pluvial period at c. 6000 cal a BP. Along the Canal Beagle this
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30 393 wetter period is broadly contemporary with an increase in aquatic and wetland taxa at Pta. Moat and
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32 394 more humid conditions and reduced fire activity at Pto. Harberton (Markgraf and Huber, 2010). This
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34 395 period may mark the return of the SWWs closer to their present focus in response to reduced SSTs and
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36 396 cooler climate (Lamy et al., 2010).
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41 398 Between 5550 and 4830 cal a BP a gradual shift to drier conditions at Cta. Eugenia leads to a contraction
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43 399 of the forest margin and expansion of steppe vegetation. However, this is not evident in other records
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45 400 from along the Canal Beagle. In contrast, sites to the north of the Canal Beagle and Cordillera Darwin
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47 401 suggest a shift to wetter conditions leading to the development of closed-canopy *Nothofagus* woodland
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49 402 and a decline in fire frequency (Markgraf and Huber, 2010; Ponce and Fernandez, 2014; Musotto et al.,
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2016; Mansilla et al., 2018). This north-south divide in the climatic signals suggests the core of the SWWs was probably focused more to the north of ~54°S.

After c. 4780 cal a BP the Cta. Eugenia record suggests a marked increase in wetter conditions and this is similarly reflected in the expansion and persistence of dense closed-canopy *Nothofagus* forest across the region (Markgraf and Huber, 2010; Ponce and Fernandez, 2014; Musotto et al., 2016; Mansilla et al., 2018). However, this increase in humidity at Cta. Eugenia is relatively short and at c. 4310 cal a BP there was a marked reversal to drier conditions that persisted until c. 3220 cal a BP. However, the pollen records from Pto. Harberton and Cta. Lacroix display minimal fluctuations in the *Nothofagus* cover between c. 5500 cal a BP and c. 1000 which suggests a degree of insensitivity. It is probable that the Cta. Lacroix record also reflects South Atlantic moisture sources during periods of less intense SWWs. Sites to the north of the Cordillera Darwin suggest the continued dominance of *Nothofagus* forest but the record at Lago Lynch does indicate a westward contraction of the forest-steppe ecotone and increase in fire activity just after the eruption of Mt. Burney (MB2) (Mansilla et al., 2018).

From c. 3220 cal a BP to the present there was a general trend to increasing wetness at Cta. Eugenia and this is also reflected in records from across the region evidenced by the continued dominance of *Nothofagus* forest and the gradual expansion of heath bog communities (Markgraf and Huber, 2010; Mansilla et al., 2016). However, the trend to wetter conditions is punctuated by several short periods of rapid climate change leading to drier intervals at c. 2390-1830 cal a BP, 1160 cal a BP and 500 cal a BP. and we argue that the drier periods at Cta. Eugenia represent warmer periods when the SWWs were driven more polewards. The evidence for the sequence of drier intervals between c. 4300 and 500 cal BP suggests the geographical location of Cta. Eugenia and its mire hydrology render it acutely sensitive to latitudinal shifts in the moisture bearing SWWs.

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5 428 4.2. Mid-Holocene marine incursion and implications for the human record
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10 430 The mid-Holocene marine incursion at Cta. Eugenia occurred at c. 8640 cal a BP and the contact
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12 431 between the underlying peat and the marine sediments indicates a sub-millimetre boundary to deeper
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14 432 water clays which, within the constraints of the age-depth model, suggests the transition took place
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16 433 over less than tens of years. At present there are no estimates of the rate of isostatic rebound in the
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18 434 region but the inundation at Cta. Eugenia appears to have been rapid at a time when global sea level rise
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20 435 was also rapid (Fleming et al., 1998). Holocene neotectonic displacement of palaeoshorelines has been
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22 436 identified along the South American – Scotia plate boundary (McCulloch and Bentley, 2005) and
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24 437 discordant data has been obtained from marine transgression sites along the Canal Beagle (Borromei
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26 438 and Quattrocchio, 2007). However, the mid-Holocene marine transgression shoreline is a consistent
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28 439 feature along much of the north shore of Isla Navarino and indicates the spatial extent of the changing
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30 440 nature of the coastline that probably affected early humans living along the Canal Beagle.
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36 442 Archaeological evidence in the form of abundant shell middens, usually located within embayments
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38 443 along the shore of Isla Navarino, suggest a close association between human activity and proximity to
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40 444 the shoreline. The arrival of early people has been estimated at c. 8700 to 8400 cal a BP (Zangrando et
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42 445 al., 2019) in the Canal Beagle but evidence for earlier presence of human populations has potentially
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44 446 been lost during the transgressive phase of the marine incursion between c. 8640 and 6690 cal a BP.
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46 447 Continued isostatic uplift resulted in coastal emergence, relative sea level lowering and the isolation of
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48 448 the basin at Cta. Eugenia. This pattern is tentatively reflected in the spatial and temporal distribution of
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50 449 shell middens and other domestic archaeological assemblages recently excavated by the authors at
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54 450 Bahia Mejillones on the north shore of Isla Navarino. The oldest shell midden layer is dated to c. 6890 cal
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451 a BP and is located at ~7.5 m a.s.l., while the age distribution of the lower shell middens declines with
452 altitude and increasing proximity to the present shoreline (San Roman et al., 2017).

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454 5. Conclusions

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456 The palaeoenvironmental evidence from Cta. Eugenia provides new insights into the sequence of
457 environmental and climatic changes that have driven landscape evolution along the north shore of Isla
458 Navarino and the Canal Beagle. After deglaciation at c. 16,200 cal a BP cooler climatic conditions
459 persisted until gradual warming led to the establishment and expansion of *Nothofagus* forest between c.
460 12,390 and c.10,640 cal a BP. However, during the early to mid-Holocene we argue for increased
461 temperatures and / or a poleward intensification of the SWWs leading to drier conditions in Fuego-
462 Patagonia. The rapid inundation of Cta. Eugenia by the mid-Holocene marine transgression interrupts
463 the climate signal from the site but offers additional insights into the timing and nature of changes that
464 impacted on the coastal landscape and availability of resources to early humans along the north coast of
465 Isla Navarino. The emergence of the site following relative sea-level lowering at c. 6690 cal a BP re-
466 establishes the climatic record from Cta. Eugenia. After c. 4780 cal a BP there is trend to increasing MSW
467 which is punctuated by several periods of rapid climate change which produced drier conditions (c. 4310
468 to c. 3220 cal a BP; c. 2390-1830 cal a BP, 1160 cal a BP and 500 cal a BP). The intervening wetter
469 periods recorded at Cta. Eugenia probably reflect a more equatorward latitudinal position of the SWWs
470 during relatively cooler periods. We suggest the geographical position of Cta. Eugenia, to the south-east
471 of the Cordillera Darwin divide has rendered the site sensitive to latitudinal shifts in the SWWs along the
472 west coast of southern Patagonia and the Antarctic Peninsula. The sensitivity of Cta. Eugenia is also
473 reinforced by the application of multiple lines of evidence from the pollen record; sediment

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3 474 stratigraphy, percentage pollen, pollen influx and particularly pollen preservation, which combined
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5 475 support robust climatic and ecological inferences.
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Table 1

Laboratory Code	Depth (cm)	Material	^{14}C yr (1σ)	$\delta^{13}\text{C}$ ‰	Calibrated age range (95.4%) cal. yr BP†	Calibrated age range (WMA) (95%) cal. yr BP‡
UGAMS38371	140	Bulk peat	2260 ± 20	-26.7	2156 - 2320	2161 – (2248) - 2339
Tephra MB2 ¹	236	-	3860 ± 50	-	4013 - 4413	3905 – (4151) - 4375
UGAMS38372	342	Bulk peat	4710 ± 20	-32.0	5315 - 5566	5328 – (5437) - 5583
UCIAMS189842	409	Bulk lacustrine mud	5970 ± 20	na	6670 - 6843	6472 – (6696) - 6814
Tephra H1 ²	612	-	7241 ± 23	-	7949 - 8153	7972 – (8124) - 8360
UCIAMS189841	637	Bulk peat	7925 ± 25	na	8589 - 8951	8547 – (8672) - 8892
UGAMS38373	712	Bulk peat	9360 ± 30	-27.7	10,407 - 10,653	10,272 – (10,499) - 10,701
Beta522335	752	Bulk lacustrine mud	10,520 ± 30	-29.2	12,156 – 12,554	11,921 – (12,301) - 12,569
UCIAMS189840	840	Fine plant material	13,020 ± 50	na	15,289 – 15,743	15,025 – (15,425) - 15,737
UCIAMS189839	882	Fine plant material	13,260 ± 45	na	15,705 - 16,076	15,574 – (16,296) - 17,351

†Calibrated age ranges by Calib 7.1 (Stuiver et al., 1993) and SH13 curve (Hogg et al., 2013).

‡Probability interval of calibrated and median ages from BACON (Blaauw and Christen, 2011).

¹ Mount Burney tephra layer (McCulloch, 1994)

² Volcán Hudson tephra layer (Stern et al., 2016)

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- 1 Table caption
- 2
- 3 Table 1. Radiocarbon and calibrated age ranges. The weighted mean ages from the BACON
- 4 Bayesian age model have been used to constrain the Caleta Eugenia record.

Figure captions

Figure 1. Fuego-Patagonia. The principal vegetation zones and isohyets are from Tuhkanen et al., (1989–1990) modified with vegetation mapping by Pisano (1994). Palaeoecological sites mentioned in the text are: ① Cta. Eugenia ② Cta. Robalo; ③ Pto. Harberton; ④ Pta. Moat; ⑤ Valle Andorra, Ushuaia I, II and III; ⑥ Cañadon del Toro and Lapataia; ⑦ Cta. Lacroix, Isla de los Estados; ⑧ Terra Australis; ⑨ La Correntina; ⑩ Lago Yehuin; ⑪ Pta. Yartou; ⑫ Lago Lynch; ⑬ Pto. del Hambre. Archaeological sites mentioned in the text are: (TA) Tres Arroyos; (M) Bahía Mejillones; (T) Tunel; (BC) Imiwaia I and Binushmuka I – Bahía Cambaceres.

Figure 2. The site at Caleta Eugenia. The storm ridges are highlighted by the arcuate strips of shrub vegetation. Inset: oblique image of the mire site at Caleta Eugenia (source: Google Earth 2019).

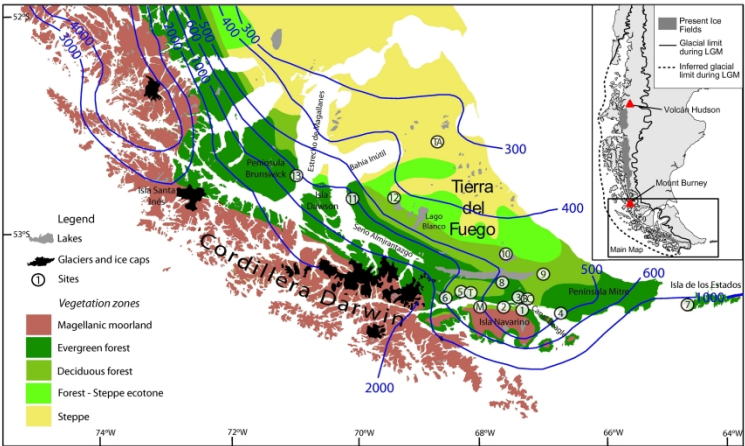
Figure 3. The Caleta Eugenia profile: sediment stratigraphy, organic content determined by LOI_{550} , and the LPAZs determined from the percentage pollen diagram (Fig. 4) by CONISS alongside the BACON age–depth model.

Figure 4. Caleta Eugenia summary percentage pollen and spore diagram. *Misodendrum* is included in the trees group as it is a hemiparasite of *Nothofagus* trees.

Figure 5. Caleta Eugenia pollen accumulation rate (influx) for selected taxa.

Figure 6. Caleta Eugenia percentage pollen preservation diagram and charcoal accumulation rate (influx).

Figure 1



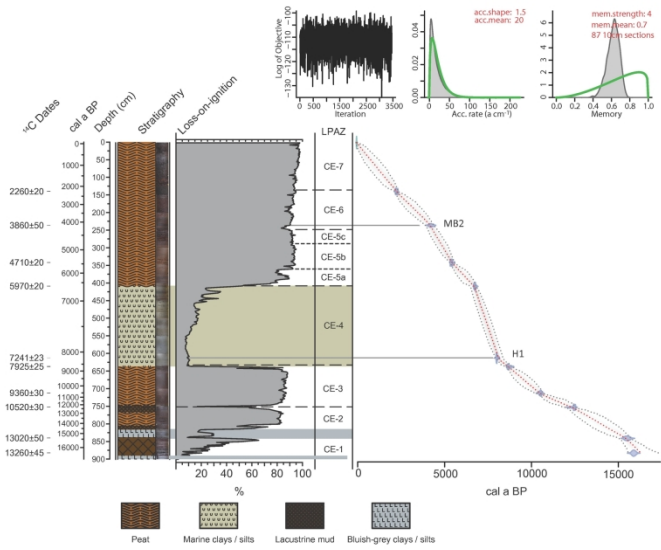
296x209mm (300 x 300 DPI)

Figure 2



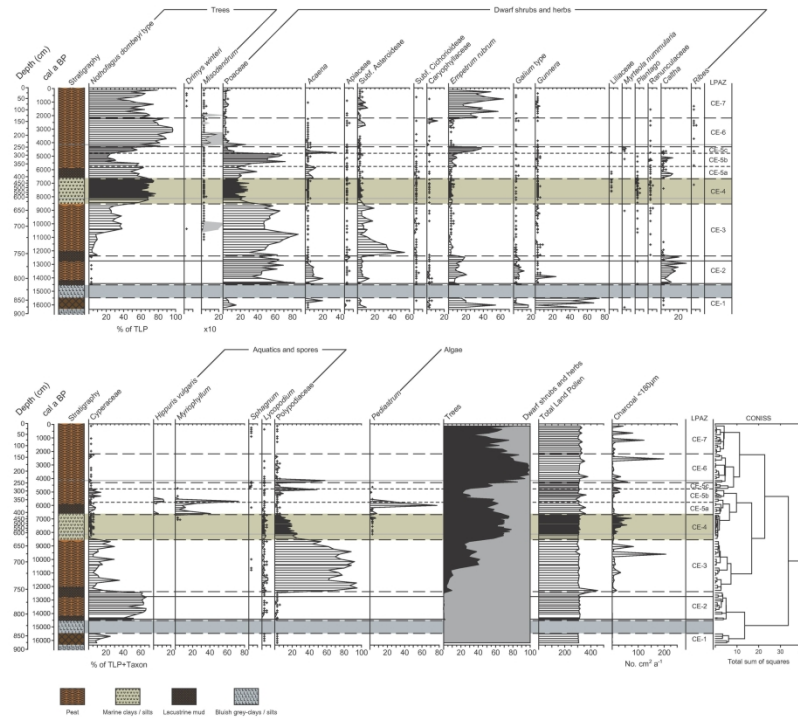
296x209mm (300 x 300 DPI)

Figure 3



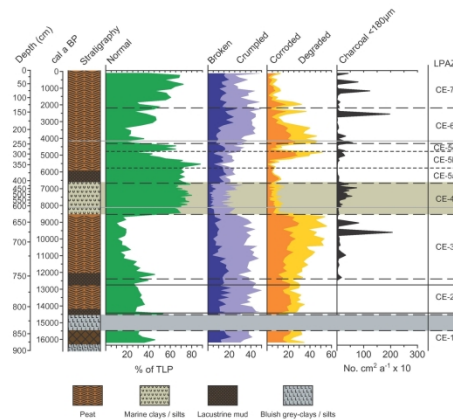
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Figure 4



209x296mm (300 x 300 DPI)

Figure 6



209x296mm (300 x 300 DPI)

Table S1: Tephra geochemistry

	Na ₂ O	MgO	Al ₂ O ₃	K ₂ O	CaO	FeO	SiO ₂	P ₂ O ₅	TiO ₂	MnO	Total
MB2											
1	4.489	0.309	12.284	1.549	1.590	1.373	75.746	0.033	0.230	0.036	97.6
2	4.558	0.332	12.723	1.533	1.729	1.219	77.637	0.037	0.226	0.050	100.0
3	4.496	0.259	12.433	1.652	1.583	1.207	77.518	0.025	0.198	0.038	99.4
4	4.550	0.244	12.017	1.565	1.596	1.209	76.649	0.033	0.208	0.032	98.1
5	4.342	0.331	12.461	1.637	1.759	1.368	77.765	0.039	0.222	0.042	100.0
6	4.588	0.288	12.480	1.636	1.572	1.354	77.351	0.028	0.202	0.046	99.5
7	3.488	0.166	12.022	3.995	1.084	0.825	74.903	0.019	0.128	0.015	96.6
8	4.493	0.333	12.422	1.683	1.740	1.224	76.616	0.037	0.234	0.041	98.8
9	4.398	0.286	12.130	1.475	1.619	1.183	76.660	0.038	0.219	0.039	98.0
10	3.325	0.169	11.898	3.948	0.989	0.872	76.558	0.017	0.131	0.029	97.9
11	4.665	0.293	12.442	1.519	1.650	1.289	76.990	0.032	0.221	0.034	99.1
12	4.442	0.361	13.047	1.630	1.800	1.373	77.649	0.044	0.237	0.024	100.6
H1											
1	5.507	1.644	15.299	2.709	3.260	5.075	63.280	0.364	1.245	0.162	98.5
2	5.944	1.119	15.332	3.026	2.387	3.804	65.215	0.320	1.170	0.140	98.5
3	5.712	1.550	15.521	2.870	3.166	5.031	64.220	0.341	1.235	0.190	99.8
4	5.655	1.633	15.497	2.728	3.116	4.994	62.925	0.431	1.306	0.165	98.4
5	5.595	1.182	15.450	3.073	2.583	4.297	66.814	0.329	1.179	0.153	100.7
6	5.944	1.199	15.711	2.893	2.770	4.228	64.502	0.381	1.261	0.138	99.0
7	5.627	1.323	15.574	3.060	2.911	4.784	65.575	0.309	1.155	0.176	100.5
8	5.504	1.615	15.152	2.981	3.287	5.146	63.079	0.357	1.216	0.172	98.5
9	5.838	1.413	15.200	2.781	2.989	5.088	63.961	0.318	1.182	0.170	98.9
10	5.770	2.420	14.887	2.627	3.782	5.324	63.487	0.393	1.299	0.200	100.2
11	5.854	1.653	15.529	2.743	3.080	4.834	62.637	0.358	1.159	0.148	98.0
12	5.726	1.479	15.532	2.958	2.994	4.800	63.269	0.348	1.205	0.144	98.5
13	5.670	1.326	15.447	3.050	2.779	4.388	63.959	0.293	1.172	0.152	98.2
14	5.976	1.189	15.253	3.139	2.559	4.546	64.479	0.297	1.111	0.170	98.7

Cameca SX100 Electron Microprobe
Column conditions: Cond 1: 15keV 2nA, Cond 2: 15keV 80nA
Condition 1: Na Ka, Mg Ka, Al Ka, K Ka, Ca Ka, Fe Ka, K Ka, Ca Ka, Si Ka
Condition 2: P Ka, P Ka, Ti Ka, Mn Ka, Ti Ka