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1 **First high-resolution multi-proxy palaeoenvironmental record of the Late Glacial**

2 **to Early Holocene transition in the Ría de Arousa (Atlantic margin of NW Iberia)**

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18 **Abstract**

19 A 322-cm-long sedimentary sequence obtained in the shallow marine basin of the Ría de

20 Arousa—a submerged unglaciated river valley on the Atlantic margin of northwestern Iberia—

21 was analysed using a multi-proxy approach to study how climatic and sea level changes affected

22 the coastal ecosystems during the Last Glacial–Interglacial Transition. Past sedimentation,

vegetation and marine productivities were inferred from palynological, radiocarbon, seismic and lithological data. A substantial reduction in the pollen and dinoflagellate cyst accumulation rates is observed at ~12,700 to 11,700 cal a BP, suggesting lower marine and vegetation productivities likely as a response to the Younger Dryas cooling event. Overall, the regional vegetation changed from cold-tolerant open woodlands (Pinus sylvestris/P. nigra and Betula) dominating before ~10,200 cal a BP to coastal wetlands and the regional spread of Quercus-dominated forests after ~9800 cal a BP. Cluster analysis and principal component analysis allowed the identification of several small environmental oscillations, such as the 11.4 ka and 10.5 ka cooling events. After that, a conspicuous heath expansion was likely favoured by the palaeotopography, the increased precipitation and the relative sea level rise, which might have caused a profound change in the coastal configuration. Concurrently, both the dinoflagellate cyst and non-pollen palynomorph records reveal variations in the marine productivity and coastal hydrodynamics that also agree with a period of marked marine transgression, warming and increasing river flow. New sedimentary data highlight the high sensitivity of the ria᾽s ecosystems to environmental oscillations and show a close temporal correspondence between terrestrial and marine responses to climate change.

1. Introduction

Coastal ecosystems are some of the most productive marine systems, but they are also very vulnerable to climate, relative sea level (RSL) and other environmental oscillations (e.g. Watson and Byrne, 2009). Looking back into their environmental history is essential to understand the effects that future environmental changes may have on these ecosystems, and to plan management strategies (e.g. Swetnam et al., 1999). In particular, the study of the Last Glacial–Interglacial Transition (LGIT), a period of intense environmental variability that has played an important role in shaping the current ecosystems (e.g. Moreno et al., 2014; de Beaulieu et al., 2017), might be key to understanding the response of coastal ecosystems to climate and RSL changes.

Northwestern Iberia (Fig. 1) is sensitive to the major climatic oscillations detected in both the subtropical (deMenocal et al., 2000) and the Boreal North Atlantic (Johnsen et al., 1992). In this region, palaeobotanical evidence from continental (e.g. Allen et al., 1996; Ramil-Rego et al., 1996, 1998; Muñoz Sobrino et al., 2001, 2004, 2005, 2007, 2013; Iriarte-Chiapusso et al., 2006, 2016; Moreno et al., 2011; Morales-Molino and García-Antón, 2014) and oceanic deposits (Naughton et al., 2007; 2015; Penaud et al., 2011) reflect noticeable changes in climate and biogeography during the Pleistocene/Holocene transition. Some reconstructions of sea surface temperature (SST), salinity (SSS) and productivity (SSP) have been made from dinoflagellate cysts in deep sediments on the Iberian Atlantic margin (Boessenkool, et al., 2000; Turon et al., 2003; Roucoux et al., 2005; Naughton et al., 2007, 2015; Penaud et al., 2011; Eynaud et al., 2016; Datema et al., 2017). Furthermore, in sensitive mountainous areas, high-resolution pollen records have allowed a reliable chronology to be established for the main climatic phases that affected inner areas of NW Iberia and reveal that marine conditions governed postglacial inland vegetation dynamics (e.g. Muñoz Sobrino et al., 2005, 2013; Roucoux et al., 2005; Jalut et al., 2010; Iriarte-Chiapusso et al., 2016). However, the LGIT is still poorly represented in coastal environments of NW Iberia, where little terrestrial palaeobotanical evidence is available (Gómez-Orellana et al., 1998; 2007; 2012; Iriarte-Chiapusso et al., 2006), making it difficult to establish an integrated picture of the regional variability in NW Iberia.

Shallow marine sedimentary deposits can provide very valuable archives of past environmental changes, due to the high deposition rates and the possibility of making direct land-sea comparisons by studying terrestrial and marine palynomorphs simultaneously. Recent studies have been performed in the nearby Ría de Vigo to investigate the environmental changes that occurred at the end of the Pleistocene (e.g. Martínez-Carreño and García-Gil, 2017; Martínez-Carreño et al., 2017). Two palynological sequences spanning the MIS-3 and the Early Holocene (Muñoz Sobrino et al., 2018; García-Moreiras et al., 2019) highlight the great sensitivity of the rias to abrupt climatic events. However, due to sedimentary hiatuses, a continuous record of that period could not be achieved in the Ría de Vigo. In this study, we present the first coastal

palaeoenvironmental record of the LGIT obtained in the region. In the Ría de Arousa, the warming and RSL rise that characterized the LGIT are expected to have had profound impacts on the ecosystems. Tidal transgression, the development of continental wetlands and the expansion of Quercus-dominated forests are expected in the study region, as has been observed in related areas (e.g. Gómez-Orellana et al., 2007, 2012; Iriarte-Chiapusso et al., 2016; García-Moreiras et al., 2019). Moreover, terrestrial warming should have been in phase, with increasing river inputs and water depths, SST rise, and other hydrological changes that affected phytoplankton productivities in the Ría de Arousa.

The new sedimentary record from the Ría de Arousa provides an uninterrupted high-resolution (decadal to centennial) record of the main environmental changes that occurred at the seashore during the transition between the Late Glacial and the Early Holocene. We combined pollen analyses—including pollen, dinoflagellate cysts and non-pollen palynomorphs (NPPs)—with other sedimentary data (seismic stratigraphy, grain size, carbon content and ^{14}C-dating) to reconstruct the local hydrological and sedimentation conditions, as well as the regional vegetation dynamics on the adjacent land. New palaeoenvironmental data will help to assess the environmental heterogeneity in NW Iberia during this key period and to understand how coastal ecosystems responded to past climatic and other environmental changes.

2. Site

The Ría de Arousa (length = 33 km; area = 230 km^2) is the largest of the Galician rias, which are submerged unglaciated river valleys located on the coast of NW Iberia (Fig. 1a). The ria is oriented in a NE-SW direction, and its mean tidal range is 2.7 m. The water depth in its inner part is <20 m (Fig. 1b); in contrast, in the outer area, the Sálvora Archipelago divides the ria entrance into a narrow and shallow northern mouth (~10 m deep) and a wider and deeper southern mouth (60–70 m deep) (Rosón et al., 1995; Diez, 2006). In the middle part of the ria, Arousa Island is the largest surface that remains emerged inside the flooded valley. This complex embayment is also characterized by other topographical features such as smaller

102   islands, capes and small bays (Fig. 1b). The average salinity is 35.5±0.6 PSU, and the average

103   water temperature is 15 ± 6 ℃ (Rosón et al., 1999). The main tributaries that flow into the ria

104   are the Ulla (total emerged basin = 2803 km^2) and Umia (440 km^2) rivers, the former having the

105   highest average flow rate (79.3 m$^3 \cdot$s^{-1}) (Río Barja and Rodríguez Lestegás, 1992).

106   The distribution of the bottom sediments in the Ría de Arousa is heterogeneous. Muds (silt +

107   clay) and muddy sands mainly extend along the central channel and the shallower internal area

108   of the embayment. Sandy deposits increase in the river mouths, whereas coarser materials and

109   bioclasts increase towards its margins and the outer part of the ria. The distribution pattern of

110   organic matter shows a decrease from the inner towards the outer part of the ria (Vilas et al.,

111   2005).

112   The Atlantic coast of NW Iberia is affected by a sub-Mediterranean variation of the oceanic

113   climate, with mild temperatures, abundant annual rainfall and a certain degree of drought in

114   summer. Mean annual air temperature is 15 ℃ and mean annual precipitation is ~1500 mm

115   (Ninyerola et al., 2005). The hydrography of the Ría de Arousa is mainly influenced by shelf

116   wind variability (Rosón et al., 1995). Upwelling-favourable northerly winds prevail from

117   March/April to September/October, while downwelling-favourable southerly winds dominate

118   the rest of the year.

119   The study area is situated at the northern margin of the NW African coastal upwelling system

120   and is influenced by the Eastern North Atlantic Central Water (ENACW) (Fig. 2a). Surface

121   offshore western Iberian waters are dominated by the Portugal Current System (PCS) flowing

122   towards the Equator in summer and towards the Arctic in winter (Sprangers et al., 2004; Otero

123   et al., 2008). Two branches of the ENACW flow under the PCS: the subtropical water

124   (ENACWst) and the subpolar water (ENACWsp) (Fig. 2b).

125   A two-layered positive residual circulation characterizes the Ría de Arousa. During summer,

126   when northerly winds prevail, this circulation pattern is reinforced due to the intensification of

127   upwelling events, when nutrient-rich cold ENACW waters (mainly of subtropical origin) flow

5

128 into the ria and enhance phytoplankton growth (Álvarez-Salgado et al., 1996). In general,

129 diatoms dominate the phytoplankton communities in the upwelling season (spring–summer),

130 whereas abundances of dinoflagellates increase over the summer and reach maximum values in

131 autumn, i.e. in periods of stronger stability of the water column and higher SST (Rosón et al.,

132 1995; Tilstone et al., 2000). In the Ría de Vigo, some studies on the composition of

133 phytoplankton indicate that dinoflagellates rarely dominate the phytoplankton communities

134 (Crespo et al., 2006). However, in some cases, under downwelling conditions, dinoflagellates

135 represent >70% (e.g. Figueiras et al., 1994).

136 Currently, the Galician rias hold very diverse and productive ecosystems that provide extremely

137 important ecological and economic services and deserve special attention with regard to climate

138 change. A large part of the economic activities rely on fishery and mussel farming. The latter, in

139 the case of the Ría de Arousa, involves more than one-third of world production (Figueiras et

140 al., 2002). Regarding land-use and current vegetation, most of the basin is moderately populated

141 and consists of a complex mosaic of urban soil, forest plantations (mainly *Eucalyptus* spp. and

142 *Pinus* spp.) and shrubs (such as *Erica* spp., *Calluna vulgaris* (L.) Hull. and *Ulex* spp.). In

143 addition, sparse stands of deciduous oak forests with *Quercus robur* L. and riparian woodlands

144 (mainly formed by *Alnus glutinosa* (L.) Gaertn., *Corylus avellana* L., *Fraxinus angustifolia*

145 Vahl. and *Salix* spp.) can be found in some less human-transformed areas. Fluvio-marine

146 transition areas encompass diverse habitats related to marshes, sandy intertidal flats, estuarine-

147 deltaic complexes, beaches and muddy intertidal flats (Ramil-Rego et al., 2008). Because of

148 their unique flora and fauna, many of them are protected areas, including the Sálvora and

149 Cortegada archipelagos (forming part of the Galician Atlantic Islands Maritime-Terrestrial

150 National Park) and the wetland complexes of Corrubedo and Umia-O Grove (Fig. 1b).

151 **3. Methodology**

152   3.1. Seismic surveys and lithological analyses

153   High-resolution seismic profiles were recorded on R/V Mytilus using a modified boomer. This

154   equipment employs a single boomer-type source (AAE CSP300) together with two receivers: a

155   sub-bottom profiler (ORE 3.5 kHz) and a Geopulse (AAE 8- and 20-monochannel streamer)

156   system. A resolution of 15–100 cm with 30–50 m penetration was obtained (Fig. 3a). For

157   navigation and positioning, an AgGPS 132 differential GPS model from Trimble Inc. was used.

158   Lithological descriptions of core A14-VC15 (Fig. 3b) are mainly based on grain size and carbon

159   content data, as well as on visual observations. Grain size distributions were determined at 10–

160   20 cm intervals. H_2O_2 was added to the sediment to destroy the organic matter and $(NaPO_3)_6$ to

161   disperse the clay. The suspension was then sieved to separate the different fractions (large

162   fragments of shells were excluded to avoid data biasing). The sandy fraction was dried at 60 ℃

163   and determined by a standard dry-sieving procedure. The distribution of clay and silt was

164   determined by laser diffraction using a Beckman Coulter LS 13 320 Coulter counter. Grain size

165   results were classified following the nomenclature of Wentworth (1922). Total inorganic carbon

166   (TIC) and total organic carbon (TOC) contents were determined at 20-cm intervals by

167   combustion with a LECO CNS-2000 elemental analyser.

168   3.2. Chronology

169   The chronology of core A14-VC15 from the Ría de Arousa is primarily based on six ^{14}C dates

170   and four pollen-inferred dates (Table 1) obtained from the correlation of the pollen stratigraphy

171   with dated climatic events in NW Iberia (Muñoz Sobrino et al., 2013; Iriarte-Chiapusso et al.,

172   2016).

173   Radiocarbon dates (Beta Analytic Laboratory, Florida, USA) were obtained from shells using

174   AMS Standard dating methods and were calibrated using a MARINE13.14C calibration curve

175   (Reimer et al., 2013) and applying a local marine reservoir correction of σR = -7±90 (Reimer

176   and Reimer, 2001), which corresponds to the nearest point in Stuiver et al. (1986–2018). This

7

177 correction has been useful for dating shells found in Early and Late Holocene sediments from

178 the Ría the Vigo (e.g. Muñoz Sobrino et al. 2007, 2014, 2018). An age-depth model was

179 constructed using CLAM 2.2. (Blaauw, 2010).

180 3.3. Pollen, dinoflagellate cyst and NPP analyses

181 Pollen, dinoflagellate cysts and NPPs were studied in the 322–50 cm section of core A14-VC15

182 from the Ría de Arousa. We studied that section because this work focuses on the LGIT, a

183 period that is still poorly represented in coastal environments, and also because an abrupt

184 change in the sedimentation rates, probably indicating a hiatus, occurs at the top of that section

185 (see Discussion and Fig. 4).

186 Most of the palynological samples were collected at 2–4 cm intervals, depending on the

187 deposition rate. Only in the upper part (130–50 cm) were larger intervals (4–8 cm) used. A total

188 of 63 samples were processed using standard methods (Moore et al., 1991; Mertens et al.,

189 2009), which included oven drying (80ºC), treatment with HCl and HF at room temperature,

190 addition of exotic markers (Lycopodium spores) for concentration estimates and sieving to

191 remove coarse (>120 µm) and fine (<10 µm) materials. No acetolysis or oxidation was involved

192 in the palynological extractions, as heterotrophic dinoflagellate cysts can be degraded by these

193 methods (Eynaud et al., 2016).

194 Palynomorphs were identified and counted using a Nikon Eclipse 50i light microscope at 400x

195 and 600x magnifications (1000x for critical determinations). More than 250 pollen and fern

196 spores were counted per sample. Despite the low concentrations of dinoflagellate cysts observed

197 (average = 1893 cysts·cm^{-3}), a minimum of 100 dinoflagellate cysts were counted in the

198 majority of samples. However, cyst counts were lower in some samples (<50 cysts in six

199 samples with very low concentrations). Total cyst sums are shown in the diagrams to assess

200 percentage reliability. Concurrently, Lycopodium spores and NPPs—which include fungal

201 remains, algal spores and foraminiferal linings—were counted. The identification and

8

202 nomenclature of pollen types are mainly based on Moore et al. (1991), dinoflagellate cysts

203 mainly follow Zonneveld and Pospelova (2015), and NPPs were identified following van Geel

204 et al. (2011), Medeanic (2006) and Gelorini (2011). All pollen, dinoflagellate cyst and NPP

205 types identified in this study can be seen in Supplementary Fig. 1.

206 In accordance to Desprat et al. (2015), Pinus pollen with total body length <85µm were

207 classified as Pinus sylvestris-type, which may include pollen grains of P. sylvestris and P. nigra

208 (see Supplementary Plate 1—Image 6), while larger grains were classified as Pinus pinaster-

209 type, which may include grains of P. halepensis, P. pinaster or P. pinea. Because the

210 occurrence of pollen aggregates might indicate that the corresponding taxa were locally present

211 (or grew near the sedimentary point) their occurrence in the sedimentary samples was noted

212 down (Supplementary Fig. 1). Moreover, due to some common difficulties with the

213 identification of spiny brown cysts (see Radi et al., 2013), unidentifiable spiny brown cysts that

214 were <30 µm were grouped as "small spiny brown cysts" or SSB.

215 Palynomorph percentages and accumulation rates (microfossils·cm^{-2}·yr^{-1}) were calculated in all

216 samples using the TILIA software v. 1.17.16 (Grimm, 1990–2011). The percentages of all

217 pollen types and fern and bryophyte spores (hereinafter pollen and spores) were calculated from

218 the total pollen sum. Arboreal pollen (AP) refers to the sum of all tree pollen types. Percentages

219 of NPPs were calculated from a sum that included pollen and spores and NPPs. Finally,

220 percentages of dinoflagellate cysts were calculated considering the total sum of dinoflagellate

221 cysts. Additionally, D/P and H/A ratios were calculated (both with values between 0 and 1): D/P

222 is the ratio of dinoflagellate cysts to total pollen and spores + dinoflagellate cysts; and H/A is

223 the ratio of heterotrophic cysts to total cysts (heterotrophic + autotrophic cysts).

224 Statistical analyses included classification (cluster analysis) and ordination (principal

225 component analysis, PCA). A depth constrained cluster analysis was applied on square root-

226 transformed percentages using the CONISS application of TILIA software, v. 1.17.16 (Grimm,

227 1990–2011). The total sum of squares and Edwards and Cavalli-Sforza's chord distance were

228 used as dissimilarity coefficients, according to Grimm (1987). Furthermore, a PCA was

229 performed on a covariance matrix of square root-transformed pollen and spore percentages to

230 help in the identification of the main local pollen assemblage zones (LPAZ). PCA was used

231 after applying a detrended correspondence analysis for verification that the length of the first

232 gradient was <2 SD (ter Braak and Prentice, 1988) and that the use of linear methods such as

233 PCA was justified in our dataset. PCA was performed using the vegan package developed for R

234 v. 3.0.2. (R Development Core Team, 2013). Only significant tree and shrub pollen taxa (>

235 0.5% in at least two samples), as well as some relevant herbaceous types that were considered

236 especially sensitive to environmental changes, were included for statistical analysis (23 taxa in

237 total). No statistical analyses were applied to the dinoflagellate cyst counts because of the small

238 number of cysts obtained in some samples.

239 **4. Results**

240 4.1. Seismic units and lithology of core A14-VC15

241 Within the Ría de Arousa sedimentary infill, up to nine seismic units were identified according

242 to the interpretation of available seismic stratigraphic data by Cartelle (2019). Sediment core

243 A14-VC15 penetrated the four youngest seismic units (U6 to U9, Fig. 3). However, the

244 recovered material only corresponded to three of them (U6, U7 and U9). This set of seismic

245 units (U6 to U9) is bounded at its base by an irregular disconformity (D5), which deeply erodes

246 underlying seismic units, particularly in the axis of the ria. Disconformity D5 was interpreted by

247 Cartelle (2019) as the subaerial unconformity generated during the Last Glacial Maximum

248 lowstand.

249 According to sedimentological analyses performed on core A14-VC15, three main sedimentary

250 facies associations were identified, each one coinciding with one of the seismic units (Fig. 3).

251 The basal sedimentary succession (f$_1$, 322–135 cm) consists of interbedded layers of silty sand

252 (~60% silt 40% sand) and sandy silt (> 70% sand), with small gravel-sized bioclastic fragments

253 and a relatively low organic carbon content (Fig. 3b). This facies association (f_1) corresponds to

254 seismic unit U6, although the core recovered only the upper part. In this sector of the ria, U6

255 displays a wedge-shaped morphology thinning seawards (i.e. southwards in Fig. 3a). U6 is

256 characterized by high-amplitude, low-frequency and low-continuity reflectors, which are almost

257 chaotic in some parts (Fig. 3a). Towards its top, these deposits are eroded by small-scale

258 concave-up channels that display lateral and vertical accretion and are characterized by seismic

259 facies of higher continuity. Sediment core A14-VC15 recovered part of these channel deposits.

260 The upper boundary of seismic unit U6 (disconformity D6) is highly irregular, deeply eroding

261 seismic unit U6 towards the outer areas of the basin but smoother landwards and in shallow

262 sectors (northwards in Fig. 3a).

263 Between 135 and 43 cm, facies association f_2 is mainly composed of grain-supported bioclastic

264 and siliciclastic gravels and sands with a massive aspect, displaying a slightly fining-upwards

265 trend. The matrix mainly corresponds to fine sand with high TIC values ($< 5\%$). The sharp

266 increase in grain size and the basal erosive surface indicates more energetic conditions due to

267 greater marine influence. Reworking of coarse materials is very likely during highly dynamic

268 phases of rapid sea level rise (e.g. Fanget et al., 2016). Therefore, ^{14}C dates VC15-3 to VC15-6

269 from shells obtained in this facies association (Table 1) should be interpreted with caution (see

270 discussion below). Facies association f_2 corresponds to seismic unit U7, consisting of sub-

271 horizontal sheet-shaped deposits with high-amplitude and low-frequency reflectors (Fig. 3a),

272 mainly displaying an aggrading configuration, although some prograding sedimentary bodies

273 are observed locally. This unit is bounded at its top by disconformity D7 (Fig. 3a), which is very

274 irregular towards the basin margins but smoother in the ria axis and deeper areas.

275 Seismic unit U8 is very thin in the ria axis, thickening towards the basin margins and shallower

276 areas. It is characterized by seismic facies with medium-amplitude, high-frequency and high-

277 continuity reflectors, with sheet-shaped deposits displaying an aggrading configuration. This

278 seismic unit was not recovered in sediment core A14-VC15.

279　In the upper facies association (f$_3$), mud and TOC contents progressively increase towards the

280　top in a fining-upwards sedimentary succession. Sediments mainly correspond to sands (>80%)

281　in the basal section (43–7 cm) and muds (>50% of silt and clay) in the upper levels (<7 cm; Fig.

282　3b). The facies association (f$_3$) mainly corresponds to seismic unit U9, representing the

283　youngest infill of the ria. This seismic unit is thicker on the basin margins, where large-scale

284　prograding sedimentary bodies occur, but thinner on the basin axis with sheet-shaped aggrading

285　deposits.

286　4.2. Chronology

287　An age-depth model was constructed for core A14-VC15 using six absolute ages from [14]C

288　dating and four inferred ages from the interpretation of the pollen stratigraphy. One ^{14}C date

289　obtained from facies f$_2$ was excluded from the age-model because it was incongruent with the

290　pollen stratigraphy (Table 1). In view of the basal erosive surface described at the lower limit of

291　f$_2$ (~135 cm), as explained above, we assume that the shell dated could be reworked material;

292　hence, the possibility that the pollen stratigraphy could also be affected must be considered.

293　According to the linear interpolation model (Fig. 4), core A14-VC15 was deposited during the

294　last 14,400 cal a BP. However, a conspicuous change in the sedimentation rate is detected

295　between 49 and 31 cm depth. The presence of a hiatus is very probable and has been indicated

296　in Fig. 4. Therefore, the palynological sequence presented here (322–50 cm section of core

297　A14-VC15) extends from 14,400 to 9400 cal a BP.

298　Table 1 Radiocarbon dates and pollen-inferred ages for core A14-VC15. All radiocarbon dates were

299　obtained from shells using AMS Standard dating methods (Beta Analytic Laboratory, Florida, USA) and

300　calibrated using the calibration curve MARINE13.14C (Reimer et al., 2013) by applying a local marine

301　reservoir correction of σR = -7 ± 90 (Reimer and Reimer, 2001).

302

Label	Mean depth (cm)	Method	^{14}C age (a BP)	Calibrated age (cal a BP) 95%	Comments
vi	0.5	Surface sample		-60	
VC15-7	31	^{14}C dating	4670 ± 30	4687–5236	
VC15-6	49.5	^{14}C dating	8740 ± 40	9145–9599	
VC15-5	81.5	^{14}C dating	9140 ± 30	9622–10168	
VC15-4	108.5	^{14}C dating	9890 ± 30	10,621–11,109	Outlier (probably reworked)
VC15-3	121.5	^{14}C dating	9590 ± 30	10,232–10,683	
VC15-2	154.5	^{14}C dating	9770 ± 40	10,470–11,014	
iii	165	Pollen stratigraphy		11,500–11,300	The onset of the 11.4 ka event (Iriarte-Chiapusso et al., 2016)
ii	210	Pollen stratigraphy		12,926–12,534	The onset of the Younger Dryas (Muñoz Sobrino et al., 2013)
VC15-1	277.5	^{14}C dating	12510 ± 40	13,752–14,258	
i	310	Pollen stratigraphy		14,400–14,100	The onset of the Dryas-II (Muñoz Sobrino et al., 2013)

4.3. Palynology

In total, 75 types of pollen and spores, 31 types of dinoflagellate cyst and 29 types of NPP, excluding undetermined types, were identified in the Ría de Arousa record (Supplementary Fig. 1). Pollen and spore accumulation rates ranged between 10 and $5 \cdot 10^3$ grains·cm^{-2}·a^{-1} (average = $8 \cdot 10^2$ grains·cm^{-2}·yr^{-1}), with the lowest rates occurring between 110 and 70 cm depth (Fig. 5). Dinoflagellate cysts were generally scarce, and the mean accumulation rate was $1.2 \cdot 10^2$ cysts·cm^{-2}·a^{-1} (ranging from 2.5 cysts·cm^{-2}·a^{-1} to $1.2 \cdot 10^3$ cysts·cm^{-2}·a^{-1}).

4.3.1. Cluster analysis and PCA results

Cluster analysis and PCA (Figs. 6 and 7) were independently performed on core A14-VC15 pollen samples from sections 322–50 cm and 322–100 cm depth, given that the 100–50 cm section was deposited within a very different sedimentary environment (see discussion below). Only 23 taxa were considered in PCA: significant tree and shrub pollen taxa (>0.5% in at least two samples), and a number of herbaceous types that were considered relevant because of their

316 high abundance or/and their potential value as palaeoenvironmental indicators (i.e. *Artemisia*,

317 Asteraceae, Chenopodiaceae, Poaceae, Cyperaceae, *Isoetes*, *Sphagnum* and *Pteridium*

318 *aquilinum*). In accordance with changes in the pollen assemblages detected by both statistical

319 methods, sediment samples of the 322–50 cm section of A14-VC15 were grouped into four

320 local pollen assemblage zones (LPAZ 1-4; Fig. 6).

321 PCA also helped in the identification of valuable environmental indicators through the ordering

322 of the pollen types along the first two components (Fig. 8a), which respectively explain 47%

323 (PC1) and 12% (PC2) of the variance. *Quercus*, *Pteridium aquilinum*, *Pinus pinaster*-type and

324 *Alnus* are located in the first quadrant (Q1; negative scores on PC1 and PC2). Ericaceae/*Corema*

325 and *Isoetes* show negative scores on PC1 and positive ones on PC2 (Q2). *Helianthemum*-

326 type/Cistaceae, *Betula*, and Poaceae are located in Q3 (positive scores in both PC). Finally,

327 *Pinus sylvestris*-type, Cyperaceae and *Artemisia* show positive scores on PC1 and negative ones

328 on PC2 (Q4).

329 Downcore variations of sample scores are plotted in Fig. 6. The main change indicated by PC1

330 scores occurs at ~100 cm depth when abundances of taxa with negative PC1 scores (mainly

331 *Quercus* and Ericaceae/*Corema*) increase. Between 100 and 70 cm depth, an increase of PC2

332 scores is observed, which is mainly influenced by increases in Q2 taxa (mainly

333 Ericaceae/*Corema* and *Isoetes*). Towards the top of the record (70–50 cm depth), PC2 scores

334 shift to negative values, indicating a significant increase in Q1 taxa (primarily *Quercus*).

335 Both cluster analysis and PCA show little variation in the pollen assemblages in the 322–100

336 cm section of core A14-VC15 (Fig. 6). In this section, it is likely that some taxa (e.g.

337 Ericaceae/*Corema*) that show very high proportions in the upper section of the sequence (100–

338 50 cm depth; Fig. 6) obscure the signal of other less well-represented taxa. To attenuate the

339 likely overrepresentation of Ericaceae/*Corema* (and probably other pollen types) and be able to

340 see whether any significant changes occured in the 322–100 cm depth section, another PCA was

341 performed only on this section (Fig. 7). This method summarizes the variability of pollen

342   assemblages in only two variables (PC1 and PC2). Therefore, it can make it easier to identify

343   the main environmental variations during the period 14,400–10,200 cal a BP. Scores of the first

344   component (PC1 = 20.6%) show decreases (<-0.2) at 305–298 cm, 277–271 cm, 255–238 cm,

345   205–180 cm and 172–164 cm (purple bands; Fig. 7a), coinciding with increases in the cold-

346   tolerant Betula and Juniperus-type (negative PC1 scores; Fig. 8b). Another relevant change in

347   PC1 is observed at 137–127 cm (green band, Fig. 7a), where higher scores indicate a significant

348   increase in Pinus sylvestris-type and P. aquilinum abundances (positive PC1 scores; Fig. 8b).

349   4.3.2. Zonation of the palynological record

350   LPAZ reveals changes in the vegetation composition that correlate with other environmental

351   oscillations (climate and marine environment) and are reflected by changes in other

352   palynomorph abundances (Fig. 7). Therefore, the LPAZ descriptions below also include some

353   relevant changes in NPPs and dinoflagellate cyst assemblages that occurred in each pollen zone.

354   **LPAZ-1; 322–135 cm (~14,400–10,600 cal a BP).** In this zone, Betula (5%–25%) and Pinus

355   sylvestris-type (15%–50%) dominate the tree pollen (AP), and Poaceae shows relatively high

356   abundances (~10%–20%). Ferns and deciduous mesophilous trees are scarce, and Quercus

357   (<5%) and Corylus (<2.5%) are the most frequent taxa (Fig. 6). The presence of Juniperus-type,

358   Ephedra distachya-type, Artemisia and Plantago is noteworthy. Furthermore, this zone

359   coincides with the dominance of the heterotrophic cysts Brigantedinium spp. and

360   Selenopemphix quanta. Spiniferites spp. is the most frequent autotrophic taxon.

361   Although no major changes in the pollen assemblages were detected within this zone, changes

362   in other proxies (Fig. 7) helped identify at least three stages of palaeoenvironmental conditions:

363   Stage 1 (322–260 cm), in which the foraminiferal lining contents are low (< 3%), and

364   proportions of fungal remains are >15%; Stage 2 (260–207 cm), in which proportions of

365   Spiniferites spp. and fungal remains diminish, while the D/P ratio (0.1–0.2) increases; and Stage

366   3 (207–135 cm), which primarily reflects lower values of PC1 (Fig. 8), with higher proportions

367   of Betula and some shrubs (Helianthemum-type/Cistaceae and Juniperus-type), and also shows

368   a considerable decrease in the D/P ratio (<0.1) at 195–185 cm.

369   **LPAZ-2; 135–103 cm (~10,600–10,200 cal a BP).** The representations of Betula and

370   Juniperus-type decline in this zone; in contrast, proportions of Quercus, Pinus sylvestris-type,

371   Isoetes and Pteridium aquilinum generally increase. Furthermore, percentages of heterotrophic

372   dinoflagellate cysts and fungal remains decrease.

373   **LPAZ-3; 103–70 cm (~10,200–9700 cal a BP).** This zone mainly represents the expansion of

374   heaths (Ericaceae/Corema; ~40%) and other hygrophytes/aquatics (e.g. Isoetes) and shows a

375   sharp decline in AP (10–40%), except Quercus and Corylus. In the dinoflagellate cyst record,

376   Spiniferites spp. become dominant (~80%) and Lingulodinium machaerophorum increases

377   notably (5%–15%). Moreover, a marked increase in the D/P ratio and in freshwater

378   palynomorphs (particularly Pseudoschizaea spp.) is observed, while values of foraminiferal

379   linings and fungal remains decrease.

380   **LPAZ-4; 70–50 cm (~9700–9400 cal a BP).** This zone is characterized by notable increases in

381   Quercus and some ferns (e.g. P. aquilinum), and the decline of Betula, Poaceae, Artemisia and

382   Asteraceae. In addition, both the H/A ratio and foraminiferal linings increase but the D/P ratio

383   decreases.

5. Discussion

385   5.1. Chronolitostratigraphy of core A14-VC15

386   One ^{14}C date (VC15-4) was rejected as it was stratigraphically incongruent (Table 1). Sequential

387   stratigraphic analyses indicated that an erosive tidal ravinement surface (disconformity D6; Fig.

388   3a) occurs at the upper limit of f$_1$ (~135 cm) (Cartelle, 2019). During high-dynamic and

389   transgressive periods, it is likely that cannibalization (through ravinement) of previously

390   deposited sediments occurs (e.g. Cattaneo and Steel, 2003). In dating, the presence of outliers as

391   a result of material reworking might be a common issue in sedimentary records that were

392   deposited during a highly dynamic phase of rapid sea level rise and coarse material deposition,

393   as in the Ría de Arousa during the Early Holocene (f_2; Fig. 3b).

394   The combination of the available ^{14}C dates with the high-resolution pollen stratigraphy obtained

395   and their comparison with the Late Glacial to Early Holocene zonation scheme (Fig. 7), defined

396   for littoral and sublittoral sites of NW Iberia by combining radiocarbon dates with pollen

397   evidence and isotopic stages (Muñoz Sobrino et al., 2013; Iriarte-Chiapusso et al., 2016; García-

398   Moreiras et al., 2019), allowed us to obtain a reliable relative chronology for the 322–50 cm

399   section of core A14-VC15 (Fig. 4).

400   According to the radiocarbon date VC15-1 (Table 1), an age of >13,752 cal a BP can be

401   attributed to the bottom levels (>277.5 cm). Five age-control points were established from the

402   pollen stratigraphy (Table 1). The lowest D/P ratios (<0.03) detected at the bottom of the core

403   (310–290 cm), which also coincide with high proportions of Juniperus-type and fungal remains

404   (Fig. 7), were correlated with the Dryas-II cold event, as these lines of evidence might indicate

405   lower RSL, or a slowing down of the RSL rise, and colder conditions (see explanation below

406   and Fig. 7). The Dryas-II cooling event has been dated to 14,250–14,000 cal a BP in NW Iberia

407   (Muñoz Sobrino et al., 2013). Therefore, the onset of Dryas-II (14,250 cal a BP) was used to

408   date the bottom levels of core A14-VC15 (date i; Table 1).

409   The Younger Dryas in the Ría de Arousa is reflected by decreases in pollen and dinoflagellate

410   cyst accumulations rates, and higher representation of cold-tolerant vegetation such as Betula

411   and Juniperus-type at ~210–180 cm depth (Figs. 6 and 7), which may reflect colder conditions.

412   Moreover, changes in pollen concentrations and accumulation rates might indicate

413   modifications in the coastal environments in response to climatic and sea level oscillations (e.g.

414   Muñoz Sobrino et al., 2016). This is in line with the interpretation of other sedimentary records

415   in the Ría de Vigo (e.g. Martínez-Carreño, 2015; Martínez-Carreño et al., 2017), where seismic

416   disconformities are interpreted as variations in the rates of sea level rise during the Younger

417   Dryas. The timing of this climatic reversal was established in inner NW Iberia (Muñoz Sobrino

418   et al., 2013; Iriarte-Chiapusso et al., 2016), and its beginning (12,850 cal a BP) was extrapolated

419   to coastal areas to be used in the A14-VC15 age-depth model (date ii; Fig. 4).

420   Additionally, the cold 11.4 ka event can be identified in the A14-VC15 record as a marked

421   increase in Pinus sylvestris-type and Juniperus-type, and a short regression in deciduous trees,

422   including Quercus and Corylus (Figs. 6 and 7). The onset of this event was established at

423   ~11,500 a BP in coastal areas (Ría de Vigo; Fig. 1a) (García-Moreiras et al., 2019) and in

424   coastal mountains (e.g. Serra do Xistral; Fig. 1a) (Iriarte-Chiapusso et al., 2016), and was used

425   to refine the A14-VC15 chronology (date iii; Fig. 4).

426   5.2. Sedimentation and marine environments in the Ría de Arousa during the Late

427   Glacial to Early Holocene transition

428   Palynomorph concentrations greatly fluctuate through the entire record, and in the upper section

429   (130–50 cm) values are very low (Fig. 5). This may be mainly interpreted as the result of

430   coarser sediment composition and poorer preservation conditions (Fig. 3b), rather than as

431   significant changes in vegetation or phytoplankton productivities. A deterioration of the

432   preservation conditions (i.e. more oxygenic and saline, and probably warmer, environments)

433   from the bottom to the top of the record (Fig. 7) might also be inferred from the progressive

434   decrease in fungal remains (e.g. van Geel, 2001; García-Moreiras et al., 2015). A general

435   tendency of RSL rise during the Late Glacial to Early Holocene transition is inferred. Moreover,

436   the progressive upwards increase in carbonate content (Fig. 3b) agrees with a period of RSL

437   rise, with higher D/P ratio (Fig. 7) indicating increasing rates of marine sedimentation at 130–50

438   cm depth.

439   The lower facies association (f₁, Fig. 3b) corresponds to heterolithic bedding displaying

440   interbedded layers of sandy and muddy material, which is commonly found in tide-related

441   depositional environments (e.g. Reineck, 1967, Tessier et al., 2010). Vertically and laterally

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442 accreting small-scale channels are identified at the top of seismic unit U6 (Fig. 3a), where core

443 A14-VC15 was recovered, agreeing with the general tendency of RSL rise indicated by

444 palynological analyses. Accordingly, the presence of brackish environments is confirmed by the

445 occurrence of terrestrial (pollen and fungi) and marine (dinoflagellate cysts and foraminiferal

446 linings) microfossils, with very low D/P ratios (between 0.04 and 0.24) indicating very shallow

447 water depths. Therefore, during deposition of facies association f_1, a tide-dominated estuary

448 (sensu Dalrymple et al., 1992) was probably set within the Ría de Arousa, where small tidal

449 channels eroded the previous deposits.

450 We interpret from the multi-proxy data of core A14-VC15 that the RSL generally increased

451 from 14,400 to 9400 cal a BP. However, at least two minor phases of higher terrestrial inputs

452 that may be related to a stabilization or slowing down of the RSL (310–270 cm and at 195–180

453 cm depth; Fig. 7) are identified from significant declines in marine palynomorphs, i.e.

454 dinoflagellate cysts (D/P and accumulation rates) and foraminiferal linings (Fig. 7).

455 The dominance of the dinoflagellate cyst Brigantedinium spp. over the period 14,400–10,200

456 cal a BP, as well as the predominance of heterotrophic cysts (H/A = 0.7–1.0; Fig. 7) and the low

457 total cyst concentrations obtained (Fig. 6), would indicate that diatoms were the main

458 component of phytoplankton (e.g. Price and Pospelova, 2011; Bringué et al., 2013) in this part

459 of the palaeo-ria. Heterotrophic cyst production (particularly of the species Brigantedinium

460 spp.) and diatom production are usually positively correlated because diatoms are the preferred

461 prey of some heterotrophic dinoflagellates. Furthermore, many studies (e.g. Radi and de Vernal,

462 2008; Pospelova et al., 2008; Bringué et al., 2013; de Vernal et al., 2013) support the hypothesis

463 that the dominance of Brigantedinium spp. is related to high upwelling influence, high primary

464 productivity and relatively low SST.

465 At ~10,200 cal a BP (~103 cm depth, Fig. 6), a strong change in the marine conditions is

466 detected in the sediment record. Facies association f_2, related to seismic unit U7 (Fig. 3),

467 denotes a sharp increase in energetic conditions, with deposition of gravel-sized bioclasts. The

468   basal bounding surface (disconformity D6) has been interpreted as a tidal ravinement surface

469   (Cartelle, 2019), denoting an increased tidal influence within the ria, slightly eroding underlying

470   deposits, where material reworking may occur. A higher marine influence extends along the Ría

471   de Arousa, with higher D/P ratios, lower proportions of fungal remains and sheet-shaped, sub-

472   horizontal aggrading deposits (Fig. 3a) that are thicker towards the basin margins. Furthermore,

473   conspicuous decreases in the H/A ratio, Brigantedinium spp. and Selenopemphix quanta (Figs. 6

474   and 7) reflect a marked change in the marine productivity towards the dominance of autotrophic

475   dinoflagellates to the detriment of diatoms (Price and Pospelova, 2011; Bringué et al., 2013;

476   Ellegaard et al., 2017).

477   From 10,200 cal a BP, higher proportions of L. machaerophorum (and lower ones of

478   Brigantedinium spp.) may indicate increasing SST and stronger stratification (e.g. Leroy et al.,

479   2013; García-Moreiras et al., 2015; Pospelova et al., 2015). This hypothesis is supported by the

480   increasing abundance of freshwater palynomorphs (taxa of a mainly continental origin: spores

481   of cf. Mougeotia spp., Pseudoschizaea spp., Pediastrum spp., Zygnema-type and Spirogyra spp.

482   and eggs of Neorhabdocoela oocytes), which indicate higher precipitations and river inputs.

483   Furthermore, in the pollen record, a warming and more humid phase is detected, with the

484   regional development of coastal heaths and wetlands (Ericaceae/Corema and Isoetes) and an

485   expansion of mesophilous forests (Quercus, Corylus, etc.) (see below).

486   5.3. Climate and vegetation dynamics during the Late Glacial to Early Holocene

487   transition in the Ría de Arousa

488   Relatively cool and dry climate conditions can be inferred from the pollen record (Fig. 6) during

489   the period 14,400–11,700 cal a BP. This is reflected by the dominance of Pinus sylvestris-type

490   and Betula, and the great abundance of Poaceae. Furthermore, the occurrence of local cold and

491   arid conditions may be inferred from the presence of other pollen types produced by xerophytes,

492   such as Ephedra distachya-type, E. fragilis-type, Juniperus-type and Artemisia. It may be noted,

493   however, that most of these pollen types (particularly Pinus spp., Juniperus-type and other

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494   shrubs, as well as many herbaceous types such as Artemisia, Centaurea nigra-type and

495   Asteraceae) can form part of the common coastal flora and vegetation (dunes, marshes, rocky

496   habitats, etc.) and may be well represented in the pollen records even under warm climatic

497   conditions (e.g. Muñoz Sobrino et al., 2016).

498   Some short cold events with summer temperatures dropping by ~0.5–1ºC have been detected

499   during the Late Glacial Interstadial in La Roya, a small lake at the NW Iberian highlands

500   (Muñoz Sobrino et al., 2013). Two of them, dated to ~13,600–13,499 cal a BP and 13,300–

501   12,900 cal a BP (La Roya-I and La Roya-II, respectively) caused a lowering of the tree line in

502   this highly climatic-sensitive site and other mountain sites in the region (Iriarte-Chiapusso et al.,

503   2016). In the Ría de Arousa, these two minor climatic reversals do not seem to have caused

504   major changes in the regional landscape or the hydrology, as between 14,400–12,800 cal a BP

505   no major changes are detected in the pollen or dinoflagellate cyst records (Figs. 6 and 7).

506   However, statistical analyses performed in the 322–100 cm depth section (Fig. 7) show a few

507   pollen changes that could indicate minor changes in the coastal configuration and the local

508   vegetation. These could be related to the above-mentioned Late Glacial Interstadial climatic

509   oscillations that affected the inland vegetation of NW Iberia. Concretely, three decreases in PC1

510   scores (Purple bands; Fig. 7a) that are related to increases in cold indicators such as Betula and

511   Juniperus-type, and decreasing proportions of Quercus, could be related to short events of lower

512   temperatures or changes in the coastal configuration. These events normally coincide with

513   higher mud contents and increasing fungal remains (at ~300–290 and 250–235 cm depth; Fig.

514   3b), which may be indicative of less energetic tidal environments and the expansion of

515   supratidal and intertidal zones.

516   Many fungi find their ideal habitats in halophilous and hygrophilous plants associated with

517   marshes and coastal meadows (Muñoz Sobrino et al., 2014; García-Moreiras et al., 2015), and

518   they can increase in the sediment record under situations of deceleration of the RSL rise or RSL

519   stabilization. Under these circumstances, shore progradation and expansion of supratidal

520   habitats may occur due to an increase in sediment supply (Allen, 2000; Muñoz Sobrino et al.,

521   2014). Our interpretation could be supported by the increase normally observed in those phases

522   in the pollen representation of some indicators of continental wetlands and other supratidal

523   environments (such as coastal meadows, shrublands and dunes): i.e. Juniperus-type, freshwater

524   spores, Sphagnum, Ephedra distachya-type, Artemisia and Plantago (Figs. 6 and 7)

525   Overall, vegetation dynamics in the Ría de Arousa followed the typical pattern described for

526   other sites in NW Iberia (Ramil-Rego et al., 1996, 1998; Muñoz Sobrino et al., 2001; Iriarte-

527   Chiapusso et al., 2016), i.e. formations with Pinus and Betula dominating the Late Glacial that

528   are substituted by Quercus-dominated forests towards the Holocene. Additionally, in the Ría de

529   Arousa, after the climatic cooling event of the Younger Dryas, two clear changes in the

530   vegetation composition (at ~11,400 and ~10,500 cal a BP) can be recognized as decreases in

531   Quercus and increases in Pinus spp. and Juniperus spp. proportions. These two events also

532   coincide with lower proportions of foraminiferal linings and increases in fungal remains (Fig.

533   7), so they may be related to cooler conditions (a decrease in mesothermophilous woodlands)

534   and higher terrestrial inputs (a deceleration of RSL rise). Their chronological framework makes

535   it obvious to correlate these environmental changes with the climatic anomalies of 11.4 and 10.5

536   ka already described at other NW Iberian sites (Muñoz Sobrino et al., 2013; Iriarte-Chiapusso et

537   al., 2016; García-Moreiras, 2019).

538   In contrast, previous cooling phases during the Late Glacial in the Ría de Arousa (e.g. Younger

539   Dryas) were related to Betula increases and Pinus decreases (Fig. 7). In the Early Holocene, the

540   regional vegetation and probably the littoral configuration were different from those in the Late

541   Glacial. The Juniperus-Betula-Pinus succession that is typically observed within a warming

542   phase in mountain areas of NW Iberia (Peñalba et al., 1997; Muñoz Sobrino et al., 2013) and

543   lowlands close to the North Sea (Bos et al., 2017) would have already finished in our region.

544   Therefore, increases in Pinus after the deciduous mesophilous forests started their expansion

545   (Early Holocene) can be considered as indicative of cooler conditions (Fig. 7). Moreover, it

546   might be taken into account that the RSL rose and the coastal configuration changed radically

547 during the transition: i.e. different sedimentation conditions are expected between the Late

548 Glacial and Early Holocene periods, so changes in the indicator value of some vegetation types

549 (and the related pollen evidence) can also be expected.

550 Finally, a rise in temperatures and precipitation (with increases of mesic taxa such as Quercus,

551 Corylus and Isoetes) is detected from 10,600 cal a BP (Fig. 7). However, it was not until after

552 the cold 10.5 ka event that the climate significantly improved, as is reflected by the substantial

553 increase in the representation of temperate forests with Quercus and Corylus, which must reflect

554 a significant warming and higher fluvial inputs (Fig. 6). Furthermore, the increase in

555 dinoflagellate cyst species such as Lingulodinium machaerophorum would agree with this

556 interpretation, as this species increases with relatively high SST and stratified waters (Leroy et

557 al., 2013). Higher abundances from ~10,200 cal a BP of heaths (Ericaceae/Corema),

558 hygrophilous/aquatic types (Isoetes, Sphagnum, etc.) and freshwater algae (e.g. Pseudoschizaea

559 spp.) are also related to increased rainfall and river inputs.

560 5.4. Coastal palaeoenvironments at the beginning of the Holocene: a comparison

561 between two rias (the Ría de Arousa and the Ría de Vigo)

562 Recently, a sedimentary record of the Early Holocene has been obtained in the nearby Ría de

563 Vigo (core MVR-3; Fig. 1a). However, due to major RSL drops and erosion processes that

564 occurred during the MIS-2 and the Younger Dryas, no record has been obtained for the Late

565 Glacial (Martínez-Carreño and García-Gil, 2017; García-Moreiras et al., 2019).

566 Here, we compare the palaeoenvironmental conditions inferred in the Ría de Vigo (MVR-3

567 record) with those inferred in the Ría de Arousa (A14-VC15) for the common recorded period

568 of ~11,200–9,400 cal BP. Reconstructed vegetation changes in the Ría de Arousa for the Early

569 Holocene are consistent overall with the vegetation dynamics observed in the Ría de Vigo

570 (García-Moreiras et al., 2019), although some differences can be discussed. In the Ría de Vigo,

571 which also forms part of the Rías Baixas (Fig. 1a), Quercus expansion is already observed after

572   the 11.4 ka event (at ~11,200 a BP), with percentages of Quercus pollen of >20% (Fig. 9). In

573   contrast, in the Ría de Arousa, Quercus proportions did not significantly increase (>20%) until

574   after ~9800 a BP (Fig. 6). A delay of >1000 years in the onset of Quercus expansion between

575   these two close basins is improbable. However, it is possible that Quercus started its expansion

576   in the Ría de Arousa earlier and that this fact was not detected in the A14-VC15 sediment

577   record until later because of the very high Ericaceae/Corema representation, which may be

578   explained by the local development of wet or dry heaths on the closest emerged lowlands.

579   Moreover, in both rias a significant increase in continental aquatic/hygrophilous environments

580   in the coastal area is detected (mainly represented by increases in Ericaceae/Corema and Isoetes

581   in the pollen record) at the beginning of the Holocene. However, in the sediment core from the

582   Ría de Arousa the representation of these habitats is higher than in that of the Ría de Vigo, with

583   a conspicuous expansion of heaths and Isoetes dated between 10,200 and 9700 cal a BP (Fig. 9).

584   The different core locations inside their respective rias (with different degrees of river

585   influence) and the unequal coastal configuration of the two valleys (palaeotopography) during

586   the LGIT may explain these results (note that the central channel of the Ría de Arousa is

587   considerably deeper and has steeper slopes than the Ría de Vigo). More favourable biotopes

588   (such as larger coastal plains) probably occurred at the site sampled in the Ría de Arousa and, in

589   combination with moister conditions, might have favoured the expansion of wet heaths and

590   other hygrophilous ecosystems. Consistently, Gómez-Orellana et al. (2007) describes the

591   development of heaths in coastal lowlands of this region during different stages of the Late

592   Pleistocene.

593   It is worth noting that Carpinus-type is almost absent in the Ría de Arousa record, while in the

594   MVR-3 record from the Ría de Vigo it is relatively abundant (<2.1%). In addition, this pollen

595   type consistently appears at 9200–7000 cal a BP (with similar abundances) in the inner part of

596   the Ría de Vigo (core B5; Fig. 1a) and also in other coastal areas of NW Iberia (Muñoz Sobrino

597   et al., 2018; García-Moreiras et al., 2019). These findings support the hypothesis of a fairly

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598   local pollen signal for the pollen records, which is very useful for assessing the environmental

599   heterogeneity of the NW Iberian region.

600   During the LGIT, the Ría de Vigo area could have contained favourable biotopes for the

601   development of ravine, alluvial and hardwood floodplain forests that may have acted as a refuge

602   for many meso-thermophilous species such as Carpinus betulus (Muñoz Sobrino et al., 2018).

603   Contrastingly, palaeotopography reconstructed for the Ría de Arousa using seismic stratigraphy

604   (Cartelle, 2019) indicates that its deepest parts (in the central channel) would have been flooded

605   much earlier than those of the Ría de Vigo (García-Moreiras et al., 2019), which could have

606   contributed to the earlier retreat of part of the hornbeam-favourable habitats when the RSL rose,

607   a likely major cause of the regional disappearance of Carpinus according to Muñoz Sobrino et

608   al. (2018). In addition, outside its main channel, most of the inner part of the ancient valley of

609   the Ría de Arousa was probably flat, and likely held extensive coastal plains before the RSL

610   rose at the beginning of the Holocene (Cartelle, 2019). Pollen evidence presented in this paper

611   suggests that these biotopes were mainly occupied by dunes, wet/dry heaths, coastal meadows,

612   marshes and other hygrophilous ecosystems, where Carpinus may be locally excluded (Muñoz

613   Sobrino et al., 2018). Finally, the Ría de Arousa emerged catchment area (> 3000 m^2) is much

614   larger than that of the Ría de Vigo (709 m^2; Pérez-Arlucea et al., 2005). Therefore, those

615   hypothetical biotopes that presumably sheltered Carpinus during the LGIT might be further

616   away from our sampling point, and their pollen evidence may be under-represented.

617   Local factors such as very different basin sizes and topographies, local currents and the

618   overrepresentation of coastal vegetation could be interfering in the pollen signal of part of the

619   vegetation existing in the A14-VC15 catchment area and partially explain the differences found

620   between the two sedimentary records (Fig. 9). Therefore, additional sedimentary records from

621   other points within the Ría de Arousa would be needed to definitively rule out the presence of

622   hornbeams in its fluvial valleys during the LGIT.

25

623   Regarding marine productivity, the A14-VC15 dinoflagellate cyst record reveals that, during the

624   period 11,700–10,200 cal a BP, a high production of heterotrophic cysts (mainly

625   Brigantedinium spp.) prevailed, likely related to high diatom production and upwelling

626   influence (Price and Pospelova, 2011; Bringué et al., 2013; Ellegaard et al., 2017). Such

627   conditions were probably also driven by the position of the North Atlantic oceanic polar front

628   close to the Galician coasts (e.g. NASP members, 1994).

629   The MVR-3 cyst record from the Ría de Vigo indicates that, during the same period,

630   phytoplankton communities may have been dominated by dinoflagellates and that autotrophic

631   dinoflagellates prevailed (with very high abundances of L. machaerophorum) (Fig. 9). This

632   finding may be related to a lower upwelling influence and higher river influence in the Ría de

633   Vigo (Sprangers, 2004; Leroy et al., 2013; García-Moreiras et al., 2018). However, differences

634   in the two cyst records may be affected by differences in the core locations within the

635   (palaeo)rias: one closer to the river plume (core MVR-3) and one in a position that may be more

636   strongly influenced by the marine currents and the upwelling (core A14-VC15). From ~10,000

637   cal a BP, higher marine influence (a higher D/P ratio) is detected in both the A14-VC15 and

638   MVR-3 records. RSL and coastal configuration may have changed significantly at both sites,

639   and marine environments in both rias became more comparable (Fig. 9): both records show

640   higher autothrophic cyst proportions (L. machaerophorum and Spiniferites spp.), which indicate

641   increasing water stratification, river inputs and more stable conditions (Leroy et al., 2013;

642   Donders et al., 2018; García-Moreiras et al., 2018).

643   **5. Conclusions**

644   High-resolution multi-proxy analyses on core A14-VC15 allowed us to reconstruct the past

645   ecosystems in the Ría de Arousa during the period 14,400–9400 cal a BP and to study how they

646   responded to the regional climatic variability of the LGIT. Seismic, lithological and

647   palynological data agree in indicating that the transition was a period of marked marine

648   transgression, warming and increasing river flow. During the Younger Dryas (~12,700–11,700

649 cal a BP), a sharp reduction in the pollen and dinoflagellate cyst accumulation rates

650 accompanied by a higher representation of cold-tolerant plant species (Betula spp. and

651 Juniperus spp.) is observed, and may be related to lower marine and vegetation productivities as

652 the result of lower rates of RSL rise and colder climate. From the pollen record, we infer the

653 regional expansion of Quercus-dominated forests at <9800 a BP, as well as a conspicuous heath

654 expansion at 10,200–9200 cal a BP. The latter was likely favoured by the palaeotopography, the

655 higher precipitation and the RSL rise, which would have resulted in major changes in the

656 coastal configuration. Concurrently, the dinoflagellate cyst and NPP records indicate higher

657 SST and river inputs, as well as a stronger water stratification, which would have favoured a

658 change from diatom-dominated phytoplankton communities (14,400–10,200 cal a BP) towards

659 higher dinoflagellate productivities (< 10,200 cal a BP), as is reflected by a marked increase in

660 autotrophic cysts. Overall, vegetation in the Ría de Arousa changed from rather open woodlands

661 with cold-tolerant trees (Pinus sylvestris/P. nigra and Betula) dominating the Late Glacial

662 Interstadial and Younger Dryas to a more densely forested landscape with deciduous,

663 broadleaved forests and abundant continental wetlands developing on the lowlands in the Early

664 Holocene. Other shorter events of cooling affected the coastal ecosystems of the Ría de Arousa

665 during the LGIT. The two most obvious ones were characterized by the retreat of mesophilous

666 forests and were dated to ~11,400 and ~10,500 cal a BP. These Early Holocene abrupt cooling

667 events have already been described in the nearby Ría de Vigo.

668 New sedimentary data from the Ría de Arousa highlight the high sensitivity of coastal

669 ecosystems to the LGIT environmental variability, generally showing a close temporal

670 correspondence between terrestrial and marine responses. Moreover, comparison with

671 sedimentary data obtained from the Ría de Vigo suggests marked differences in the regional

672 vegetation and the hydrology between the two sites, thus supporting the high environmental

673 heterogeneity of NW Iberia during the study period. We contribute new valuable data from

674 coastal palaeoecosystems that could help establish an integrated picture of the environmental

675 variability in NW Iberia.

683 References

684   1.   Allen J.R.L., 2000. Morphodynamics of Holocene salt marshes: a review sketch from the

685   Atlantic and Southern North Sea coasts of Europe. Quat Sci Rev 19, 1155–1231.

686   2.   Allen, J.R.M., Huntley, B., Watts, W.A., 1996. The vegetation and climate of northwest Iberia

687   over the last 14000 yr. J Quat Sci 11, 125–147.

688   3.   Álvarez-Salgado, X.A., Rosón, G., Pérez, F.F., Figueiras, F.G., Pazos, Y., 1996. Nitrogen

689   cycling in an estuarine upwelling system, the Ria de Arousa (NW Spain). I. Short-time-scale

690   patterns of hydrodynamic and biogeochemical circulation. Mar Ecol Prog Ser 135:259–273.

691   4.   Blaauw, M., 2010. Methods and code for "classical" age-modelling of radiocarbon sequences.

692   Quaternary Geochronology 5 (5), 512–518.

693   5.   Bos., J.A.A., De Smedt, P., Demiddele, H., Hoek, W.Z., Langohr, R., Marcelino, V., Van Asch,

694   N., Van Damme, D., Van der Meeren, T., Verniers, J., Boeckx, P., Boudin, M., Court-Picon, M.,

695   Finke, P., Gelorini, V., Gobert, S., Heiri, O., Martens, K., Mostaert, F., Serbruyns, L.,Van

696   Strydonck, M, Crombé, P., 2017. Multiple oscillations during the Lateglacial as recorded in a

697   multi-proxy, high-resolution record of the Moervaart palaeolake (NW Belgium). Quat Sci Rev

698   162, 26–41.

699   6.   Bringué, M., Pospelova, V., Pak, D., 2013. Seasonal production of organic-walled dinoflagellate

700   cysts in an upwelling system: A sediment trap study from the Santa Barbara Basin, California.

701   Mar Micropaleontol 100, 34–51.

702   7. Cartelle, V., 2019. Estratigrafía, ambientes de sedimentación, gas somero y análisis sísmico-
703   secuencial del registro sedimentario de las rías de Arousa y Ferrol. PhD. Thesis, University of
704   Vigo, 339 pp.

705   8. Cattaneo, A., Steel, R.J., 2003. Transgressive deposits: a review of their variability. Earth-
706   Science Reviews 62, 187–228.

707   9. Crespo, B.G., Figueiras, F.G., Porras, P., Teixeira, I.G., 2006. Downwelling and dominance of
708   autochthonous dinoflagellates in the NW Iberian margin: the example of the Ría de Vigo.
709   Harmful Algae 5 (6), 770–781.

710   10. Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models; conceptual basis and
711   stratigraphic implications. Journal of Sedimentary Research 62, 1130–1146.

712   11. Datema, M., Sangiorgi, F., de Vernal, A., Reichart, G-J.,Lourents, L. J., Sluijs, A., 2017.
713   Comparison of qualitative and quantitative dinoflagellate cyst approaches in reconstructing
714   glacial-interglacial climate variability at West Iberian Margin IODP 'Shackleton' Site U1385.
715   Mar Micropaleontol 136, 14–29

716   12. De Beaulieu, J-L., Brugiapaglia, E., Joannin, S., Guiter, F., Zanchetta, G., Wulf, S., Peyron, O.,
717   Bernardo, L., Didier, J., Stock, A., Rius, D., Magny, M., 2017. Lateglacial-Holocene abrupt
718   vegetation changes at Lago Trifoglietti in Calabria, Southern Italy: The setting of ecosystems in
719   a refugial zone. Quat Sci Rev 158, 44–57.

720   13. de Menocal, P. B., Ortiz, J., Guilderson, T., Sarnthein, M. 2000. Coherent high- and low-latitude
721   climate variability during the Holocene warm period. Science 288, 2198–2202

722   14. de Vernal, A., Hillaire-Marcel, C., Rochon, A., Fréchette, B., Henry, M., Solignac, S., Bonnet,
723   S., 2013. Dinocyst-based reconstructions of sea-ice cover concentration during the Holocene in
724   the Arctic Ocean, the northern North Atlantic Ocean and its adjacent seas. Quat Sci Rev, 79,
725   111–121, doi: 10.1016/j.quascirev.2013.07.006.

726   15. Desprat, S., Díaz Fernández, P. M., Coulon, T., Ezzat, L., Pessarossi-Langlois, J., Gil, L.,
727   Morales-Molino, C., Sánchez-Goñi, M., F., 2015. Pinus nigra (European black pine) as the
728   dominant species of the last glacial pinewoods in south-western to central Iberia: a
729   morphological study of modern and fossil pollen. J Biogeog, doi: 10.1111/jbi.12566.

730   16. Diez, R., 2006. Gas somero y estratigrafía sísmico-secuencial del registro cuaternario reciente de
731   la Ría de Arousa (noroeste de España). Tesis doctoral, Universidad de Vigo.

732   17. Donders, T.H., Niels, A.G.M., van Helmond, Verreussel, R., Munsterman, D., ten Veen, J.,
733   Speijer, R.P., Weijers, J.W.H., Sagiorgi, F., Peterse, F., Reichart, G-J., Sinninghe Damsté, J.S.,
734   Lourens, L., Kuhlmann, G., Brinkhois, H., 2018. Land–sea coupling of early Pleistocene glacial
735   cycles in the southern North Sea exhibit dominant Northern Hemisphere forcing. Clim. Past, 14,
736   397–411, https://doi.org/10.5194/cp-14-397-2018

737   18. Ellegaard, M., Dale, B., Mertens, K.N., Pospelova, V., Ribeiro, S., 2017. Book chapter #12:
738   "Dinoflagellate cysts as proxies for Holocene and recent environmental change in estuaries:
739   Diversity, abundance and morphology." In: Weckström, K., Saunders, K., Gell, P.A. & Skilbeck
740   G. (eds.), "Application of Paleoenvironmental Techniques in Estuarine Studies." Book series:
741   "Developments in Paleoenvironmental Research," Ed. J.P. Small. Berlin, Germany: Springer,
742   295–312 pp.

743   19. Eynaud, F., Londeix, L., Penaud, A., Sanchez-Goñi, M-F., Oliveira, D., Desprat, S., Turon, J-L.,
744   2016. Dinoflagellate cyst population evolution throughout past interglacials: Key features along
745   the Iberian margin and insights from the new IODP Site U1385 (Exp 339). Global Planet.
746   Change 136, 52–64.

747   20. Fanget, A-S., Bassetti, M-A., Fontanier, C., Tudryn, A., Berné, S., 2016. Sedimentary archives
748   of climate and sea-level changes during the Holocene in the Rhône prodelta (NW Mediterranean
749   Sea). Clim. Past 12, 2161–2179, doi: 10.5194/cp-12-2161-2016

750   21. Figueiras, F.G., Jones, K.J., Mosquera, A.M., Alvarez-Salgado, X.A., Edwards, A., MacDougall,
751   N., 1994. Red tide assemblage formation in an estuarine upwelling ecosystem: Ria de Vigo.
752   Journal of Plankton Research 16(7), 857–878, doi: 10.1093/plankt/16.7.857

753   22. Figueiras, F. G., Labarta, U., Reiriz, M. F., 2002. Coastal upwelling, primary production and
754   mussel growth in the Rías Baixas of Galicia. Hydrobiología 484, 121–131.

755   23. García-Moreiras, I., Sánchez, J.M., Muñoz-Sobrino, C., 2015. Modern pollen and non-pollen
756   palynomorph assemblages of salt marsh and subtidal environments from the Ría de Vigo (NW
757   Iberia). Rev Palaeobot Palynol 219, 157–171.

758   24. García-Moreiras, I., Pospelova, V., García-Gil, S., Muñoz Sobrino, C., 2018. Climatic and
759   anthropogenic impacts on the Ría de Vigo (NW Iberia) over the last two centuries: a high-
760   resolution dinoflagellate cyst sedimentary record. Palaeogeogr Palaeoclimatol Palaeoecol 504,
761   201–218, doi: 10.1016/j.palaeo.2018.05.032.

762   25. García-Moreiras, I., Delgado, C., Martínez-Carreño, N., García-Gil, S., Muñoz Sobrino, C.,

763   (2019). Climate and vegetation changes in coastal ecosystems during the Middle Pleniglacial and

764   the early Holocene: Two multi-proxy, high-resolution records from Ría de Vigo (NW Iberia).

765   Global Planet Change https://doi.org/10.1016/j.gloplacha.2019.02.015

766   26. Gelorini, V., 2011. Diversity and palaeoecological significance of non-pollen palynomorph

767   assemblages in East African lake sediments. Ph.D. thesis. Universiteit Gent.

768   27. Gomez-Orellana, L., Ramil-Rego, P., Muñoz Sobrino, C., 1998. Una nueva secuencia polínica y

769   cronológica para el depósito pleistoceno de Mougás (NW de la Península Ibérica). Rev Paléobiol

770   17, 35–47.

771   28. Gómez-Orellana, L., Ramil-Rego, P., Muñoz Sobrino, C., 2007. The Würm in NW Iberia, a

772   pollen record from Area Longa (Galicia). Quat Res 67, 438–452.

773   29. Gómez-Orellana, L., Ramil-Rego, P., Muñoz Sobrino, C., 2012. The response of vegetation at

774   the end of the last glacial period (MIS 3 and MIS 2) in littoral areas of NW Iberia. Boreas 42,

775   729–744. http://dx.doi.org/10.1111/j.1502-3885.2012.00310.x.

776   30. Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster

777   analysis by the method of incremental sum of squares. Computers & Geosciences 13 (1), 13–35.

778   31. Grimm, E., 1990–2011. TILIA and TILIA graph: PC spreadsheets and graphics software for

779   pollen data. INQUA Commission for the Study of the Holocene Working Group Data Handling

780   Methods. Newsletter 4, 5–7.

781   32. Iriarte Chiapusso, M.J., Agirre, M., Quintana, J.C.L., Peña, L.Z., 2006. Dinámica del paisaje en

782   la Reserva de la Biosfera del Urdaibai durante el Holoceno. In: Comunicaciones/III Congreso

783   Español de Biogeografía, Universidad del País Vasco, 113–117 pp.

784   33. Iriarte-Chiapusso, M. J., Muñoz Sobrino, C., Gómez-Orellana, L., Hernández-Beloqui, B.,

785   García-Moreiras, I., Fernández Rodriguez, C., Heiri, O., Lotter, A.F., Ramil-Rego, P., 2016.

786   Reviewing the Lateglacial–Holocene transition in NW Iberia: A palaeoecological approach

787   based on the comparison between dissimilar regions. Quat Int 403, 211–236

788   34. Jalut, G., Michels, V.T., Dedoubat, J.J., Otto, T., Ezquerra, J., Fontugne, M., Belet, J.M., Bonnet,

789   L., García de Celis, A., Redondo-Vega, J.M., Vidal-Romaní, J.R., Santos, L., 2010.

790   Palaeoenvironmental studies in NW Iberia (Cantabrian range): Vegetation history and synthetic

791   approach of the last deglaciation phases in the western Mediterranean. Palaeogeogr

792   Palaeoclimatol Palaeoecol 297(2), 330–350.

793   35. Johnsen, S. J., Clausen, H. B., Dansgaard, W., Furher, K.,Gusdestrup, N., Hammer, C. U.,

794   Iversen, P., Jouzel, J., Stauffer, B., Steffensen, J. P. 1992. Irregular glacial interstadials recorded

795   in a new Greenland ice core. Nature 359, 311–313.

796   36. Leroy, S.A.G., Lahijani, H.A.K., Reyss, J.-L., Chalié, F., Haghani, S., Shah-Hosseini, M.,

797   Shahkarami, S., Tudryn, A., Arpe, K., Habibi, P., Nasrollahzadeh, H.S., Makhlough, A., 2013. A

798   two-step expansion of the dinocyst Lingulodinium machaerophorum in the Caspian Sea: the role

799   of changing environment. Quat Sci Rev 77, 31–45.

800   37. Martínez-Carreño, N., 2015. Análisis multidisciplinario de las acumulaciones de metano en

801   relación con la arquitectura estratigráfica y los cambios del nivel del mar durante el Cuaternario

802   en la Ría de Vigo. PhD Thesis. University of Vigo, Spain, 356 pp.

803   38. Martínez-Carreño, N., García-Gil, S., 2017. Reinterpretation of the Quaternary sedimentary infill

804   of the Ría de Vigo, NW Iberian Peninsula, as a compound incised valley. Quat Sci Rev 173,

805   124–144.

806   39. Martínez Carreño, N., García Gil, S., Cartelle, V., 2017. An unusual Holocene fan-shaped

807   subaqueous prograding body at the back of the Cíes Islands ridge (Ría de Vigo, NW Spain):

808   Geomorphology, facies and stratigraphic architecture. Mar Geol 385, 13–26.

809   40. Medeanic, S., 2006. Freshwater algal palynomorph records from Holocene deposits in the

810   coastal plain of Rio Grande do Sul, Brazil. Rev Palaeobot Palynol 141(1), 83–101.

811   41. Mertens, K. N., Verhoeven, K., Verleye, T., Louwye, S., Amorim, A., Ribeiro, S., Deaf, A S.,

812   Harding, I.C., De Schepper, S., González, C., Kodrans-Nsiah, M., De Vernal, A., Henry, M.,

813   Radi, T., Dybkjaer, K., Poulsen, N. E., Feist-Burkhardt, S., Chitolie, J.,Heilmann-Clausen, C.,

814   Londeix, L., Turon, J-L., Marret, F., Matthiessen, J., McCarthy F.M.G., Prasad, V., Pospelova,

815   V., Hughes, J.E.K.. Riding, J.B., Rochon, A., Sangiorgi, F., Welters, N., Sinclair, N., Thun, C.,

816   Solima, A., Van Nieuwenhove N., Vink, A., Young, M., 2009. Determining the absolute

817   abundance of dinoflagellate cysts in recent marine sediments: the Lycopodium marker-grain

818   method put to the test. Rev Palaeobot Palynol 157(3), 238–252.

819   42. Moore, P. D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis. Blackwell, London, 216 pp.

820   43. Morales-Molino, C., García-Antón, M., 2014. Vegetation and fire history since the last glacial

821   maximum in an inland area of the western Mediterranean Basin (Northern Iberian Plateau, NW

822   Spain). Quat Res 81(1), 63–77.

823   44. Moreno, A., López-Merino, L., Leira, M., Marco-Barba, J., González-Sampériz, P., Valero-

824   Garcés, B. L., López-Sáez, L.S., Mata, P., Ito, E., 2011. Revealing the last 13,500 years of

825   environmental history from the multiproxy record of a mountain lake (Lago Enol, northern

826   Iberian Peninsula). J Paleolimnol 46(3), 327–349, doi: 10.1007/s10933-009-9387-7

827   45. Moreno, A., Svensson, A., Brooks, S.J., Connor, S., Engels, S., Fletcher, W., Genty, D., Heiri,

828   O., Labuhn, I., Persoiu, A., Peyron, O., Sadori, L., Valero-Garcés, B.L., Wulf, S., Zanchetta, G.,

829   data contributors, 2014. A compilation of Western European terrestrial records 60–8 ka BP:

830   towards an understanding of latitudinal climatic gradients. Quat Sci Rev 106, 167–185,

831   http://dx.doi.org/10.1016/j.quascirev.2014.06.030

832   46. Muñoz Sobrino, C., Ramil Rego, P., Rodríguez Guitián, M.A., 2001. Vegetation in the

833   mountains of northwest Iberia during the last glacial–interglacial transition. Veg Hist

834   Archaeobot 7–21.

835   47. Muñoz Sobrino, C., Ramil-Rego, P., Gómez-Orellana, L., 2004. Vegetation of the Lago de

836   Sanabria area (NW Iberia) since the end of the Pleistocene: a palaeoecological reconstruction on

837   the basis of two new pollen sequences. Veg Hist Archaeobot 13(1), 1–22.

838   48. Muñoz Sobrino, C., Ramil-Rego, P., Gómez-Orellana, L., Díaz Varela, R.A. 2005. Palynological

839   data on major Holocene climatic events in NW Iberia. Boreas 34, 381–400.

840   49. Muñoz Sobrino, C., Ramil-Rego, P., Gómez-Orellana, L., 2007. LateWürm and early Holocene

841   in the mountains of northwest Iberia: biostratigraphy, chronology and tree colonization. Veg Hist

842   Archaeobot 16, 223–24, doi: 10.1007/s00334-006-0083-5.

843   50. Muñoz Sobrino, C., Heiri, O., Hazekamp, M., van der Velden, D., Kirilova, E.P., García-

844   Moreiras, I. & Lotter, A.F., 2013. New data on the Lateglacial period of SW Europe: a high-

845   resolution multiproxy record from Laguna de la Roya (NW Iberia). Quat Sci Rev 80, 58–77.

846   51. Muñoz Sobrino, C., García-Moreiras, I., Castro, Y., Martínez Carreño, N., de Blas, E.,

847   Fernández Rodríguez, C., Judd A., García-Gil, S., 2014. Climate and anthropogenic factors

848   influencing an estuarine ecosystem from NW Iberia: new high-resolution multiproxy analyses

849   from San Simón Bay (Ría de Vigo). Quat Sci Rev 93, 11–33, doi:
850   10.1016/j.quascirev.2014.03.021

851 **52.** Muñoz Sobrino, C., García-Moreiras, I., Martínez-Carreño, N., Cartelle, V., Insua, T. L.,
852   Ferreiro Da Costa, J., Ramil-Rego, P., Fernández Rodríguez, C., Alejo, I., García-Gil, S. 2016.
853   Reconstruction of the environmental history of a coastal insular system using shallow marine
854   records: the last three millennia of the Cíes Islands (Ría de Vigo, NW Iberia). Boreas 45, 729–
855   753, doi: 10.1111/bor.12178.

856 53. Muñoz Sobrino, C., García-Moreiras, I., Gómez-Orellana, L., Iriarte Chiapusso, M.J, Heiri, O.,
857   Lotter, A.F., Ramil-Rego, P., 2018. The last hornbeam forests in SW Europe: new evidence on
858   the demise of Carpinus betulus in NW Iberia. Veg Hist Archaeobot, doi: 10.1007/s00334-017-
859   0654-7.

860 54. NASP Members: Executive Group (J. J. Lowe, B. Ammann, H. H. Birks, S. Bjorck, G. R.
861   Coope, L. Cwynar, J.-L. de Beaulieu, R. J. Mott, D. M. Peteet and M. J. C. Walker), 1994.
862   Climatic changes in areas adjacent to the North Atlantic during the last glacial-interglacial
863   transition (14-9 ka BP): a contribution to IGCP-253. J of Quat Sci 9, 185-198

864 55. Naughton, F., Goñi, M.S., Desprat, S., Turon, J.L., Duprat, J., Malaizé, B., Joli, C., Cortijo, E.,
865   Drago, T., Freitas, M.C., 2007. Present-day and past (last 25000 years) marine pollen signal off
866   western Iberia. Mar Micropaleontol 62(2), 91–114

867 56. Naughton, F., Goñi, M.S., Rodrigues, T., Salgueiro, E., Costas, S., Desprat, S., Duprat, J.,
868   Michel, E., Rossignol, L., Zaragosi, S.,Voelker, A.H.L., Abrantes, F., 2015. Climate variability
869   across the last deglaciation in NW Iberia and its margin. Quat Int 414, 9–22.

870 57. Ninyerola, M., Pons, X., Roure, J.M., 2005. Atlas Climático Digital de la Península Ibérica.
871   Metodología y aplicaciones en bioclimatología y geobotánica. Universidad. Autónoma de
872   Barcelona, Bellaterra.

873 58. Otero, P., Ruiz-Villarreal, M., Peliz, A., 2008. Variability of river plumes off Northwest Iberia in
874   response to wind events. J Mar Syst 72, 238–255.

875 59. Penaud, A., Eynaud, F., Sanchez Goni, M.F., Malaizé, B., Turon, J.L., Rossignol, L., 2011.
876   Contrasting sea-surface responses between the western Mediterranean Sea and Eastern
877   subtropical latitudes of the North Atlantic during abrupt climatic events of MIS 3. Mar
878   Micropaleontol80, 1–17.

879   60. Peñalba, M.C., Arnold, M., Guiot, J., Duplessy, J-C., de Beaulieu, J-L., 1997. Termination of the
880   Last Glaciation in the Iberian Peninsula Inferred from the Pollen Sequence of Quintanar de la
881   Sierra. Quat Res 48, 205–214.

882   61. Pérez-Arlucea, M., Mendez, G., Clemente, F., Nombela, M., Rubio, B., Filgueira, M., 2005.
883   Hydrology, sediment yield, erosion and sedimentation rates in the estuarine environment of the
884   Ria de Vigo, Galicia, Spain. Jounal of Marie Systems 54, 209–226.

885   62. Pospelova, V., de Vernal A., Pedersen, T.F., 2008, Distribution of dinoflagellate cysts in surface
886   sediments from the northeastern Pacific Ocean (43-25N) in relation to sea-surface temperature,
887   salinity, productivity and coastal upwelling, Mar Micropaleontol 68(1–2), 21–48.

888   63. Pospelova, V., Price, A. M., Pedersen, T. F., 2015. Palynological evidence for late Quaternary
889   climate and marine primary productivity changes along the California margin. Paleoceanogr
890   30(7), 877–894.

891   64. Price, A. M., Pospelova, V., 2011. High-resolution sediment trap study of organic-walled
892   dinoflagellate cyst production and biogenic silica flux in Saanich Inlet (BC, Canada). Mar
893   Micropaleontol 80(1–2), 18–43.

894   65. R Development Core Team., 2013. R: A Language and Environment for Statistical Computing.
895   R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org>

896   66. Radi, T., Bonnet, S., Cormier, M.-A., de Vernal, A., Durantou, L., Faubert, É., Head, M.J.,
897   Henry, M., Pospelova, V., Rochon, A., Van Nieuwenhove, N., 2013. Operational taxonomy and
898   (paleo)autecology of round, brown, spiny dinoflagellate cysts from the Quaternary of high
899   northern latitudes. Mar Micropaleontol 98, 41–57.

900   67. Ramil-Rego, P., Gómez-Orellana, L., Muñoz Sobrino, C., Rodríguez Guitian, M., 1996.
901   Valoración de las secuencias polínicas del norte de la Península Ibérica para el último ciclo
902   glaciar–interglaciar. En: Ramil-Rego, P., Fernández-Rodríguez, C. (Coords.), 1996. Férvedes.
903   Monográfico arqueometría y paleoecología del Norte de la Península Ibérica: cambios naturales
904   y perturbaciones antrópicas. Museo de Prehistoria e Arqueoloxía de Vilalba. Férvedes 3, 33–
905   116.

906   68. Ramil-Rego, P., Muñoz Sobrino, C., Rodríguez-Guitián, M., Gómez-Orellana, L., 1998.
907   Differences in the vegetation of the North Iberian Peninsula during the last 16,000 years. Plant
908   Ecol 138, 41–62.

909   69. Ramil-Rego, P., Rodríguez Guitián, M. A., Ferreiro da Costa, J., Rubinos Román, M., Gómez-
910   Orellana, L., de Nóvoa Fernández, B., Hinojo Sánchez, B. A., Martínez Sánchez, S., Cillero
911   Castro, C., Díaz Varela, R. A., Rodríguez González, P. M., Muñoz Sobrino, C., 2008. Os
912   Hábitats de Interese Comunitario en Galicia. Fichas Descritivas. Monografías do Ibader.
913   Universidade de Santiago de Compostela, Lugo, pp. 627.

914   70. Reimer, P.J., Reimer, R.W., 2001. A marine reservoir correction database and on-line interface.
915   Radiocarbon 43, 461–463.

916   71. Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E.,
917   Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H.,
918   Hajdas, I., Hatté, C., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B.,
919   Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney,
920   C.S.M., van der Plicht, J., 2013. IntCal13 and MARINE13 radiocarbon age calibration curves 0–
921   50000 years cal BP. Radiocarbon 55, doi: 10.2458/azu_js_rc.55.16947.

922   72. Reineck, H.E, 1967. Layered sediments of tidal flats, beaches, and shelf bottoms of the North
923   Sea. AAAS Special Publication 83, 191–206.

924   73. Río Barja, F.J., Rodríguez Lestegás, F., 1992. Os Ríos Galegos. Consello de Cultura Galega,
925   Santiago de Compostela, 331 p. ISBN: 84-87172-76-8.

926   74. Rosón G., Pérez, F.F., Álvarez-Salgado, X.A., Figueiras, F.G., 1995. Variation of Both
927   Thermohaline and Chemical Properties in an Estuarine Upwelling Ecosystem: Ria de Arousa. I.
928   Time Evolution. Estuar Coast Shelf Sci 41, 195–213.

929   75. Rosón, G., Álvarez-Salgado, X.A., Pérez, F.F., 1999. A nonstationary box model to determine
930   residual fluxes in a partially mixed estuary, based on both thermohaline properties. Application
931   to the Ria de Arousa (NW Spain). Estuar Coast Shelf Sci 44 (3), 249–262, doi:
932   10.1006/ecss.1996.0127

933   76. Roucoux, K.H., de Abreu, L., Shackleton, N.J., Tzedakis, P.C., 2005. The response of NW
934   Iberian vegetation to North Atlantic climate oscillations during the last 65 kyr. Quat Sci Rev 24
935   (14–15), 1637–1653.

936   77. Sprangers, M., Dammers, N., Brinkhuis, H., van Weering, T.C.E., Lotter, A.F., 2004. Modern
937   organic-walled dinoflagellate cyst distribution offshore NW Iberia; tracing the upwelling system.
938   Rev Palaeobot Palynol 128, 97–106.

939   78. Stuiver, M., Reimer, P.J., Reimer, R.W., 1986–2018. CALIB 7.1. Available at:
940   http://www.calib.qub.ac.uk/calib/.

941   79. Swetnam, T.W., Allen, C.D., Betancourt, J.L., 1999. Applied Historical Ecology, using the past
942   to manage for the future. Ecol Appl 9 (4), 1189–1206.

943   80. ter Braak, C.J.F., Prentice, I.C., 1988. A theory of gradient analysis. Adv Ecol Res18, 271–313.

944   81. Tessier, B., Delsinne, N., Sorrel, P., 2010. Holocene sedimentary infilling of a tide-dominated
945   estuarine mouth. The example of the macrotidal Seine estuary (NW France). Bulletin de la
946   Société Géologuique de France 181, 87–98.

947   82. Tilstone, G.H., Míguez, B.M., Figueiras, F.G., Fermín, F.G., 2000. Diatom dynamics in a coastal
948   ecosystem affected by upwelling: coupling between species succession, circulation and
949   biogeochemical processes. Mar Ecol Prog Ser 205, 23–41

950   83. Turon, J. L., Lézine, A. M., Denèfle, M., 2003. Land–sea correlations for the last glaciation
951   inferred from a pollen and dinocyst record from the Portuguese margin. Quat. Res. 59, 88–96.

952   84. van Geel, B., 2001. Non-pollen palynomorphs. In: Smol, J.P., Birks, H.J.B., Last,W.M. (Eds.),
953   Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal and
954   Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, 99–120 pp.

955   85. van Geel, B., Gelorini, V., Lyaruu, A., Aptroot, A., Rucina, S., Marchant, R., Damsté, J.S.S.,
956   Verschuren, D., 2011. Diversity and ecology of tropical African fungal spores from a 25,000-
957   year palaeoenvironmental record in southeastern Kenya. Rev Palaeobot Palynol 164, 174–190.

958   86. Vilas, F., Bernabeu, A. M., Méndez, G., 2005. Sediment distribution pattern in the Rias Baixas
959   (NW Spain): main facies and hydrodynamic dependence. J MarSyst 54(1), 261–276.

960   87. Watson, E.B., Byrne, R., 2009. Abundance and diversity of tidal marsh plants along the salinity
961   gradient of the San Francisco Estuary: implications for global change ecology. Plant Ecol
962   205(1), 113–128.

963   88. Wentworth, C.K., 1922. A Scale of Grade and Class Terms for Clastic Sediments. J. Geol. 30,
964   377–392.

965   89. Zonneveld, K.A.F., Pospelova, V., 2015. A determination key for modern dinoflagellate cysts.
966   Palynol 39(3), 387–409, doi: 10.1080/01916122.2014.990115

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Figures

969 **Fig. 1** Study area: a) Location of the Ría de Arousa and the Ría de Vigo within the Rías Baixas

970 on the Atlantic margin of Galicia (NW Iberia) and b) Ría de Arousa basin indicating the

971 location of core A14-VC15. Other sites and core locations mentioned in the text are also shown.

972 The bathymetric contour is in metres (cartographic data are from

973 http://mapas.xunta.gal/produtos-cartograficos/capas-six/hidrografia).

974 **Fig. 2** Schematic representations of a) the system of currents offshore of the western Iberian

975 Peninsula and b) the vertical distribution of marine waters in front of the Galician coast,

976 modified from Sprangers et al. (2004). ENACW, Eastern North Atlantic Central Water and its

977 subtropical (ENACWst) and subpolar (ENACWsp) branches; PCS, Portugal Current System;

978 MW, Mediterranean Water; LSW, lower saline Labrador Sea Water; NADW, North Atlantic

979 Deep Water.

980 **Fig. 3** a) High-resolution seismic record and its interpretation at the position where core A14-

981 VC15 was recovered. The seismic unit's notation is based on the stratigraphic interpretation of

982 Cartelle (2019). b) Sedimentological log from core A14-VC15, also showing grain-size and

983 carbon (C) analyses along the core. C values are expressed as percentages (%) of dry weight.

984 **Fig. 4** Age-depth model of core A14-VC15 obtained using CLAM 2.2. in R software (Blaauw,

985 2010). Black lines represent the isotopic dates (Table 1) and grey lines represent pollen-inferred

986 ages (length of lines corresponds to 95% confidence intervals); those considered as outliers (and

987 not included in the model) are marked with a red cross. Red dashed lines limit the 95%

988 confidence intervals of the estimated ages. GOD = Goodness of fit (-log, lower is better).

989 **Fig. 5** Distributions of the accumulation rates of selected palynomorphs in the A14-VC15

990 record. The local pollen assemblage zones (LPAZ) are represented on the right. AP = Arboreal

991 Pollen. The chronology corresponds to the age-depth model presented in Fig. 4

992   **Fig. 6** Distributions of the percentages of selected palynomorphs in the A14-VC15 record.

993   Cluster analysis results, the scores of the first two axes from PCA and the local pollen

994   assemblage zones (LPAZ) are represented on the right. Grey shading represents x10

995   exaggeration of the values. AP = Arboreal Pollen. The chronology corresponds to the age-depth

996   model presented in Fig. 4

997   **Fig. 7** Main environmental changes in the Ría de Arousa that were inferred from the A14-VC15

998   palynological record and their comparison with regional palaeoclimatic records: a) combined

999   diagram of percentages and accumulation rates of relevant pollen and NPP types from the A14-

1000   VC15 record [grey shading represents x10 exaggeration of the values; the distribution of the

1001   H/A and D/P ratios is also represented, as are the scores of the first component of PCA

1002   performed on the 322–100 cm section; freshwater palynomorphs include taxa with mainly

1003   continental origin: spores of cf. Mougeotia spp., Pseudoschizaea spp., Pediastrum spp.,

1004   Zygnema-type and Spirogyra spp., and eggs of Neorhabdocoela oocytes; local pollen

1005   assemblage zones (LPAZ) are shown on the right]. b) Regional biostratigraphy (see e.g. Iriarte-

1006   Chiapusso et al., 2016). c) Main changes in July air temperatures that occurred in La Roya Lake

1007   (1608 m amsl), inferred from the chironomid record and corresponding to the main climatic

1008   changes that occurred in the NW Iberian region. d) Oxygen isotopic record from the NGRIP ice-

1009   core that reflects the main climatic changes that occurred in the North Atlantic (NGRIP dating

1010   group, 2006). e) Climatic phases in the North Atlantic defined by the INTIMATE group

1011   (Rasmunssen et al., 2014).

1012   **Fig. 8** PCA plots for a) the complete A14-VC15 pollen record and b) only for the bottom

1013   section (322–100 cm). In the second case, only pollen types that are significant in PC1 are

1014   represented.

1015   **Fig. 9** Comparison of A14-VC15 (continuous lines) and MVR-3 (dashed lines) records. MVR-3

1016   was obtained in the nearby Ría de Vigo (Fig. 1a; García-Moreiras, 2017). Only the D/P ratio

1017   and some selected pollen and dinoflagellate cyst types are represented. Local pollen assemblage

1018 zones (LPAZ) of the Ría de Arousa and the Ría de Vigo are shown in the uppermost part.

1019 Vertical grey bars represent the main cold events that occurred in the region during the Early

1020 Holocene period.

1021 Supplementary material

1022 **Fig. 1** Complete percentage diagram of the A14-VC15 palynological record with all identified

1023 types. Grey shading represents x10 exaggeration of the values. Pollen aggregates are indicated

1024 with a red asterisk (*) where found.

1025 **Plate 1** Images (light microscopy) of relevant palynomorphs from the A14-VC15 record of the

1026 Ría de Arousa (NW Iberia). Scale bars are 10 μm except in Pinus sylvestris-type where the scale

1027 bar is 50 μm. 1,2) cf. Cosentinia vellea/Anogramma leptophylla (88–89 cm); 3) Osmunda

1028 regalis (104–105cm); 4) Carpinus-type (248–249 cm); 5) Ephedra distachya-type (316–

1029 317cm); 6) Epilobium-type (244–245 cm); 7) Juniperus-type (180–181 cm); 8) Pinus sylvestris-

1030 type (140–141 cm); 9) Myriophyllum spicatum/M. alterniflorum (244–245 cm); 10)

1031 Nematosphaeropsis labirinthus (276–277 cm); 11) cf. Operculodinium israelianum (256–257

1032 cm); 12) Spiniferites membranaceus (56–57 cm); 13) Protoperidinium americanum (104–105

1033 cm); 14) Selenopemphix undulata (224–225 cm); 5) Islandinium? cf. cezare (310–311 cm).