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Holocene paleoenvironmental reconstructions in western Brittany (Bay of Brest): Part II – A 7 kyr human-environment story with a focus on the Neolithic-Bronze Age transition

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Abstract :

The Bay of Brest (BB, NW France) is a semi-enclosed basin of 180 km² subject to macro-tidal dynamics and to the fluvial influences of the rivers Aulne and Elorn, which combined drain watersheds of 2600 km². This coastal environment is subject to natural climate oscillations overlaid on the long-term landscape transformations inherited from the post-glacial sea level rise and increasing anthropogenic forcing since the Neolithic (6.9 ka BP), and especially from the Bronze Age (4.2 ka BP) onwards. The BB therefore appears suitable for the reconstruction of the interactions between climate, environment and human dynamics across the Holocene. In this study, a palynological stack was created based on five cores (including two new cores PALM-KS05 and PALM-KS06 from the Brest harbour), allowing us to discuss vegetation dynamics over the last 7 kyrs. Since the Neolithic period, the forest cover has decreased in favour of open and agro-pastoral landscapes. This trend is not uniform, however: forest cover first declined slowly around 4 ka BP, then strongly decreased at the end of the Iron Age, before experiencing a revival of about five centuries at the end of the Roman period (1.7–1.2 ka BP). Finally, a drastic fall of tree pollen taxa is recorded at the start of the Middle Ages. This study is the first on long-term Holocene trends that allows discussion of both climatic and anthropogenic forcing at an unprecedent average study resolution of 35 years. We also place this local evolution in a wider context to detail interactions between natural and anthropic forcings over the last 7 kyrs BP at a regional-scale and we discuss paleoenvironments and human dynamics thanks to the incorporation of an up-to-date corpus of archaeological data.

Keywords : anthropization, Bay of Brest, Bronze Age, Holocene, Neolithic, palynology

1. Introduction

The Holocene (i.e. the period since ~11.7 ka BP) has been characterized by significant climatic variability on different timescales. At the multi-millennial timescale, the Holocene is characterized by a gradual decrease (/increase) in summer (/winter) insolation at 65°N (Berger and Loutre, 1991), leading to a cooling of global temperatures, as well as decreasing seasonality and an increasing winter precipitation regime over western Europe during the Late Holocene (e.g. Benito et al., 2015; Penaud et al., 2020). Superimposed on this long-term trend, the climate of western Europe is forced at the millennial timescale by the recurrence of abrupt climate events related to cryospheric instabilities (i.e. 'Bond events', Bond et al., 1997; or 'rapid climate change': RCC, Mayewski et al., 2004), involving a reorganization of physico-chemical exchanges at the air/ocean interface and controlling the dynamics of the North Atlantic Sub-Polar (SPG) and Sub-Tropical (STG) Gyres (e.g. Hátún et al., 2005; Morley et al., 2014; Mary et al., 2017; Colin et al., 2019). Over the Holocene, north-eastern Atlantic storminess, also implying geomorphological changes such as phases of mobility-stabilization of coastal barriers, has been related to these natural ocean-atmosphere oscillations (e.g. Sorrel et al., 2012; Van Vliet-Lanoë et al., 2014; Stéphan et al., 2015; Goslin et al., 2018, 2019; Pouzet et al., 2018; Gorczynska et al., 2023) and has often been explained through the well-known meteorological mechanisms of the North Atlantic Oscillation (NAO). Indeed, the NAO is the dominant mode of atmospheric variability at mid-latitudes in the North Atlantic region (e.g. Hurrell, 1995; Hurrell and Deser, 2009; Wang et al., 2009), as also shown for western Brittany (Tréguer et al., 2014). At the Holocene timescale (Olsen et al., 2012), these variable 'NAO-like' configurations were recently suggested as being responsible for stronger precipitation regimes over north-west Europe during positive modes (and conversely during negative ones), with impact on sediment, vegetation and marine fauna (Penaud et al., 2020; Lambert et al., 2020; David et al., 2022).

Furthermore, recent studies have reconstructed the post-glacial relative sea level (RSL) rise on Brittany's coasts (e.g. Stéphan and Goslin, 2014; Goslin et al., 2015; Stéphan et al., 2015; García-Artola et al., 2018), showing high RSL rise rates from the end of the last glacial period to 9 ka BP (10–15 mm yr^{-1}) that decreased during the Mid- to Late Holocene (4.6 mm yr^{-1} between 7.5 and 6.5 ka BP and less than 1 mm yr^{-1} after 6 ka BP). This evolution of the RSL rise generally allowed the stabilization of coastal environments during the Middle Holocene (Penaud et al., 2020) with the development of tidal flats in estuarine environments and salt marshes along coasts (e.g. Stéphan et al., 2015; Gregoire et al., 2017, for the Holocene sedimentary infilling of the Bay of Brest in north-western France). Finally, Holocene paleoenvironments of north-western France have been impacted by anthropic dynamics (i.e. cultural, technical and demographic evolution), especially since the start of the Neolithic (i.e. ~7 ka BP in Brittany), which marks the beginning of the development of agro-pastoral societies (Pailler et al., 2008; Tinévez et al., 2015). Palynological studies especially highlight the massive deforestation and intensification of agro-pastoral activities based on anthropogenic pollen indicators (API) from the start of the Bronze Age (Marguerie, 1992; Barbier, 1999; Ouguerram, 2002; Cyprien et al., 2004; Gaudin, 2004; Naughton et al., 2007; Fernane et al., 2014, 2015; Penaud et al., 2020; David et al., 2022).

This study investigates two new sequences from the Bay of Brest (BB) (cores PALM-KS05 and PALM-KS06, from Brest Harbour), a shallow macro-estuarine environment (8 m deep on average, Figure 1; Gregoire et al., 2016) in north-western France. We use a multidisciplinary approach based on sedimentological (grain size and loss on ignition) and palynological (continental and marine palynomorph) analyses. Core PALM-KS06 especially focuses on the interval 4.8–3 ka BP, not yet documented in the study area (see Lambert et al., 2019, 2020, who documented the ~9–5 ka BP interval and the last 2.5 kyrs, respectively), and allows us to discuss the climatic (Middle to Late Holocene) and cultural (Neolithic to Bronze Age) transitions centred on 4.2 ka BP. Previous and newly investigated cores collected in the BB also allow reconstruction of the first Holocene paleoenvironmental synthesis from 7 to 0.5 ka BP based on stacked palynological data. While pollen analyses provide information on vegetation dynamics on BB watersheds and are subject to both natural and anthropogenic forcings, dinoflagellate cysts (dinocysts) allow consideration of past BB sea surface conditions.

Although pollen-based studies of coastal peat deposits were recently conducted over the last 7 kyrs BP in western (Fernane et al., 2014), southern (Fernane et al., 2015) and northern (David et al., 2024) Brittany, the originality of the present work lies in the study of a western Brittany estuarine context studied at a high temporal resolution (35 years on average). Indeed, studies conducted in estuarine environments are extremely rare (e.g. Haslett et al., 2000; Allen and Dark, 2007 for the Severn Estuary, southwest England), given the complexity of estuaries from a sedimentary perspective. Furthermore, we raise the question of rapid natural climate changes and dynamics of coastal societies. While the ‘history of climate and society’ (Degroot et al., 2021) may suffer from spatiotemporal heterogeneity either from a climate or anthropogenic perspective, working at a local-scale with an interdisciplinary approach allows emphasizing the Holocene discussion between paleoenvironments, past climate pressures and human populations thanks to the inclusion of an up-to-date corpus of archaeological data restricted to the study area (i.e. watershed-to-sea link).

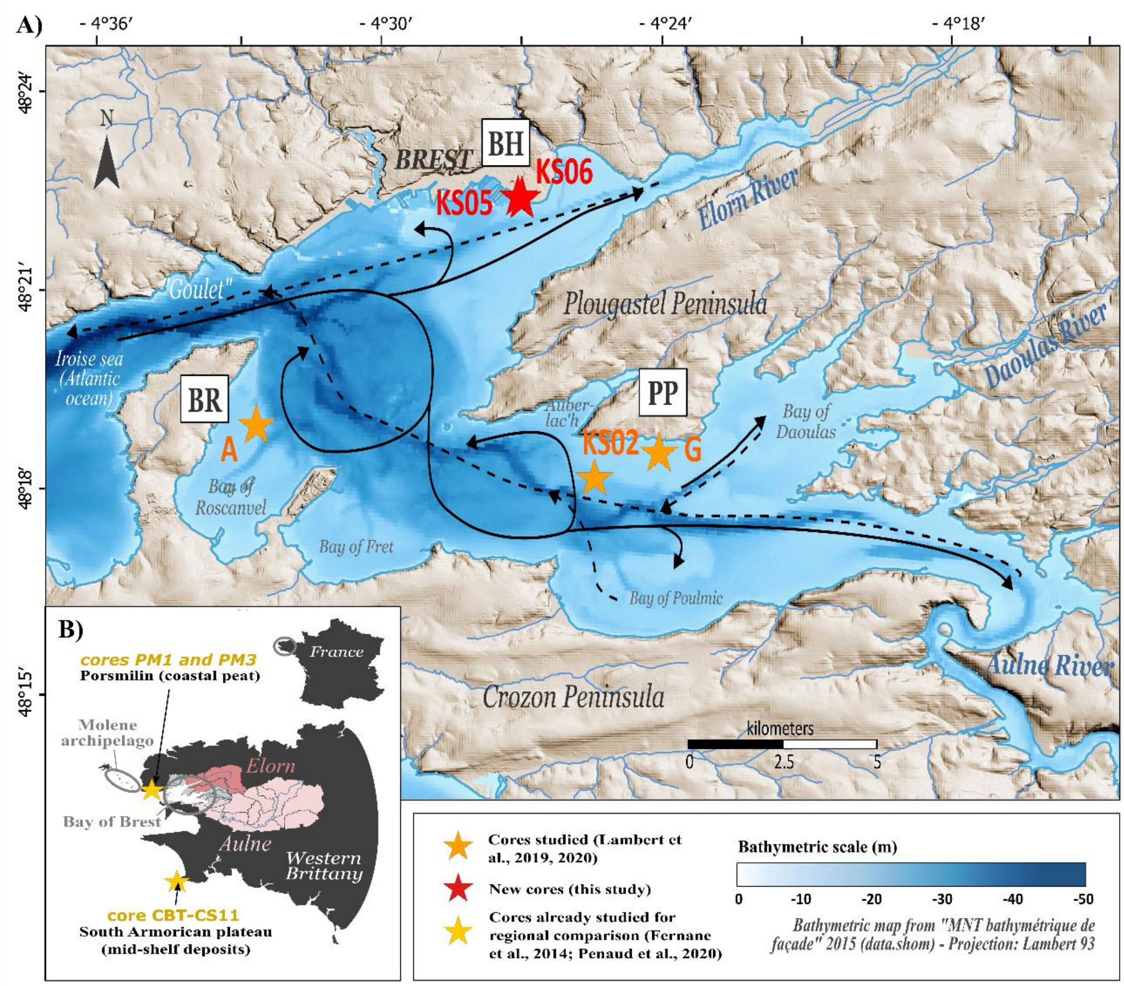

Figure 1. (a) Location of the five cores selected for this study in the Bay of Brest (BB): three cores previously analysed (core 'A': Lambert et al., 2019; cores 'G' and KS02: Lambert et al., 2020) shown with orange stars, and two new cores presented in this study (cores PALM-KS05 and PALM-KS06) shown with red stars. The cores are divided into three coring sites: Bay of Roscanvel (BR), Brest harbour (BH) and south of Plougastel peninsula (PP). The tidal currents (corresponding to a coefficient 95 at the Brest harbour; adapted from Guérin (2004) are also represented with their circulation during flow (solid line) and ebb (dashed line). B) Location cores PM1 and PM3 (Fernane et al., 2014) and core CBT-CS11 (Penaud et al., 2020), which will be compared with the BB ones. BB watersheds are shown distinguishing those of the Aulne (pale pink) and Elorn (dark pink) rivers.

2. The Bay of Brest (NW France) environmental and archaeological contexts

2.1. Geomorphological, sedimentological and climatic contexts

We refer to the Valero et al. (2024 – Part I) paper for the description of geological, geomorphological, sedimentological and climate settings, also integrating the description of the main present-day freshwater inputs coming from the Aulne and Elorn main rivers and draining 2,650 km² of BB watersheds (Delmas and Tréguer, 1983).

2.2. Cultural evolution and territorial occupation dynamics in Western Brittany

The Holocene is a period marked by complex and increasingly pronounced land-use dynamics over the last 10 kyrs BP (Visset et al., 2002). Regarding human occupation of the BB watersheds, the Mesolithic period (10.4–6.8 ka BP / 8.5–4.8 ka BC) remains little documented due to the poor preservation of archaeological sites, except for four shell middens dating from the Late Mesolithic period in south Finistère and Morbihan (Dupont et al., 2010; Marchand, 2014). However, evidence of several hunter-gather communities migrating seasonally in a defined territory has been found in western Brittany (Gouletquer et al., 1996). Major transhumance axes crossed the peninsula, passing along the Aulne and Elorn rivers, where lithic scatters were found probably linked to potentially navigable waterways (Gouletquer et al., 1996; Marchand, 2005). Due to their relatively small numbers (Giot et al., 1998), these populations only slightly modified their natural environment in Brittany (as already noted by Morzadec-Kerfourn, 1974), in particular by working of plants fibres (Guéret et al., 2014).

The Neolithic farmers then reached the Armorican Massif around 7 ka BP (5 ka BC; Blanchet et al., 2010) via Danubian-related agricultural populations, evidenced by the western extension of the Linear Pottery Culture (i.e. Blicquy-Villeneuve-Saint-Germain, in Pailler et al., 2008), and particularly in Southern Finistère (Marchand et al., 2006; Pailler, 2007; Tinévez et al., 2015). The contact between Mesolithic and Neolithic societies remains debated due to the uncertainties of precision of the carbon-14 dating method around 7 ka BP (5 ka BC) and the lack of hunter-gatherer sites contemporary with the arrival of the Neolithic communities. However, across eastern Europe, aDNA data suggest marginal interbreeding between hunter-gatherers and agropastoralists (Brunel et al., 2020). Western Europe population increased sharply as a result of increasing food production and began to settle in perennial villages (Marchand, 2014; McClatchie et al., 2014). Early Neolithic populations thus appear to have settled all over the Brittany peninsula, as attested by a number of settlement (trapezoidal houses), lithic processing sites and the manufacture of stone bracelets in the Bigouden and Léon areas (Pailler, 2007) dating from this period. Considering the emergence of agriculture, there is no clear and undisputable palynological or palaeobotanical data in western Brittany, despite several evidences of human exploitation of the environment noticeable from ~7 ka BP (5 ka BC). This early evidence points, for example, to the felling of trees and the woodworking associated with the production of polished stone axes in the Plouguin fibrolite (Pailler, 2012), as well as the use of plant fibres, attested to by the first appearance of grinding stones and traces of plant cutting detected on lithic furniture (Giot et al., 1998). Nevertheless, during the Neolithic period, cultivated areas are still limited to small areas, and only environments near megalithic constructions show evidence of deforestation (Marguerie, 1992).

At the end of the Neolithic, human impacts significantly increased with obvious regional evidence of landscape opening (e.g. Morzadec-Kerfourn, 1974; Gaudin, 2004; David, 2014; Fernane et al., 2015; Penaud et al., 2020; David et al., 2022, 2024) and the use of the ploughing to work the soil (Pailler and Nicolas, 2019, 2023, 2024). This dynamic coincides in western Brittany with the emergence of the Bell Beaker culture around 4.5 ka BP (2.5 ka BC; Nicolas et al., 2013, 2019). This cultural trend is characterized by the creation and diffusion of inverted bell-shaped beakers as well as the reuse of megalithic monuments. These practices continued until the beginning of the Early Bronze Age (4.2 ka BP / 2.1 ka BC), when new funeral and social customs (i.e. Armorican tumulus culture) and technical developments emerged (Briard et al., 1994; Nicolas, 2016; Blanchet et al., 2019). In addition, this period brought kind of agricultural revolution, with the creation of extended networks of field systems delimited by ditches or stone walls (Blanchet, 2013, 2020; Blanchet et al., 2019; Pailler and Nicolas, 2019; Marcigny, 2022).

During the Bronze Age (4.2–2.7 ka BP / 2.1–0.8 ka BC), the Armorican Massif occupied a strategic position in the circulation of metal ores and objects across the Atlantic seaboard and northern Europe (Giot et al., 1995, 1998; Briard, 1996), while only tin exploitation is locally attested. The intensification of human activities (metallurgy, land-use, agro-pastoralism) led to extensive deforestation, clearly evident in all the pollen records of the Armorican Massif (Marguerie, 1992; Barbier, 1999; Ouguerram, 2002; Cyprien et al., 2004; Gaudin, 2004; David, 2014; Fernane et al., 2014, 2015; David et al., 2022, 2024).

This dynamic then continued from the Iron Age (2.7–2 ka BP / 800–50 yr BC) to the Middle Ages (1.7 ka–450 yr BP / 460–1500 yr AD) and intensified as the economy and the environment gradually transformed completely into an increasingly agrarian landscape. However, this process was punctuated by various phases of crisis due to a number of climatic (i.e. periods of degradation, storms, silting; Sorrel et al., 2012; Pouzet et al., 2018; Gorczynska et al., 2023) and social (i.e. invaders, wars) factors (Galliou, 1991).

3. Material and methods

3.1. General information on study sediment cores

Due to the discontinuous sedimentary infilling of the BB (Gregoire et al., 2017), we used five different cores collected in three different BB areas for the Holocene palynological synthesis: the Bay of Roscanvel (BR), the Brest harbour (BH), and the south of the Plougastel peninsula (PP) (Figure 1; Table 1). Three of the five cores were previously studied: i) core 'A' (BR; Lambert et al., 2019) and ii) cores 'G' and KS02 (PP; Lambert et al., 2020). In this study, two cores (PALM-KS05 and PALM-KS06) were the subject of new palynological analyses.

Cores 'A' (BR) and 'G' (PP) were retrieved using a vibrocorer on the R/V *Côtes de la Manche* during the '*Défis Golfe de Gascogne*' program in 2003 (Ifremer and UMR 6839 LEMAR-IUEM). Core KS02 (PP) was retrieved using a gravity corer on R/V *Côtes de la Manche*, during the 'EssCALICO' cruise in 2010 (Ifremer). Finally, cores PALM-KS05 and PALM-KS06 (BH) were collected with a gravity corer onboard the R/V *Thalia* during the PALMIRA cruise in 2017 (Ifremer-DYNECO-PELAGOS).

Cores	Location	Lat/Long	Depth (m)	Length (cm)	Number of ^{14}C dates	Temporal coverage cal BP (cal AD/BC)	Number of palyno. analyses	Average resolution (yrs)	Existing references
A	Bay of Roscanvel (BR)	48°19.207'N 4°31.771'W	8.2	418	14	**6521 – 5948 BP (4571 – 3998 BC)**	35	20	Lambert et al., 2019
PALM-KS05	**Brest harbour (BH)**	**48°22.880'N 4°26.911'W**	**6**	**176**	**10**	**1402 – 810 BP (548 –1140 AD)**	**25**	**25**	**Ehrhold et al., 2021**
PALM-KS06	**Brest harbour (BH)**	**48°22.879'N 4°26.91'W**	**7.1**	**344**	**6**	**4829 – 3068 BP (2879 – 1118 BC)**	**33**	**50**	**New in this study**
G	Rozegat (PP)	48°19.241'N 4°23.082'W	7.4	358	6	**2413 – 1647 BP (463 BC – 303 AD)**	27	30	Lambert et al., 2020
KS02	Rozegat (PP)	48°18.767'N 4°24.456'W	8	253.5	9	**1605 – 559 BP (345 – 1391 AD)**	35	30	Lambert et al., 2020

Table 1. Characteristics of the Bay of Brest cores selected in this study. New core PALM-KS06 in this study is highlighted in red and core PALM-KS05 from which new palynological data were obtained in this study is shown in bold. All cores have benefitted from updated chronologies.

3.2. Chronological framework

For the two newly investigated cores PALM-KS05 and PALM-KS06, we refer to the radiocarbon dates and age-depth relationships presented in Valero et al. (2024 – PART I). All

AMS-^{14}C dates were calibrated with CALIB 8.1 software using the IntCal20 calibration curve (Reimer et al., 2020). An age reservoir of 365 yrs, previously calculated in the BB (Lambert et al., 2019), was removed from radiocarbon dates before calibration. Finally, for all the five BB cores stacked in the Holocene synthesis, the age-depth relationships were established using the rbacon package (Blaauw and Christen, 2011) in R version 4.3.0 (R Development Core Team, 2022; http://www.r-project.org/) (cf. the SEANOE repository for all age-depth models: https://doi.org/10.17882/99422).

The BB data were also compared with published palynological datasets acquired on the inner continental shelf (i.e. salt marsh environment) located at the BB outlet (core PM at Porsmilin; Fernane et al., 2014) and on the southern Brittany mid-shelf (core CBT-CS11; *Grande Vasière*, Penmarc'h sector; Penaud et al., 2020). For the two latter sediment sequences, AMS-^{14}C dates were calibrated according to the same procedure as described above (i.e. the rbacon package in R version 4.3.0 with IntCal20), taking no age reservoir into account for dates acquired on the PM continental core (age-depth model performed in this study thanks to AMS-^{14}C dates of Fernane at al., 2014) and -400 years for those acquired on the CBT-CS11 marine core (see David et al., 2022 : age-depth model recently updated thanks to AMS-^{14}C dates of Penaud et al., 2020).

3.3. Sedimentological and palynological analyses

Regarding core PALM-KS05 (BH), sedimentological analyses and X-ray radiography were previously carried out and presented in Ehrhold et al. (2021). For core 'PALM-KS06 (BH), grain-size analyses on the total and $CaCO_3$-free sediment fractions as well as total organic carbon (% TOC) and calcimetry (% $CaCO_3$) data were acquired. The detailed methodology is presented in Valero et al. (2024 – PART I).

Also, a total of 63 samples (33 for core PALM-KS06 and 30 for core PALM-KS05) were analysed for palynological analyses. For both dinocyst and pollen extraction, the palynological procedure carried out at the Geo-Ocean Laboratory (IUEM, Plouzané) is detailed in Valero et al. (2024 – PART I).

Pollen taxa were grouped according to their ecological affinities defined by Quéré et al. (2008) and previous studies on BB paleoenvironments (Lambert et al., 2018, 2019, 2020) : riparian taxa (*Alnus*, *Salix*, *Fraxinus*), arboreal taxa (AP) without *Alnus* (*Pinus*, *Abies*, *Taxus*, *Quercus*, *Corylus*, *Hedera*, *Betula*, *Fagus*, *Carpinus*, *Tilia*, *Ulmus*, *Ilex*, *Populus*, *Acer*, *Castanea*), ruderal-adventitious taxa (*Centaurea*, *Mercurialis*, *Rumex*, Urticaceae, Asteroideae, Cichorioideae, *Plantago lanceolata*), and cultivated taxa (*Cerealia*-type and *Fagopyrum*). Dinocyst taxa were grouped by their ecological affinities according to Penaud et al. (2020): estuarine (*Lingulodinium machaerophorum*), coastal (cysts of *Pentapharsodinium dalei*, *Polysphaeridium zoharyi*, *Spiniferites belerius*, *Spiniferites bentorii*, *Spiniferites lazus*, *Spiniferites membranaceus*), and Iroise Sea (*Achomosphera* sp., *Operculodinium centrocarpum*, *Spiniferites delicatus*, *Spiniferites elongatus*, *Spiniferites ramosus*), as well as strict heterotrophic taxa (*Brigantedinium* sp., *Echinidinium* sp., *Lejeunecysta* sp., cysts of *Protoperidinium nudum*, *Selenopemphix nephroides*, *Selenopemphix quanta*, *Stelladinium* sp., *Trinovantedinium applanatum, Xandarodinium xanthum*).

4. Bay of Brest past landscapes: natural vs. anthropic impacts over the last 7 kyrs

4.1. The building of a composite palynological stack

The new analysed samples from cores PALM-KS06 and PALM-KS05 (BH area) have been plotted along the previous published ones from cores 'G' and KS02 (Figure 2) in order to visualize : i) the contribution of the data compiled per core and per studied area (BH : blue colour; PP : brown colour) and ii) the good reproducibility of the signatures reconstructed on 2 records (PP vs. BH records on the 1.4–0.8 ka BP interval) located west of the limits of river-induced palynological signal (RIPS in Valero et al., 2024 – PART I).

Considering the overall spatial homogeneity of the BB palynological records shown through both modern (Lambert et al., 2017; Valero et al., 2024 – PART I) and Holocene (Valero et al., 2024 – PART I; Figure 2) sediments, it appears that: i) the BB is a sedimentary basin suitable for reconstructing paleoenvironments, ii) special caution must be taken with regard to river mouth environments where some palynological signals are highly prevalent (such as *Alnus* and *Corylus* for pollen, and *L. machaerophorum* for dinocysts). On the strength of these recommendations, we performed a palynological stack of Holocene BB palynological records over the last 7 kyrs, with a mean resolution of 35 years (Figure 3). This reconstruction stacked: i) a Mid-Neolithic interval (core 'A', BR: data from Lambert et al., 2019), ii) the transition between the Final Neolithic and the Early Bronze Age (core PALM-KS06, BH: new data), and iii) the period covering the Second Iron Age to the early Middle Ages (cores 'G' and KS02, PP: data from Lambert et al., 2020). The stack excludes Holocene BB cores located east of river-induced palynological signal limits (Aulne river sector; cf. Valero et al., 2024 – PART

I) as well as the new palynological data from core PALM-KS05 that were previously used for spatial comparison in Valero et al. (2024 – PART I) and that overlap an interval already described by the two cores from the PP area (Lambert et al., 2020).

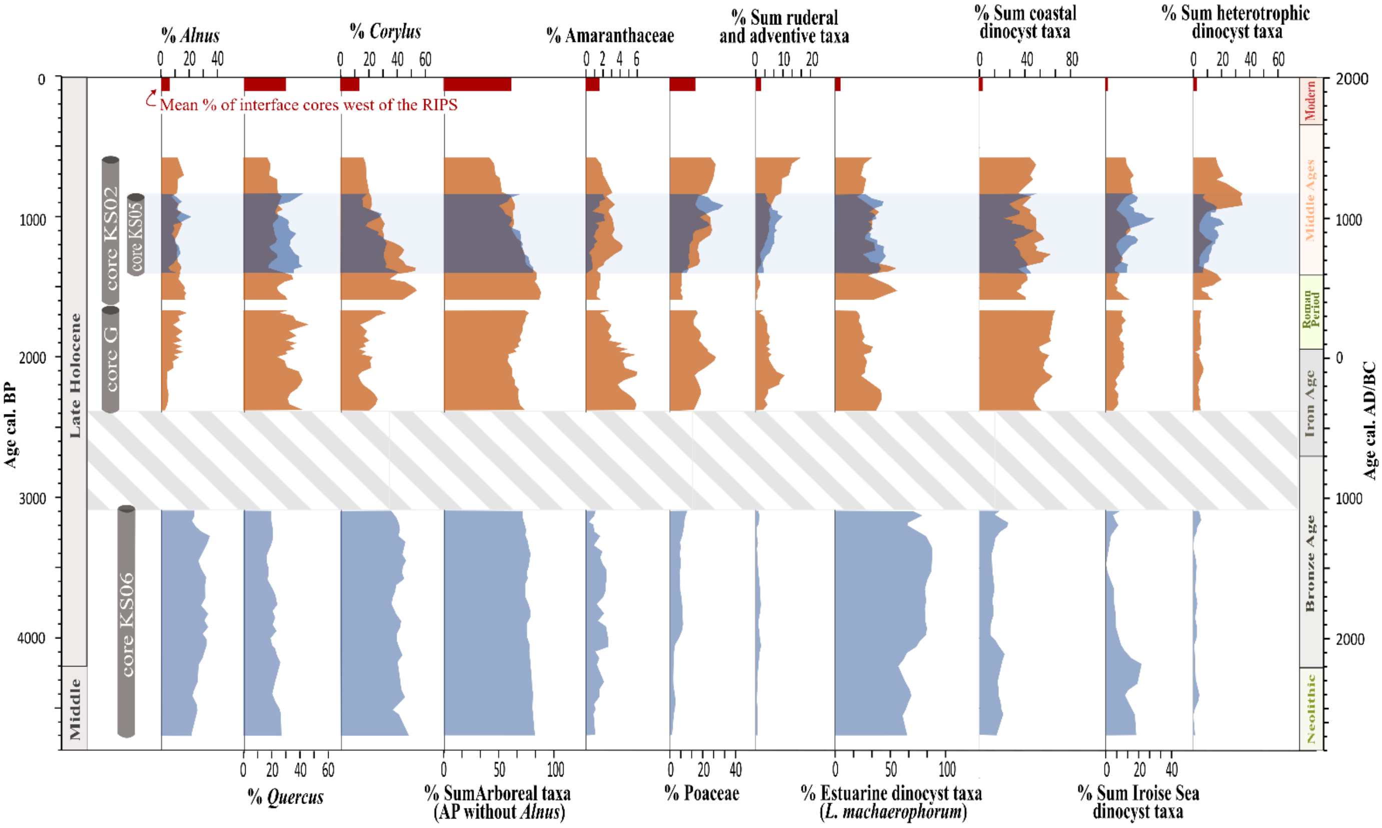

Figure 2. Percentages and concentrations of palynological data from two sectors of the Bay of Brest: south of Plougastel Peninsula (PP) sector in orange (cores 'G' and KS02) and Brest harbour (BH) sector in blue (cores PALM-KS05 and PALM-KS06). Mean of palynological percentages of interface cores situated west of the located west of the limits of river-induced palynological signal (RIPS in Valero et al., 2025 – PART I) are also indicated to provide a modern reference. The grey striped band highlights a major gap not available for the building of the palynological stack.

4.2.The Neolithic in the Bay of Brest (6.6–5.8 ka BP / 4.6–3.9 ka BC)

Between 6.6 and 5.8 ka BP (4.6–3.9 ka BC), in the context of sea level rise stabilization (García-Artola et al., 2018), the *Alnus* percentages are starting to increase (Figure 3e) in relation to the colonization of BB river banks and, more generally, of the alluvial plains and marshes of western France (David, 2014; Penaud et al., 2020; David et al., 2022), a trend that continues throughout the Middle Holocene. The strengthening of the palynological estuarine signature in BB sediments is also attested by the increasing trend in *L. machaerophorum* percentages

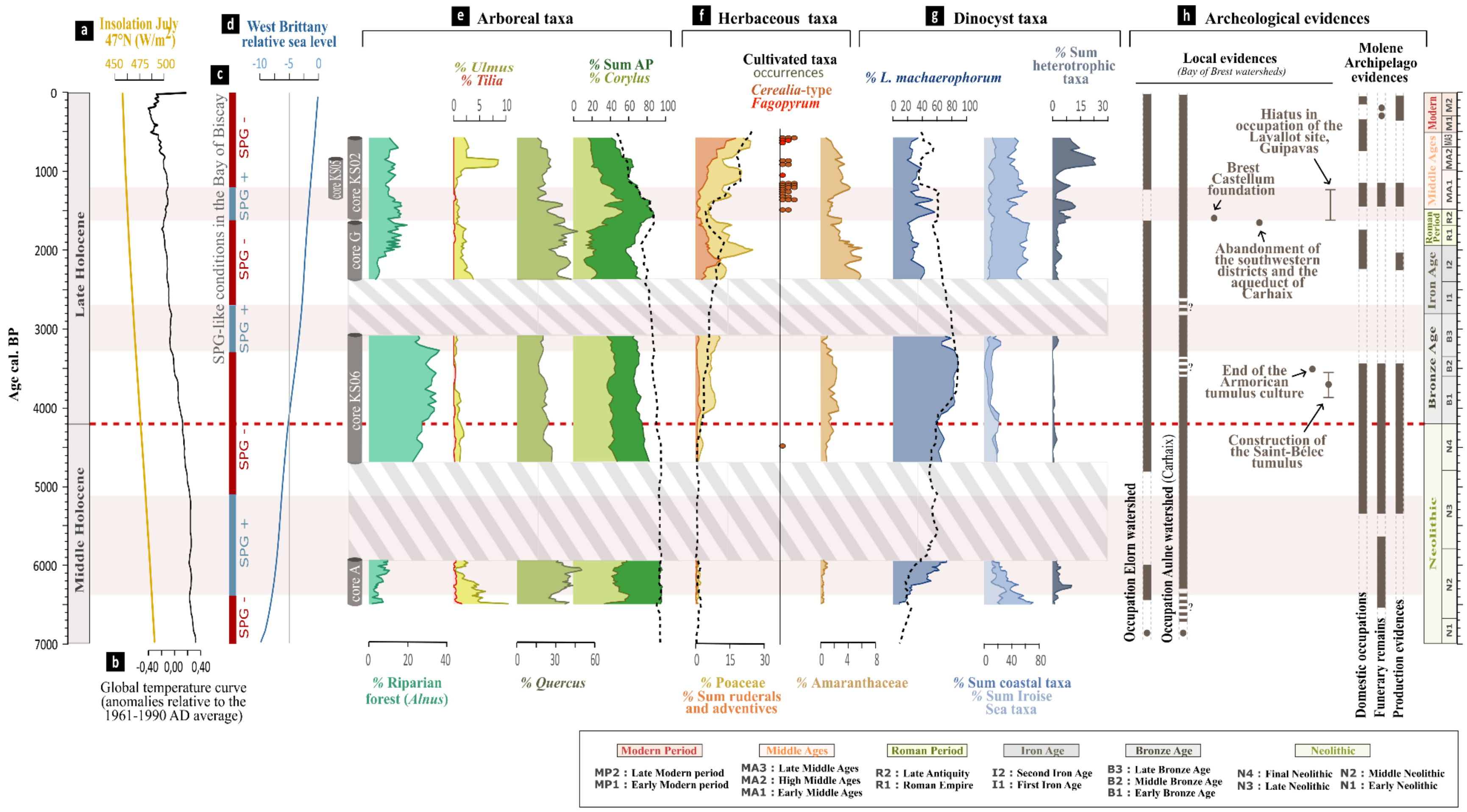

Figure 3. Holocene stack of palynological records (with different scales for the representation of pollen and dinocyst taxa percentages) from the Bay of Brest (BB; (e) and (f): pollen percentages without Alnus and (g): dinocyst data for cores ‘A’, PALM-KS05, PALM-KS06, KS02 and ‘G’) along Northern Hemisphere or global palaeoclimatic reconstructions: (a) summer insolation at 47°N (Berger and Loutre, 1991), (b) global temperature curve (Marcott et al., 2013), (c) subpolar gyre dynamic (pink bands represent SPG-like positive periods; Penaud et al., 2020), (d) relative sea level for western Brittany (García-Artola et al., 2018) and (h) archaeological data (from Galliou, 2010; Galliou and Simon, 2015; Nicolas and Pailler, 2023; Pailler et al., 2015) and occupation synthesis for BB watersheds (Elorn watershed with the sites of Guipavas, St-Divy, Plouedern and Landerneau; Blanchet, 2022; Dieu et al., 2018; Hamon, 2023; Pailler, 2014; Roy, 2010a, 2010b; Simier, 2017; and Aulne watershed with the site of Carhaix; Cousseau, 2020, 2021; Fily, 2012, 2022; Gandini et al., 2022; Le Cloirec, 2008; Raudin, 2020; Toron, 2013) and Molène archipelago (Pailler and Nicolas, 2019). All these data are presented alongside chronological boundaries of archaeological and historical periods in western France (adapted from Gorczyńska et al., 2023). Palynological data from core CBT-CS11 (Penaud et al., 2020) are also represented with black dotted lines for (e) sum of arboreal, (f) Poaceae and (g) L. machaerophorum percentages, highlighting regional changes for western French paleoenvironments. The grey striped bands highlight the two gaps in our vertical Holocene reconstruction.

(Figure 3g), echoing the regional model discussed at the scale of the southern Brittany shelf under the fluvial dynamics of the Loire river (superimposed black dashed curve in Figure 3g: Penaud et al., 2020). At that time, the thermophilous taxa *Ulmus* and *Tilia* declined in the context of the end of the Holocene climatic optimum (Lambert et al., 2019; Figure 3e), which was characterized by an overall decrease in Northern Hemisphere temperatures (Marcott et al., 2013; Figure 3b), mainly driven by the long-term decreasing trend of summer insolation at 65°N (Berger and Loutre, 1991; Figure 3a).

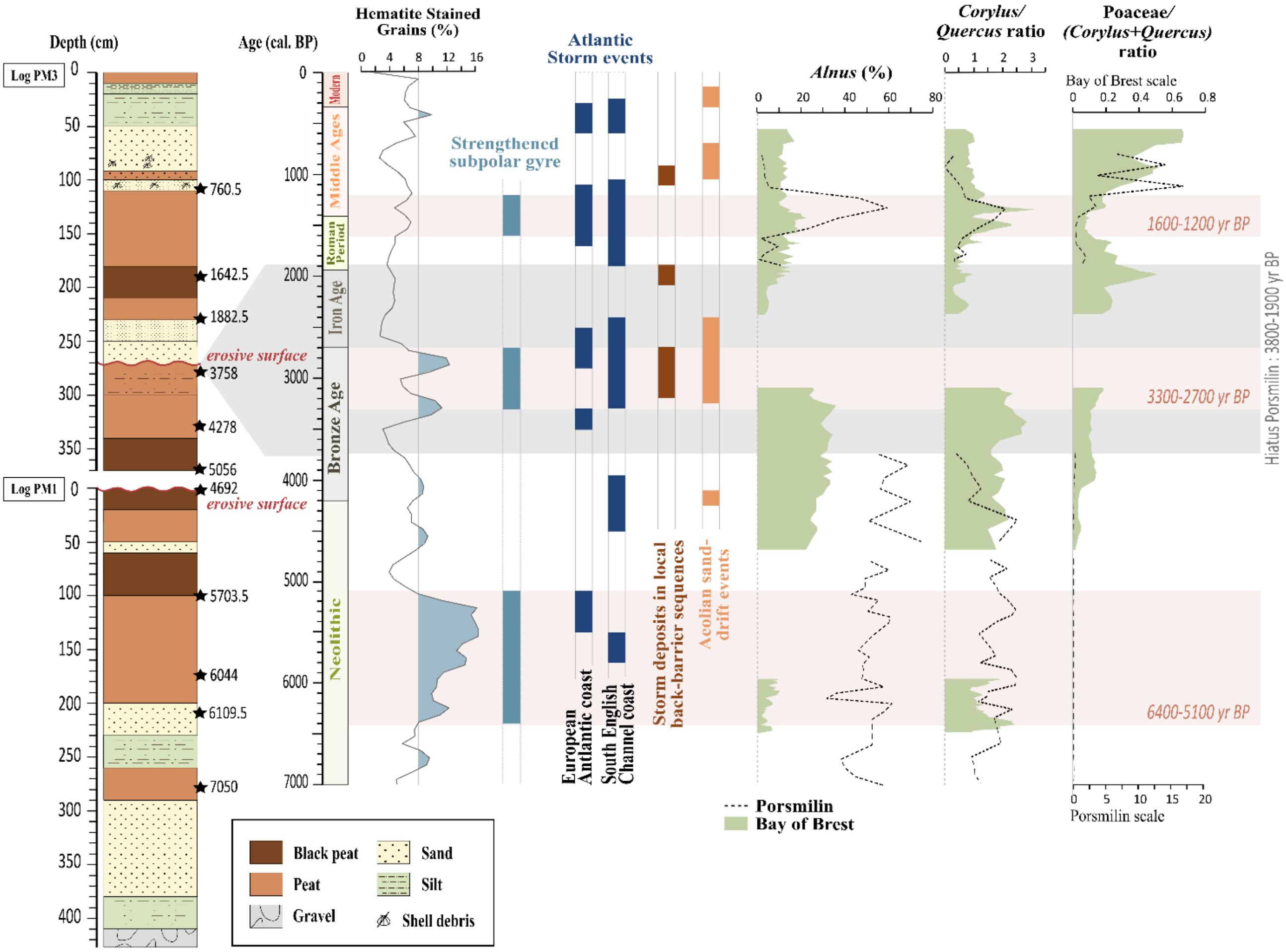

Figure 4. Comparison between palynological data from the Bay of Brest (BB) and Porsmilin (PM1 and PM3; Fernane et al., 2014) stacks, represented along updated PM1-PM3 stratigraphic logs as well as palaeoclimatic data for the North Atlantic: (i) detrital grain percentages (Bond et al., 2001), (ii) subpolar gyre dynamic (pink bands represent SPG-like positive periods; Penaud et al., 2020), (iii) Atlantic storm event reconstructed for the European Atlantic coast (Pouzet et al., 2018) and South English Channel coast (Sorrel et al., 2012), (iv) storm deposits in back-barrier sediment sequences around BB (i.e. Troaon, Arun and Loc'h sequences; Stéphan et al., 2015; Stéphan and Laforge, 2013) and (v) Aeolian sand-drift events for western Brittany (Gorczyńska et al., 2023).

During this Mid-Holocene interval, arboreal pollen taxa represent ~95% of pollen assemblages and are mainly characterized by *Corylus* and *Quercus* (Figure 3e), confirming that the landscape surrounding the BB was dominated by woodlands, with *Corylus* probably occupying the drained slopes of the BB watersheds, as has also been discussed for the regional level (Gaudin et al., 2008; David, 2014; Fernane et al., 2014; Lambert et al., 2019; David et al., 2022; black dashed curve in Figure 3e: Penaud et al., 2020). Even though tree taxa percentages remain stable, it is noteworthy that the two main tree taxa show a pronounced anti-correlation during this period, characterized by an increase in *Corylus* and a decrease in *Quercus* and *vice versa*, superimposed on a trend still dominated by *Corylus* trees (Figures 3e and 4). These Mid-Holocene infra-millennial oscillations are reminiscent of the ones previously discussed at Porsmilin (PM), where the amplifications of the *Corylus* signal were suggested to be related to climate phases of winter humidity increase over western Brittany (Fernane et al., 2014; cf. *Corylus*/*Quercus* or C/Q ratio oscillations in Figure 4). In our pollen record, the C/Q ratio is also fluctuating over the 6.6–5.8 ka BP (4.6–3.8 ka BC) time window. Interestingly, *Corylus* percentages fell as well as the C/Q ratio between 6.2–5.9 ka BP (4.2–3.9 ka BC) quite synchronously with a short drop of *Alnus* percentages and of the C/Q ratio in the PM core (Figure 4). This may correspond to a slightly drier period over the interval (Bond et al., 2001; Naughton et al., 2007) as also suggested with previous BB cores (Ehrhold et al., 2021). Regarding the spatial comparisons we performed at different timescales based on modern and Holocene BB sediments (Valero et al., 2024 – PART I), we argue for a modulation of the higher C/Q ratio, either in the BB as a whole or just at PM (see Figure 4), by increasing winter floods in northern Europe, which supports a regional hydro-climatic forcing hypothesis rather than an anthropic one (Joly and Visset, 2009).

Regarding human occupation of the BB watersheds during this Neolithic period, anthropogenic pollen indicators are not clearly seen either in our BB record or in PM (Fernane et al., 2014), despite obvious archaeological evidence of the development of agriculture by Neolithic communities in western Europe (Childe, 1952; Demoule, 2007; Pailler et al., 2008). Indeed, although early Mesolithic proto-agriculture has been hypothesized locally in north-western France, these instances remain rare and debated (Visset et al., 2002; Joly and Visset, 2009; Lambert et al., 2019). Until the end of the first half of the Neolithic period, this lack of evidence of agro-pastoralism in our pollen assemblages could reflect : i) the limited size of the first agricultural areas in favour of pastoralism in parallel with the continued exploitation of natural resources (Entwhislte and Grant, 1989; Stevens and Fuller, 2012), ii) a strong dilution of cultivated taxa in BB sediments due to the small size of the study area and/or the distance from pollen sources, or iii) identification issues regarding pollen grains of *Cerealia* due to ambiguous and still debated morphometric criteria (see Lambert et al., 2019, unpublished data), including large uncertainties regarding the discrimination of cultivated vs. wild Poaceae based on the size of the pollen grain and of its annulus diameter (Lambert et al., in prep.).

4.3.Between the Neolithic and Bronze Age periods, a paleoenvironmental and societal shift in several stages (4.8–3 ka BP/ 2.8–1 ka BC)

The 4.2 ka BP (2.2 ka BC) threshold is characterized by both climatic (Middle-Late Holocene) and cultural (Neolithic-Bronze Age) transitions. This limit is detected in our study by a decrease of arboreal taxa percentages (Figure 3e), in parallel with an increase in both Poaceae values and anthropogenic pollen indicators (i.e. ruderal-adventitious taxa) (Figure 3f), and attests to landscape opening, as discussed locally approximately at the same time for PM (Fernane et al., 2014), as well as at the regional scale of Brittany (e.g. Morzadec-Kerfourn, 1974; Gaudin, 2004; David, 2014; Fernane et al., 2015; David et al., 2022, 2024) and in western France (Penaud et al., 2020).

In the BB, arboreal pollen taxa seem to decrease before the major transition recorded here, dated around 4.1 ka BP (2.1 ka BC; Figure 5), and the landscape seems to open unevenly between 4.8 and 3 ka BP (1 ka BC). Until 4.1 ka BP, there is a consistent decline in the forest (i.e. both *Corylus* and *Quercus*, Figures 3e,5f), accompanied by a relatively modest rise in Poaceae and the detection of very low proportions of ruderal-adventitious taxa (i.e. *Centaurea*, *Mercurialis*, *Rumex*, Urticaceae, Asteroideae, Cichorioideae, *Plantago lanceolata*; Figure 5h). This early but relatively slow landscape transformation is concomitant with the development of the Bell Beaker culture (the first metal-working society) in western Brittany during the Final Neolithic (for BB watersheds, see Le Goffic, 1994; Blanchet, 2013; Toron, 2013; Pailler et al., 2015). It also corresponds to very high pollen concentrations (Figure 5i) and a significant rise in riparian tree percentages (Figure 5d). This rise occurs synchronously with the Bond 3 event (4.5–4 ka BP / 2.5–2 ka BC, Figure 5b; Bond et al., 2001), in a climate context likely corresponding to an increase in humidity and storminess.

From 4.1 ka BP (2.1 ka BC; yellow band in Figure 5), at the onset of the Early Bronze Age, a major shift is recorded in pollen data marked by a sharp increase in Poaceae and ruderal-adventitious taxa, accompanied by a drastic fall in palynomorph concentrations.

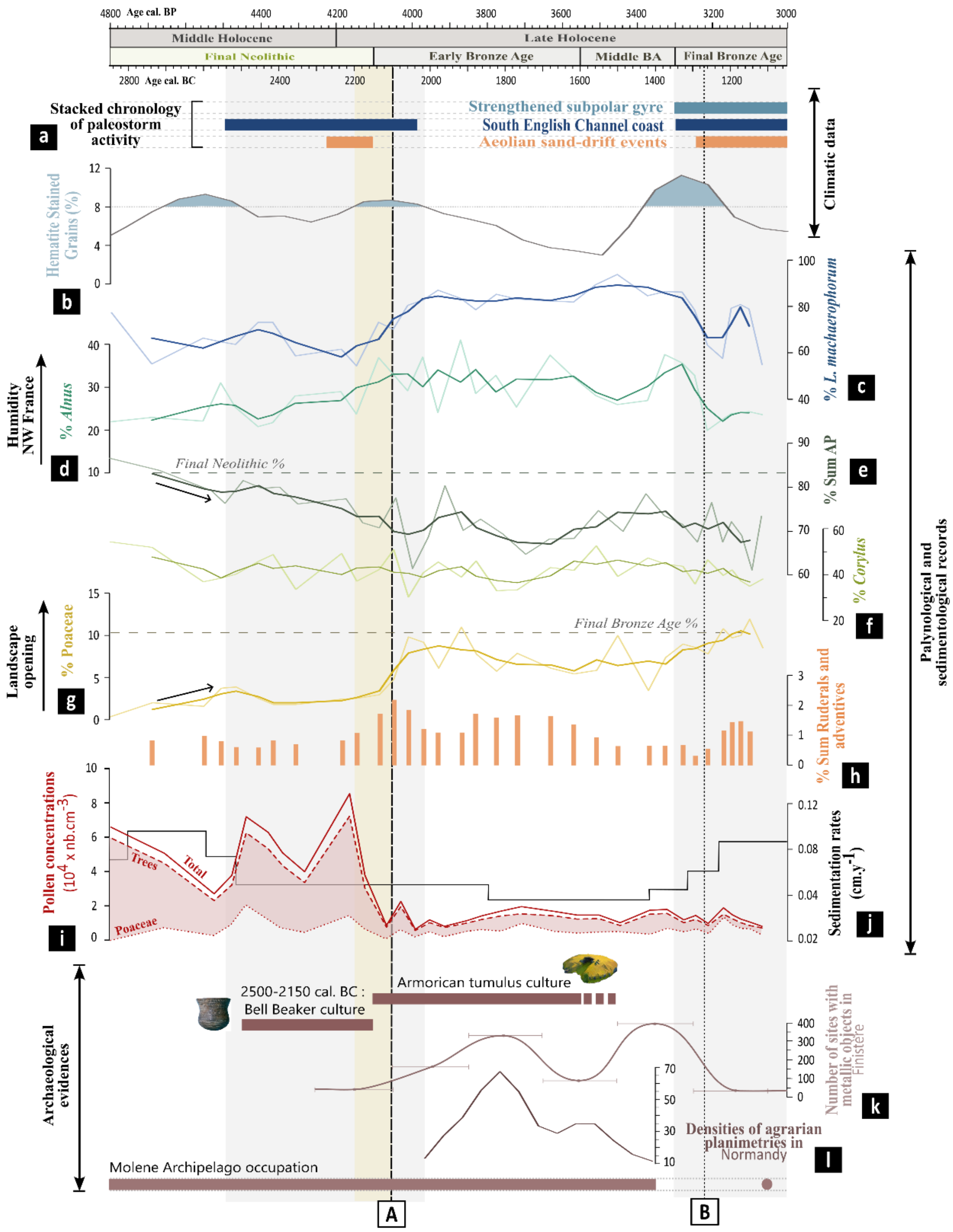

Figure 5. Comparison of palynological and sedimentological signals for the Neolithic-Bronze Age transition (4.8–3 ka BP interval covered by core PALM-KS06) with palaeoclimatic records from the North Atlantic: (a) stacked chronology of paleostorm activity (Gorczyńska et al., 2023; Penaud et al., 2020; Sorrel et al., 2012) and (b) detrital grain percentages (Bond et al., 2001). Main results from the study sequence: (c) percentages of the dinocyst L. machaerophorum, (d) percentages of Alnus, (e) sum of tree pollen percentages, (f) percentages of Corylus, (g) percentages of Poaceae, (h) sum of ruderal-adventive taxa percentages (represented as a histogram as few specimens were counted), (i) concentrations of total pollen, as well as tree and Poaceae taxa (the difference between arboreal and Poaceae concentrations is highlighted with a coloured red area) and (j) sedimentation rates. (c)–(g): raw palynological data with thin coloured curves and 3-point moving average palynological data with thicker coloured lines. The dotted horizontal lines for % sum AP (e) and % Poaceae (g) highlight the differential

between the values found at the beginning (% Final Neolithic) and end (% Final Bronze Age) of the sequence. Archaeological markers are also represented in parallel, including: (k) the number of sites with metallic objects in Finistere (Gabillot et al., 2004) and (l) the density curve of agrarian planimetries in Normandy (Marcigny, 2022). Light grey bands highlight intervals likely characterized by stronger storminess phases. The yellow band highlights the period of transition in our data around 4.1 ka BP. The main limits between palynozones (i.e. limits A and B: cf. Valero et al., 2025 – PART I) have also been highlighted.

The latter observation is probably linked with a change in sedimentation (from fine to coarser sediments, Valero et al., 2024 – PART I: cf. limit A in Figure 3B). However, even though total tree and Poaceae concentrations follow strictly the same trends (sedimentation effect), and total concentrations are particularly explained by trees, there is a marked difference between the tree and Poaceae concentrations before (mean difference of 38,000 grains cm^{-3}) and after (8,000 grains cm^{-3}) 4.1 ka BP (2.1 ka BC). This could be explained by a reduction in tree pollen influxes to the BB, reflecting a significant development dynamic that started with the Bell Beaker and hugely accelerated with Early Bronze Age societies (Armorican tumulus culture, Figures 5) in BB watersheds (for example, in the site of the Saint-Bélec tumulus in the south of the Aulne river : Nicolas and Pailler, 2023). In fact, a large number of funerary sites (barrows and cemeteries with graves), settlements, field systems and plough marks dating from this period have been documented, particularly in the sectors located upstream from the rivers (i.e. north Elorn, or *Monts d'Arrée*: Briard et al., 1994; Fily, 2008; Blanchet, 2013; Nicolas, 2016) and on the Molène archipelago (Figure 3h; Pailler and Nicolas, 2019, 2023, 2024).

Then, the opening of this increasingly structured landscape appears to stabilize for several centuries until the beginning of the Middle Bronze Age (3.6–3.5 ka BP / 1.6–1.5 ka BC), where a slight re-increase in forest cover (10–15%) is observed, occurring within the context of a climatic cooling (Magny, 2004) and a significant change in land occupation (i.e. 1.7–1.4 ka BC interval) as also observed at European scale (Demény et al., 2019; Molloy et al., 2023). In fact, during this period, a number of factors seem to point to a restructuring of societies in north-western France, such as a decrease in the density of agrarian planimetrics in Normandy (Marcigny, 2022, Figure 5l), a reduction in the number of metal sites recorded in Finistère (Gabillot et al., 2004, Figure 5k), the gradual decline of the Armorican elites and also the emergence of cremation as a new funeral practice. It is not until the Late Bronze Age (~ 3.2 ka BP / 1.3 ka BC, limit B in Figure 5) that clearings seem to resume in our assemblages with the increase of Poaceae taxa, although evidence of agro-pastoralism and cultivation remains very limited. This discrepancy between the highly localized archaeological findings, based on the study of burnt seed remains, and paleoenvironmental reconstructions, suggests a bias in the transport of agricultural pollen signals from a landscape environment where cultivated areas would still be disconnected from the main rivers feeding the BB.

4.4.A significant sedimentary gap at the end of the Bronze Age (3–2.4 ka BP / 1–0.4 ka BC)

The final pollen stack is characterized by two major gaps. The first of these (5.9–4.8 ka BP / 3.9–2.8 ka BC; striped band in Figure 3) is explained by a deposition dominated by sandy sediments that prevents us from conducting palynological analysis (cf. sandy interval described in Valero et al., 2025 – PART I: cf. Figure 3A). At that time, successive deposits of tidal bars were described continuously between 6.8 and 3 ka BP; Gregoire et al., 2017). The second gap (3–2.4 ka BP / 1–0.4 ka BC; striped band in Figure 3) deserves particular attention because it coincides not only with erosional surfaces or high-energy deposits in BB sediments for the interval (i.e. maximum flooding surface described by Gregoire et al., 2017; Ehrhold et al., 2021) but also to a hiatus in the PM record (3.8–1.9 ka BP / 1.8–0 ka BC; Fernane et al., 2014; Figure 4) and in the sedimentary sequences of the back-barrier marshes (2.9–2.7 ka BP / 0.9–0.7 ka BC; Stéphan and Laforge, 2013; Stéphan et al., 2015; Figure 4), with marked erosive surfaces and washover deposits. This interval is centred around an important threshold of sea level rise stabilization (3–2.5 ka BP / 1–0.5 ka BC; García-Artola et al., 2018), which was a period of reduced accommodation space, i.e. a reduced space available for the deposition of sediments in the BB (Gregoire et al., 2017). In addition, the period around 3 ka BP (1 ka BC) has been widely recognized as a period of climate deterioration across north-west Europe (Geel et al., 1996; Barber et al., 2003, 2004; Magny, 2004; Tisdall et al., 2013), especially characterized by an increase in storminess (Stéphan et al., 2011; Sorrel et al., 2012; Pouzet et al., 2018; Figure 4). Major disturbances to coastal sedimentary environments have also been identified along the European coasts, both in the English Channel sector (Sorrel et al., 2009; Tessier et al., 2012) and along the Atlantic coast (Pontee et al., 1998; Moura et al., 2007; Sorrel et al., 2009). Archaeological evidence suggests that there were less dense settlement patterns at this time at the end of the Late Bronze Age (Coquillas, 2001; Pailler et al., 2011; Stéphan et al., 2011) as well as abandonments of several sites on low-lying coastal areas such as observed for the Molène archipelago (Figure 3h), notably due to a major aeolian event in north-western European coastal areas (Fernane et al., 2014; Tisdall et al., 2013; Gorczynska et al., 2023).

Nevertheless, it seems that this extreme event had less impact on populations installed further inland (Figure 3h) and was therefore concentrated in areas very close to the coast.

4.5.From the Iron Age to the Middle Ages (2.4–0.6 ka BP / 0.4–1.4 ka AD): climatic and anthropic impacts

After the major sedimentary hiatus, the second Iron Age (Figure 3) is characterized by an intensification of landscape opening (Figure 3e,f), which is part of a regional scale dynamic (Marguerie, 1991; Gaudin, 2004; Van Beek et al., 2018; Penaud et al., 2020), concomitant with the intensification of the metallurgic economy. This increasing anthropic pressure occurred in the context of spreading agriculture and the development of an iron and salt economy that was particularly marked in Brittany at the end of the Iron Age (Sanquer and Galliou, 1972; Daire, 1994; Menez and Lorho, 2013; Gandini et al., 2022). The Armorican settlements then developed on a new economic model based on agriculture during the Gallo-Roman period. The rural areas therefore remained relatively prosperous until around 1.7 ka BP (0.3 ka AD) when the situation deteriorated. In fact, in addition to a significant reduction in the density of archaeological evidence dating from this period, several *villae* (i.e. agricultural sites and resorts for wealthy citizens) around the BB were abandoned in a context of invasions and internal troubles during the Late Antiquity (Galliou, 1991; Galliou and Simon, 2015; Dieu et al., 2018; Figure 3h). At the same time, our palynological records are marked by a significant recovery in forest cover at Mesolithic rates, mainly driven by *Corylus*, and coinciding with a decrease in Poaceae and ruderal-adventitious taxa (Figure 3e,f). This 'arboreal pollen rise event' straddling the Late Antiquity and the Early Middle Ages (1.7–1.2 ka BP / 0.3–0.8 ka AD; Lambert et al., 2020), was previously discussed in relation to concomitant climate degradation, with positive NAO-like conditions (i.e. increase in winter precipitation regimes and storminess over northern Europe; Sorrel et al., 2012; Stéphan and Laforge, 2013; Stéphan et al., 2015; Pouzet et al., 2018; Penaud et al., 2020; Figure 4), confirmed by the parallel increase in fluvial discharge signals (i.e. *Alnus* and *L. machaerophorum;* Figure 3e,g) in western Brittany (Fernane et al., 2014; Lambert et al., 2020). As previously discussed by Lambert et al. (2020), it may have resulted from a superimposition of European climatic (i.e. Büntgen et al., 2011, 2016) and anthropogenic factors such as also discussed in north-western Europe for the best documented regions from an archaeological point of view (e.g., Gandini, 2008; Gandini et al., 2012), although it is difficult to determine any prevalence or clear causal relationship between these two forcings (Ouzoulias et al., 2001; Harper, 2016). Once the climatic conditions became favourable during the High Middle Ages (Figure 3), a decrease in sediment fluxes is recorded in the southern BB (Ehrhold et al., 2021) associated with a new boom in agriculture marked by the appearance of cultivated pollen (*Cerealia*-type and *Fagopyrum*) in our pollen assemblages (Figure 3f), accompanied by a significant and rapid retreat of the forest cover (Figure 3e). Finally, by the Late Middle Ages, this dynamic led to a landscape fairly similar to modern-day conditions (i.e. limited woodlands and well-developed agricultural areas; Lambert et al., 2017).

5. Conclusion

The present study focuses on the Bay of Brest (BB), a macro-tidal estuarine area of north-western France characterized by the dual influence of both oceanic currents and fluvial discharges, resulting in complex hydro-climatic and hydro-sedimentary processes varying through time. Sedimentation inputs in the BB have been mainly driven by natural climate oscillations (through varying precipitation regimes and related seasonal fluvial discharges) as well as by human practices on BB watersheds (human dynamics inherited from cultural changes over time). Also, because the shallow BB (8 m deep on average) has been subject to the Holocene rise in relative sea level, progressively flooding paleoriver terraces, several sediment cores were required to reconstruct the long-term environmental trajectory of BB paleoenvironments across the Holocene. In this study, two BB cores (PALM-KS05 and PALM-KS06) were examined by performing new palynological (pollen and dinoflagellate cyst) analyses, which were considered in addition to previously published data acquired on three other BB cores published in Lambert et al. (2019, 2020).

We performed an unprecedented palynological reconstruction of Holocene BB paleoenvironments from 7 ka BP to the end of the Middle Ages at 35 years resolution in average. However, two gaps (5.9–4.8 ka BP / 3.9–2.8 ka BC and 3–2.4 ka BP / 1–0.4 ka BC) are recorded in our composite sequence due to either erosional surfaces or high-energy sandy deposits previously documented in sedimentological studies. The final reconstruction also contributes new information on the Middle to Late Holocene transition corresponding to the major Neolithic-Bronze Age cultural transition never previously studied in this estuarine environment. The composite record highlights that the main anthropic influence (especially through the opening of the landscape) is not obvious before 4.1 ka BP (2.1 ka BC; Early Bronze Age) in the BB. The rate of this opening was not constant but punctuated by a number of steps: the forest cover first gradually declined at the end of the Neolithic, then strongly decreased at the end of the Iron Age before experiencing a revival of about five centuries at the end of the Roman period, echoing climatic deterioration combined with unfavourable geopolitical circumstances. Finally, a drastic fall in the forest cover occurred at the start of the Middle Ages. This study allows emphasizing the Holocene discussion between paleoenvironments, past climate pressures and human populations thanks to the inclusion of an up-to-date corpus of archaeological data restricted to the study area. It will provide a solid base for future discussions between specialists in archaeology and in paleoenvironmental studies.

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7. Data availabitity

All the data acquired on Bay of Brest cores (Holocene and modern surface sediments), and those discussed in the manuscript (Porsmilin cores PM1 and PM3) are available in the SEANOE repository: https://doi.org/10.17882/99422.

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