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A. Fernane, Emmanuel Gandouin, Aurélie Pénaud, Brigitte van Vliet-Lanoë, Jean Goslin, et al.. Coastal palaeoenvironmental record of the last 7 kyr BP in NW France: Sub-millennial climatic and anthropic Holocene signals. *The Holocene*, 2014, 24 (12), pp.1785-1797. 10.1177/0959683614551223 . insu-01100322

HAL Id: insu-01100322

<https://insu.hal.science/insu-01100322>

Submitted on 15 Oct 2018

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Coastal palaeoenvironmental record of the last 7 kyr BP in NW France: Sub-millennial climatic and anthropic Holocene signals

Assia Fernane,^{1,2} Emmanuel Gandouin,² Aurélie Penaud,¹ Brigitte Van Vliet-Lanoë,² Jérôme Goslin,¹ Muriel Vidal¹ and Christophe Delacourt¹

Abstract

To date, Holocene palaeoecological signatures on the Northwestern coast of France have not been thoroughly investigated. In this study, environmental changes related to both climate processes and human disturbances were reconstructed over the last 7000 cal. yr BP, based on pollen and chironomid assemblages from four coastal cores retrieved in Western Brittany (Porsmilin beach, NW France). Pollen and chironomid records show an environmental response to both millennial- and centennial-scale climate changes. During the mid-Holocene (until around 4200 cal. yr BP), when human impact was low, Porsmilin's landscape was characterized by a mixed oak forest dominated by *Corylus* trees. Comparison of our data with other palynological data from the NW French Atlantic coast shows that this dominance may be related to more humid conditions prevailing at Porsmilin. Furthermore, over the mid-Holocene, *Corylus* and *Quercus* patterns appear anti-correlated, with *Quercus* declines appearing synchronous with major storms revealed by data recently compiled for the Holocene in Brittany, suggesting that cold conditions probably caused the *Quercus* contractions, which in turn favoured the rise of the heliophile taxon *Corylus*. Regarding chironomids over this period, our results show variations in lotic–lentic taxa related to hydrological conditions, more specifically changes in river run off strength. Over the Late Holocene, the Porsmilin palynological record shows progressive vegetation changes mainly related to human settlement and development of agricultural activities.

Keywords

Brittany, chironomids, North Atlantic Oscillation, peat, pollen, storm events

Introduction

Climate in the Holocene has not been uniformly warm, but was instead influenced at an orbital scale by decreasing summer insolation in the Northern Hemisphere (Berger and Loutre, 1991), and punctuated by abrupt climatic events at millennial timescales (Mayewski et al., 2004). At sub-millennial timescales, as well as over the past two millennia, numerous climate reconstructions suggest various forcing mechanisms and climate feedbacks for Holocene climate fluctuations, generally involving North Atlantic Oscillation (NAO) modes, solar activity, ocean circulation or volcanic eruptions (Bond et al., 2001; Fletcher et al., 2013; Van Loon and Meehl, 2014; Wanner et al., 2008). Consequently, multidisciplinary palaeoclimate studies from different ecosystems are necessary to understand how these forcing mechanisms interact to define Holocene climate at a regional/global scale. At a local scale, multiproxy investigations are also crucial since some ecosystems, such as coastal ones, do not respond homogeneously to global changes, as suggested by Najjar et al. (2000).

In the northern part of Brittany, few palaeoenvironmental studies have been conducted, and have often applied a mono-disciplinary palynological approach (e.g. Giot and Monnier, 1972; Morzadec-Kerfourn, 1974; Van Zeist, 1963). However,

southern Brittany is well documented with continental (e.g. Barbier and Visset, 1997; Bernard, 1995; Gaudin, 2004; Joly and Visset, 2009; Visset et al., 1994) and marine (Naughton et al., 2007) palaeoenvironmental investigations. In this study, we present a multidisciplinary Holocene climate study based on pollen and chironomid (Insect, Diptera) analyses, as well as radiocarbon and lithological data from a Northwestern Brittany coastal area (Porsmilin (PM); NW France; 48°21'N). Studies associating chironomid and aquatic botanical proxies, both considered to be fast migrating biotic proxies, have increasingly been used in palaeoecological analysis of past environmental changes. Chironomids have emerged as promising tools for palaeoecological investigations. Their modern characteristic assemblages give diversified information such

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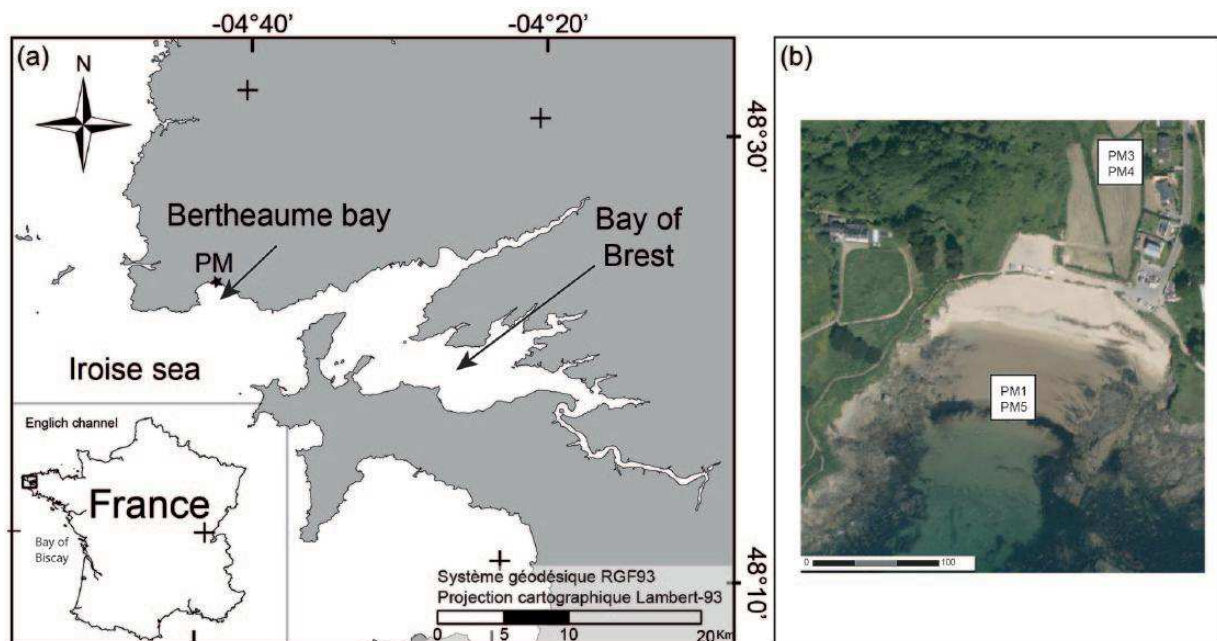


Figure 1. Location map of the Porsmilin (PM) study area: (a) Western France showing core sites; (b) sediment core locations.

as water trophic status (Walker and Mathewes, 1987), dissolved oxygen content (Francis, 2001), water-level change (Massafero and Brooks, 2002), types of alluvial habitats (Gandouin et al., 2006) and water (Rossaro, 1991) and air temperatures (Luoto, 2009). Their use has also enabled the successful detection of past human presence and its impact on water quality (Heiri and Lotter, 2003; Langdon et al., 2004; Ruiz et al., 2006; Taylor et al., 2013). Furthermore, pollen analysis can reveal climate variations and agro-pastoral activities over adjacent watersheds.

In this paper, we will attempt to decipher the respective influence of local versus regional/global factors over the last 7 kyr BP at PM, based on a cross-correlated pollen–chironomid analysis. At a regional scale, the present study constitutes the first coastal palaeoenvironmental investigations based on chironomids in Brittany. Furthermore, it should help improve palaeoecological knowledge of river chironomids.

Environmental setting and studied material

Sedimentary context

The PM beach is located in Northwestern Brittany within the Bay of Bertheaume and is surrounded by the Iroise Sea (Figure 1a). More precisely, our studied site is located at the outlet of a short valley and consists today of a sandy pocket beach surrounded by cliffs and limited landward by a high sandy coastal bar (Figure 1b). This geomorphological configuration encloses a marshy depression located at +6.5 m NGF (‘Nivellement Général de la France’ which is a French reference system for sea level elevation), crossed by a small stream that flows seaward. On the lower part of the beach, extensive thick layers of peat are exposed at low tide (Figure 1b), resulting from retrogressive erosion of sandy barriers.

The PM beach was cored with a 5 cm diameter percussion corer (Eikjelkamp). Twin cores were extracted in the marsh (PM3 and PM4; 48°21′24.88″N, 4°40′44.41″W; Figure 1b) and in the intertidal zone (PM1 and PM5; 48°21′18.67″N, 4°40′45.10″W; Figure 1b). The accessibility of the PM marsh did not allow us to drill intermediate cores to better constrain the geometry of the marsh infill.

Present-day climatic context and associated vegetation cover

The climate in Brittany is characterized by temperate oceanic conditions (because of the North Atlantic Ocean influence) with generally cool, rainy winters and fresh summers. Mean annual precipitation is close to 800 mm, and the mean annual temperature is around 11°C with weak thermic seasonal amplitudes. Meteorological conditions over Brittany mainly result from the NAO pattern (Hurrell, 1995). This natural pattern of atmospheric variability directly influences temperatures and hydrological conditions (precipitation, river discharges, and water table levels), which in turn influence vegetation cover (Gouveia et al., 2008).

Regarding current vegetation, the flanks of the PM valley are partly covered by a forest composed of *Quercus*, *Corylus avellana* and *Carpinus betulus*. The bottom of the valley is surrounded by woodlands dominated by *Salix fragilis* and several other herbaceous species such as *Cyperus longus*, *Juncus effusus*, *Limonium dodartii*, *Mentha suaveolens*, *Polygonum aviculare*, *Potentilla anserina* and *Rumex obtusifolius*.

Anthropogenic context

Brittany’s coasts are escarped, with intertidal zones that provide both shelter and fishery facilities which have favoured human settlement and economic development (Daire et al., 2011). Nevertheless, the human settlement chronology in Brittany is still obscure because of the scarcity of well-dated and continuous palynological records. In Southeastern Brittany, *Cerealia* pollen grains are sporadically recorded at the end of the Mesolithic and at the beginning of the Neolithic, indicating probable early human activity at that time (Ouguerram and Visset, 2001; Visset et al., 2002). In Northern Brittany, the earliest agricultural activities are marked by the presence of *Cerealia* and clearing events at the beginning of the Sub-Boreal period, that is, at the end of the Bronze Age (Barbier and Visset, 1997; Marguerie, 1992; Morzadec-Kerfour, 1974). The 1st millennium BC (i.e. from 3 kyr BP), covering the period of the late Bronze Age, the Iron Age and the first decades of the Gallo-Roman period, constitutes a key period concerning land use for agro-pastoral activities. Based on archaeological studies, human colonization of Northern Brittany at the beginning of the Bronze Age (4 kyr BP) appears conditioned by the presence of dense forest, with the first

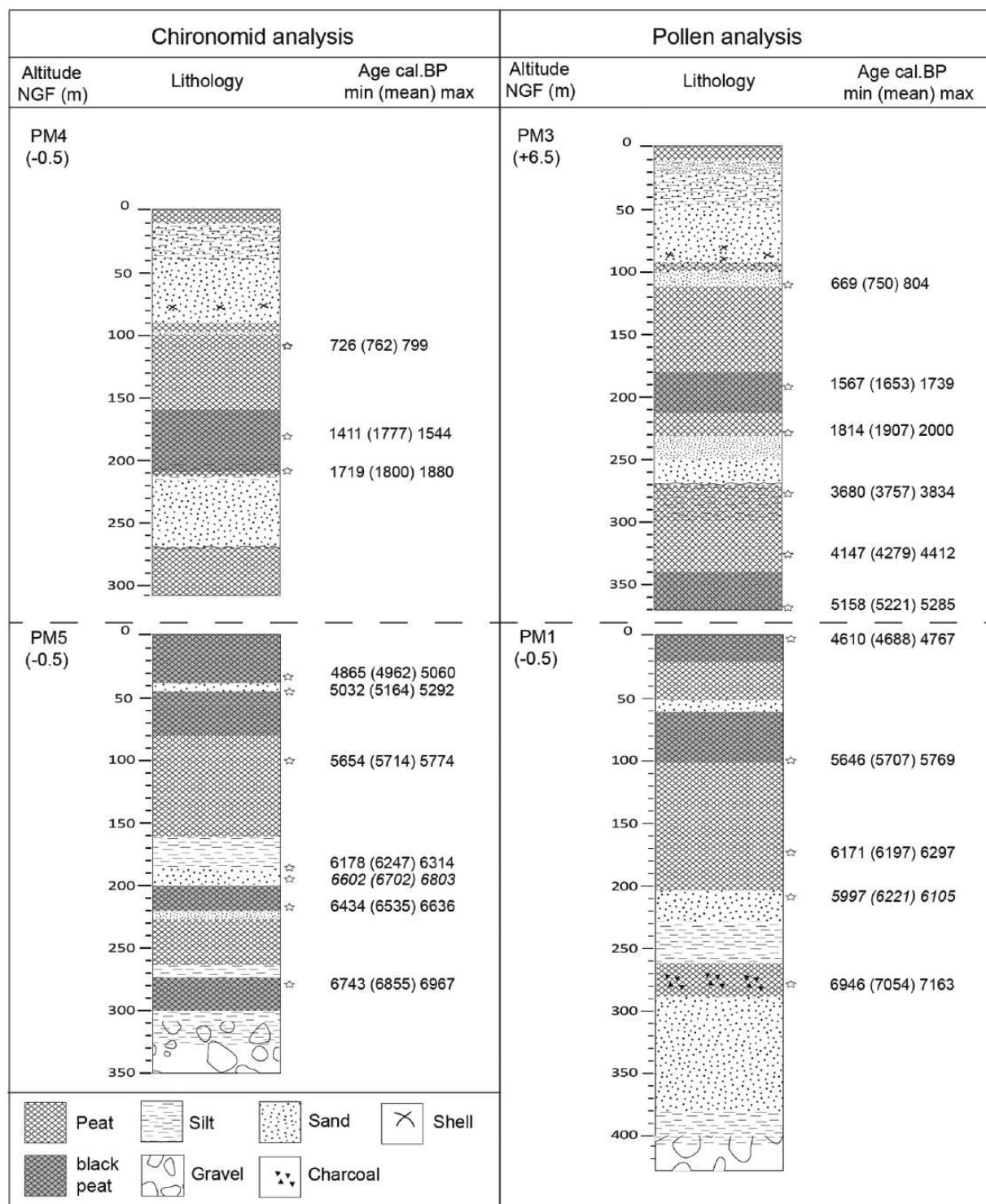


Figure 2. Stratigraphic logs of study cores.

clear events related to cultural activities occurring during the mid-Bronze Age (e.g. Daire et al., 2011). At the end of the Iron Age, from 450 to 50 BC (2.5–2 kyr BP), clearing events are intensified in parallel with a demographic expansion recorded in Western France (Giot et al., 1995). This period is marked by the development of enclosures and human settlement increases on coastal areas, which favoured marine exploitation (salt production, fishing) and maritime exchanges (e.g. Daire et al., 2011).

Nowadays, anthropic infrastructures such as the Atlantic Wall (relic of the Second World War), boarding dock, wastewater pipe, car park and access stairs artificialize PM beach. Over the last decades, agricultural activities have strongly declined in favour of tourism infrastructures such as hiking trails and camping areas,

which contribute strongly to deterioration of the environment, especially coastal dune vegetation which is very sensitive to human trampling.

Methodology

Sedimentological analysis and chrono-stratigraphy

The lithology of the cores is mainly characterized by dense peats deposited in freshwater conditions and is interrupted by sand layers (Figure 2). A detailed sedimentological and stratigraphical analysis of the coastal sedimentation of PM was recently undertaken by Goslin (2014). According to this author, major discontinuities represented by sandy layers appear related to

Table 1. List of all ^{14}C dating obtained on Porsmilin (PM) cores.

Depth sample in PM cores (cm)	Altitude NGF (m)	Laboratory code	Dated material	Date (^{14}C BP)	Age min–max (cal. BP)	Mean age (cal. BP)
PM4/MARSH/+6 m NGF						
110	4.90	Poz-48775	Peat	865 ± 25	726–799	762
180	4.20	Poz-49814	Wood fragment	1600 ± 30	1411–1544	1477
210	3.90	Poz-48774	Peat	1870 ± 35	1719–1880	1800
PM3/MARSH/+6.5 m NGF						
109	5.41	SacA 26803	Peat	870 ± 40	696–804	750
190	4.60	Poz-43078	Wood fragment	1760 ± 30	1567–1739	1653
230	4.20	SacA 26804	Organic silt	1950 ± 45	1814–2000	1907
280	3.70	Poz-43080	Wood fragment	3470 ± 35	3680–3834	3757
330	3.20	SacA 26805	Wood fragment	3840 ± 45	4147–4412	4279
370	2.80	SacA 26806	Wood fragment	4460 ± 30	5158–5285	5221
PM5/INTERTIDAL ZONE/–0.5 m NGF						
35	–0.85	SacA 26807	Peat	4410 ± 45	4865–5060	4962
40	–0.90	Poz-48777	Peat	4480 ± 30	5032–5292	5164
100	–1.50	Poz-48776	Peat	5010 ± 40	5654–5774	5714
185	–2.35	SacA 26808	Organic silt	5445 ± 45	6178–6317	6247
195	–2.45	SacA 26809 ^a	Wood	5890 ± 50	6602–6803	6702
220	–2.70	SacA 26810	Peat	5725 ± 35	6434–6636	6535
275	–3.25	SacA 26811	Peat	6015 ± 50	6743–6967	6855
PM1/INTERTIDAL ZONE/–0.5 m NGF						
0	–0.50	Poz-42857	Wood fragment	4189 ± 40	4610–4767	4688
100	–1.50	Poz-42858	Wood fragment	5000 ± 35	5646–5769	5707
175	–2.25	Poz-42860	Wood fragment	5365 ± 35	6171–6223	6197
210	–2.60	SacA 26802 ^a	Peat	5350 ± 50	5997–6221	6109
280	–3.30	Poz-42861	Charcoal	6150 ± 40	6946–7163	7054

NGF: Nivellement Général de la France.

^aRejected dates for PM stratigraphy.

dune breakdowns occurring during huge storm events (Goslin et al., 2013).

Twenty-one AMS ^{14}C dates were obtained on PM cores (PM1, PM3, PM4 and PM5) at the Poznan (Poland) and Saclay (Paris) Radiocarbon Laboratories (Table 1). Calibration of all dates was performed using the Calam program (version 2.2; Blaauw, 2010) associated with the statistical software R (version 3.0.1; R Development Core Team, 2013) and the non-marine (IntCal09) radiocarbon calibration (Reimer et al., 2013).

Because of discontinuities recorded within peat deposits and the occurrence of a sediment hiatus recorded in the PM cores (at 270 cm in PM4, and at 220 cm in PM3; Figure 2), we did not establish a complete age–depth model for PM cores. This hiatus, which corresponds approximately to the interval 3700–2000 cal. yr BP, is recorded all over Brittany and has been recently reported to relate to a major stormy period (Goslin, 2014). However, for the homogeneous and well-dated part of the PM cores, from 6221 to 4688 cal. yr BP (PM1 core), we carried out a linear interpolation between radiocarbon pointers (Figure 3).

Chironomid preparation

The PM5 and PM4 cores have both been entirely sampled for chironomid analysis (5 cm interval), representing 62 and 75 levels, respectively. Sub-fossil chironomid head capsule extractions followed the laboratory procedures of Rolland and Larocque (2007). First, 60 g of sediments were deflocculated in heated 10% KOH solution for 20 min. The solution was then sifted through a 100 μm mesh sieve, and petroleum flotation was used to condense the chironomid sub-fossils in each sample. The floating fraction was then decanted and removed in a sieve similar to that used previously. The residue was washed with detergent and stored in a beaker containing a solution of 90% alcohol. Chironomid head capsules were sorted out with fine tweezers and mounted on glass

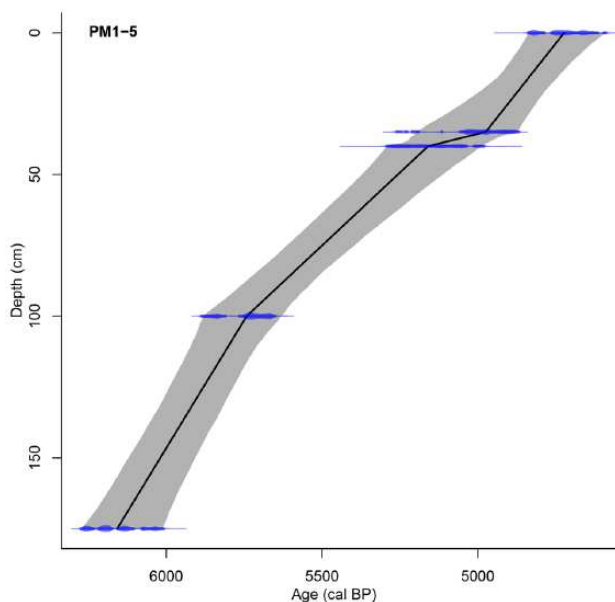


Figure 3. Calendar age–depth model based on ^{14}C dates (cf. Table 1).

slides with glycerine, ventral side up. In this study, head capsules have been identified according to Wiederholm (1983), Klink and Moller Pillot (2003) and Brooks et al. (2007). A minimum of 50 head capsules per sample were counted under a stereomicroscope at 400 \times magnification. It is worth noting that on the PM5 and PM4 cores, only 22 and 18 samples, respectively, contained head capsules. However, many of these samples contained less than 50 head capsules and were thus merged with subsequent samples for a complete chironomid stratigraphy. A total of 20 samples are

therefore presented in the simplified chironomid diagrams (10 samples for both PM4 and PM5 cores, Figure 4).

Pollen preparation

Rich organic sediments of PM1 (intertidal zone) and PM3 (marsh) were sampled at 9 and 3 cm intervals, respectively. Pollen extraction followed the laboratory procedures of Moore et al. (1991). A minimum of 300 pollen grains per sample were counted under a stereomicroscope at 500× magnification (oil immersion). Pollen frequencies for trees and herbs are expressed as percentages versus the main pollen sum, classically excluding aquatic plants, Cyperaceae and spores. *Alnus* pollen grains were also excluded from the main pollen sum since they are generally over-represented in alluvial plain sediments. A total of 46 samples are presented in the simplified pollen diagrams (20 samples for PM3 core and 26 samples for PM1 core, Figure 5). Selected pollen taxa have been grouped according to ecological affinities in order to facilitate the interpretation of catchment dynamics with respect to land use change (Behre, 1981).

Results

Chironomid assemblages

Chironomid diversity is illustrated by 51 and 39 different taxa within the PM4 and PM5 cores, respectively. Main chironomid taxa changes are presented in Figure 4. Based on differences in the composition of chironomid fauna, four stratigraphic changes (Pmch1-4) have been established. In both PM cores, Chironomini (e.g. *Polypedilum*, *Microtendipes*, *Chironomus*) and Tanytarsini (e.g. *Micropsectra*) are the most represented tribes recorded in fossil assemblages. Among main chironomid taxa reaching percentages higher than 15%, we observe more specifically *Polypedilum nubeculosum*-type, *Chironomus plumosus*-type, *Microtendipes pedellus*-type, *Brillia modesta*, *Limnophyes* and *Micropsectra* spp. (Figure 4). Differences between both cores are mainly attributed to individual relative abundance values and especially the *C. plumosus*, *P. nubeculosum*-type, *M. pedellus*-type and *B. modesta* percentages.

The lower part (PMch1) of the intertidal core PM5 is characterized by a low number of head capsules (<50), and consequently some levels have been merged. This part of the core is marked by high percentages of *Micropsectra* spp. and *B. modesta*. The second ecozone (PMch2) is marked by an increase of total of head capsules (>50) accompanied by an increase in abundances of ubiquitous and lentic taxa such as *P. nubeculosum*-type, *C. plumosus* (up to 50%), *Limnophyes* and *M. pedellus*, while percentages of the stream taxa *B. modesta* decrease. In the ecozone PMch3, the faunal assemblage is characterized by a substantial increase of *Limnophyes* synchronous with the appearance of *Heterotrissocladius grimshawi*, *Gymnometriocnemus*, *Pseudorthocladius*, *Metriocnemus* and *Corynoneura edwardsi*. In the last ecozone (PMch4), major changes consist of the disappearance of several species, especially *B. modesta*, synchronously with the exclusive dominance of the ubiquitous taxa *P. nubeculosum*-type, with abundances reaching 80%.

The high chironomid diversity observed in PM coastal cores, with the presence of lentic, ubiquitous, lotic and some terrestrial taxa, is consistent with the spatial heterogeneity and hydrological complexity which prevail in this coastal area.

Pollen assemblages

The distribution of main pollen taxa observed in both cores is displayed in Figure 5, with a diversity of 67 and 64 different taxa for the PM1 and PM3 cores, respectively. Globally, the PM1 core is relatively homogeneous in terms of vegetation, while the PM3

core is characterized by significant successive changes in terms of woodland and anthropogenic pollen grain percentages. PM vegetation dynamics between 7000 and 700 cal. yr BP (Figure 5) can be summarized as a general progression from a forested landscape dominated by arboreal taxa (Neolithic to Bronze Age), to a disturbed and cultivated landscape (Gallo-Roman period and Middle Ages).

Based on the evolution of arboreal pollen percentages, three main palynozones have been established (Pmp1-3). Based on the variation of herbaceae taxa, additional sub-palynozones have been proposed (Figure 5). Palynozone Pmp1a is dominated by high percentages of arboreal taxa (AP: 98%) such as *Corylus*, *Quercus* and *Ulmus*. The riverine forest mainly composed of *Alnus* is also highly represented in pollen assemblages. The following palynozone Pmp1b is marked by the appearance of some herbaceae such as Apiaceae and Primulaceae, suggesting a slight opening of the forest. Palynozone Pmp2a, at about 300 cm (start of the Gallo-Roman period), shows a significant decrease of arboreal forest (50%) revealed by a sharp decrease of the dominant arboreal taxa *Corylus*. This is synchronously associated with the presence of Apiaceae, *Artemisia* and Cyperaceae. Palynozone Pmp2b is characterized by a diversification of the herbaceae taxa with the presence of Asteraceae, *Plantago*, *Rumex* and aquatic taxa such as *Potamogeton*. A clear increase of anthropogenic taxa such as *Rumex* and *Plantago* is then observed within Pmp2c, suggesting increased pastoral/agricultural activities at the studied site. The last palynozone Pmp3 is characterized, from the base to the top, by a persistent increase of Poaceae, *Galium*, *Cerealia* and *Cannabis*, synchronously with a collapse of tree populations, indicating an opening of the forest directly related to human activities.

Discussion

Vegetation change: General evolution from the mid-Holocene to present

The PM pollen records reflect vegetation changes between 7000 and 700 cal. yr BP with a clear gap from c. 3750 to 1910 cal. yr BP (Figure 2), probably related to a major storm period reported in northern Europe (Sorrel et al., 2012) and Western Brittany (Van Vliet-Lanoë et al., 2014b). Our data suggest that the surrounding landscape was dominated by woodlands between 7000 and approximately 4200 cal. yr BP (Figures 6 and 7), with high percentages of *Quercus* and especially *Corylus* – the latter probably occupying the drained slopes of the watershed, while *Alnus* developed on the alluvial plain and surrounding marsh. Conversely, the late Holocene from 4200 cal. yr BP to present shows a decreasing abundance of arboreal trees (Figure 5), mainly linked to agropastoral practices at the onset of the Bronze Age. These results are in agreement with archaeological and palaeobotanical observations carried out in Northern Brittany, suggesting human installation in littoral arboreal areas at the Bronze Age (Daire et al., 2011; Marguerie, 1992). Furthermore, previous studies carried out on littoral peats revealed that the whole Iron Age occurred in a context of open landscape (Morzadec-Kerfourn, 1974) in agreement with our observations from 2000 cal. yr BP (Figure 5).

At PM, the vegetation recorded during the mid-Holocene, between 7000 and 4200 cal. yr BP, is characterized by a dominance of *Corylus* (Figures 5 and 6). However, in Brittany, it is widely recognized that this period is marked by the dominance of *Quercus* over *Corylus* (Barbier and Visset, 1997; Joly and Visset, 2009; Morzadec-Kerfourn, 1974). *Corylus* is a thermophilous and heliophilic arboreal taxon and has a wider ecological tolerance as compared with the other thermophilous taxa (Huntley, 1993). Several palynological studies carried out over Europe showed that the *Corylus* expansion at the onset of the Holocene was related to a high seasonality signal (Naughton et al., 2007;

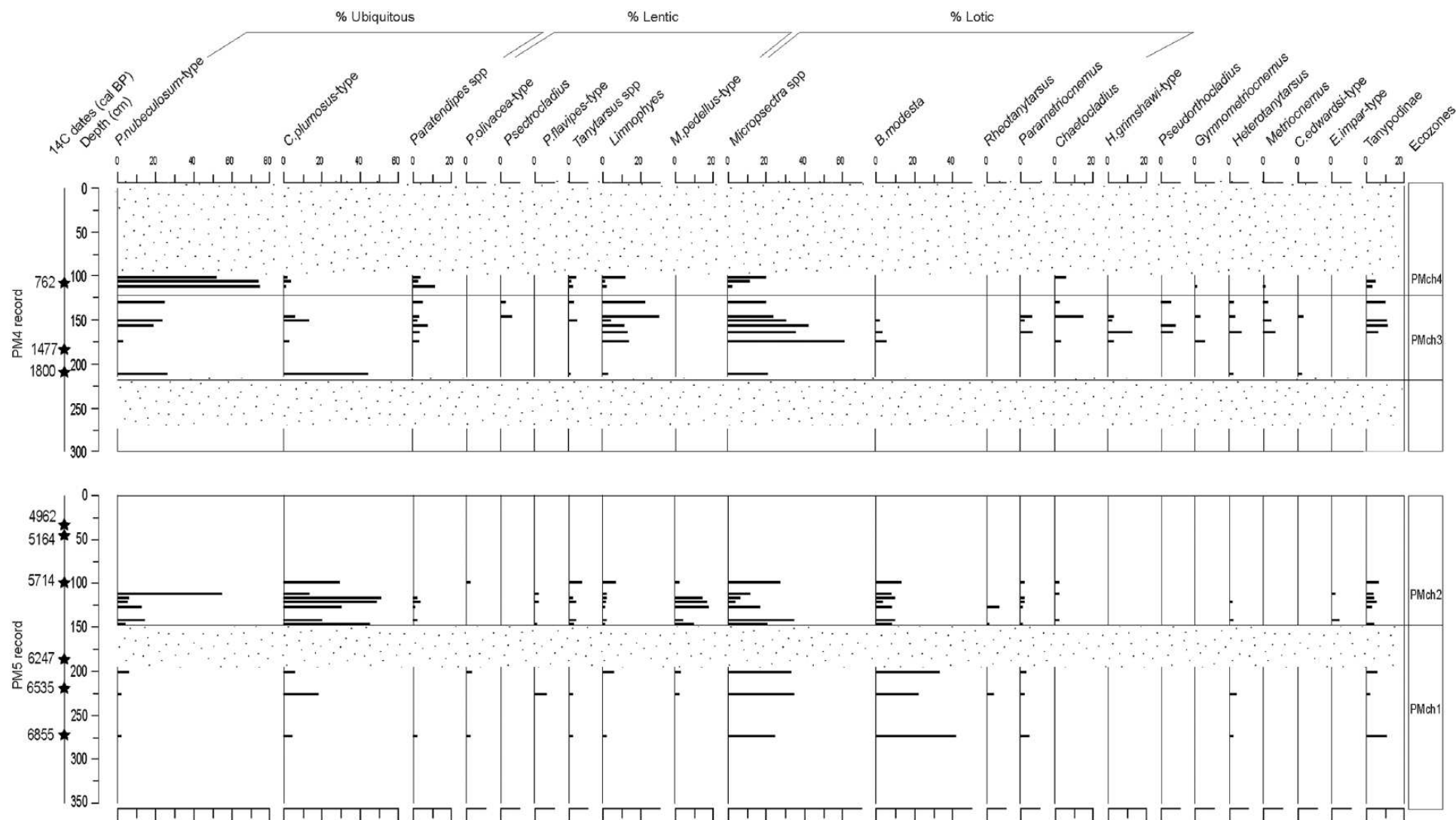


Figure 4. Percentages of chironomid species identified in PM cores. The bands represent the breakdown of the sandy dune. PM: Porsmilin.

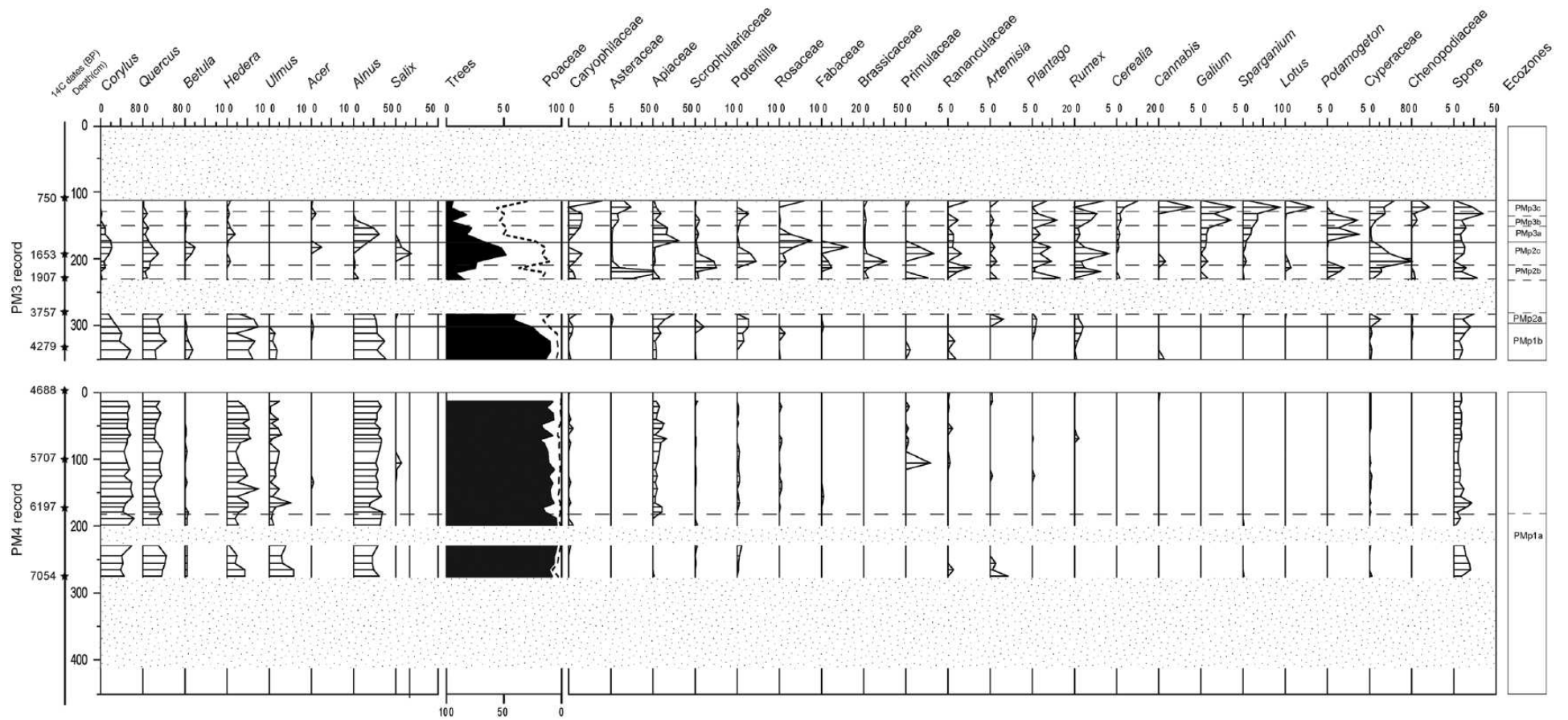


Figure 5. Percentages of pollen species identified in PM cores. The bands represent the breakdown of the sandy dune. PM: Porsmilin.

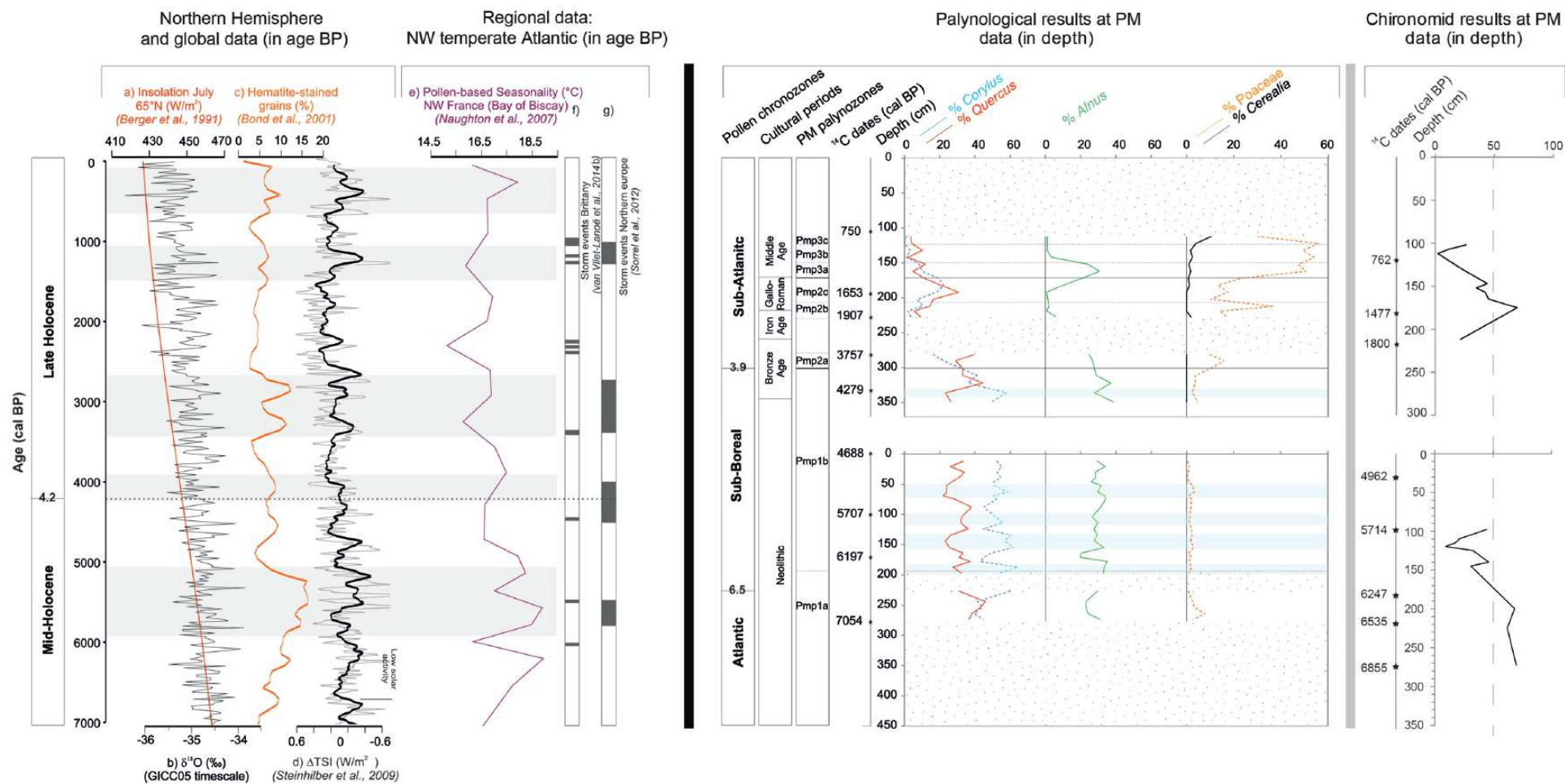


Figure 6. Palaeoenvironmental synthesis. (a) Summer insolation values at 65°N (Berger and Loutre, 1991); (b) δ¹⁸O record from Greenland ice core (NGRIP, GICC05 timescale); (c) hematite-stained grain abundances recorded over the North Atlantic (Bond et al., 2001); (d) total solar irradiance (Steinhilber et al., 2009) (grey bands represent Bond events); (e) seasonality quantification (°C) from a pollen analysis carried out in the Bay of Biscay, France (Naughton et al., 2007); (f) Brittany storms events (Van Vliet-Lanoë et al., 2014b); (g) Northern Europe storms (Sorrel et al., 2012); (h) NAO (Olsen et al., 2012).

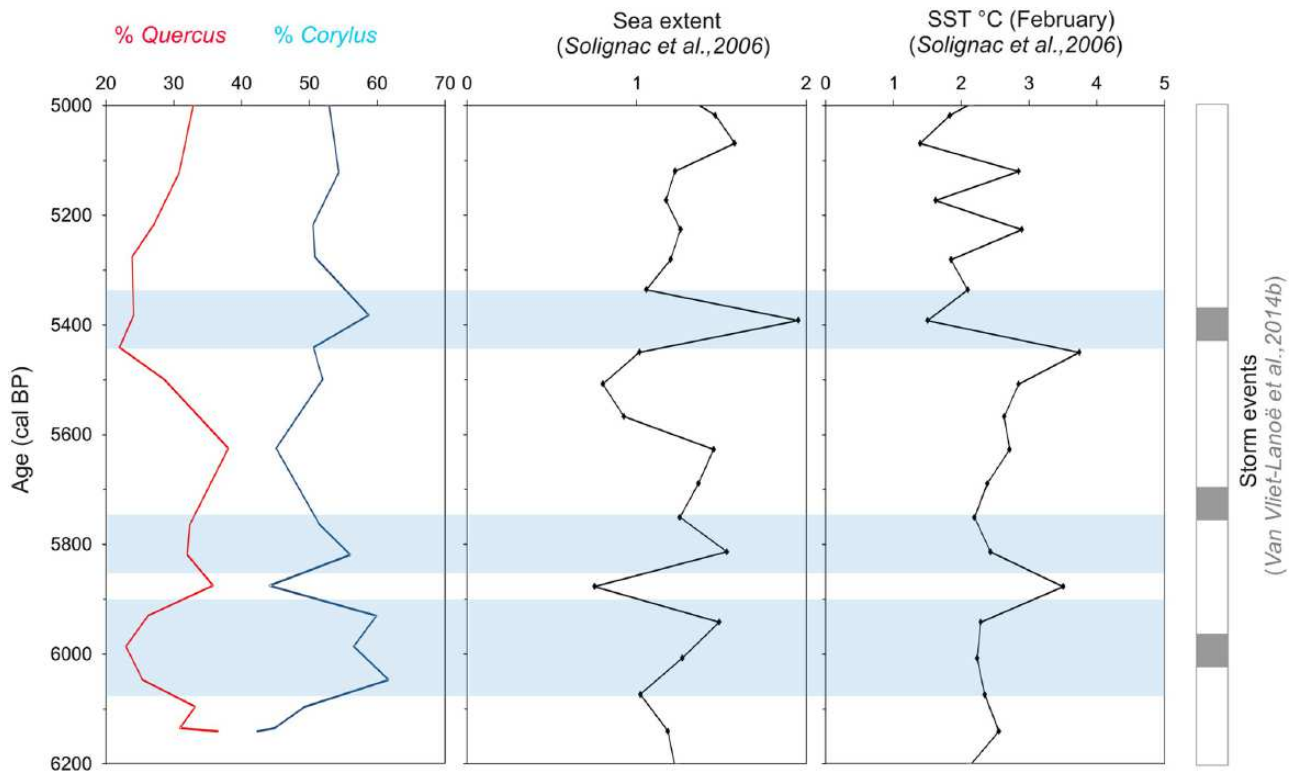


Figure 7. Zoom between 5 and 6.2 kyr BP: (a) *Corylus avellana* versus *Quercus* relative abundances recorded in PM cores; (b) sea surface temperatures reconstructed from dinocyst in Northern Iceland (Solignac et al., 2006); (c) sea extent reconstructed from dinocyst in Northern Iceland (Solignac et al., 2006).

PM: Porsmilin.

Blue bands indicate the *Corylus/Quercus* anti-correlations. Grey bands represent the storms identified in Brittany (Van Vliet-Lanoë et al., 2014b).

Tallantire, 2002) directly caused by the orbital configuration (Berger and Loutre, 1991) (Figure 5). Pollen-based temperature reconstructions carried out on a marine core from the northern Bay of Biscay, close to our studied area, showed that cold winter and warm summer conditions prevailed during the early Holocene, implying a high seasonality signal especially from 8700 to 8000 cal. yr BP, that probably favoured the expansion of *Corylus* (Naughton et al., 2007). After the well-known cooling event recorded at 8200 cal. yr BP, a collapse of *Corylus* is observed (Naughton et al., 2007). The same observation is reported from Swiss Lake (Tinner and Lotter, 2001), and the authors attribute this observation to the irreversible change in climatic conditions, consisting of a significant decrease in drought seasonal stress, which probably allowed the establishment of the other thermophilous taxa, confirming the role played by climate in vegetation changes. The persistent dominance of *Corylus* from 7000 to 4200 cal. yr BP in our study suggests that seasonality, which varied over this period, is not the main driver explaining arboreal vegetation recorded at PM (Figure 5). Throughout the mid-Holocene, contrary to our observations at PM, the palynological record from the Bay of Biscay (Naughton et al., 2007) displays a persistent dominance of *Quercus* over *Corylus*. This difference may be related to the fact that the Bay of Biscay marine core recorded a wider continuous regional signal throughout the Holocene while PM is a coastal core recording a more local signal of vegetation. The marine site is influenced by the huge and more meridional rivers situated along the Atlantic coast, including the Loire, Gironde and other French rivers (Naughton et al., 2007). Conversely, high percentages of *Corylus* recorded during the Sub-Boreal at PM may be related to local environmental conditions. Furthermore, a regional Holocene palynological study for Brittany based on a compilation of coastal pollinic spectra evidences the dominance of *Corylus* in the arboreal pollinic spectra during the Sub-Boreal (Gaudin et al., 2008). The spatial

analysis of *Corylus* distribution furthermore indicates that the highest percentages of this tree characterize sites located in the most humid areas (Gaudin et al., 2008). The same result is reported from Germany where the spread of *Corylus* during the early Holocene mainly occurred in sites characterized by wetter conditions (Theuerkauf et al., 2014). In addition, *Corylus* is more adapted to an oceanic climate compared with *Quercus*, which is considered as being more continental, as reported from a Holocene study carried out in Scandinavia (Giesecke et al., 2008). Hence, at an orbital scale at PM, the dominance of *Corylus*, synchronously with significant percentages of other taxa that require moist conditions (*Ulmus*, *Alnus*; Figure 5), is probably related to prevailing humid conditions during the mid-Holocene at our studied site.

Climate variability over the mid-Holocene: Multi-centennial to multi-decadal timescale

It is worth noting that the whole mid-Holocene is characterized at PM by recurrent short-term contractions of *Quercus* coeval with a short-term increase of *Corylus*, superimposed on the long-term vegetation pattern described above, still dominated by *Corylus* trees (Figure 6). These *Quercus* drops are recorded around approximately 4000, 4500, 5400 and 6000 cal. yr BP and possibly 6500 cal. yr BP according to the radiocarbon pointers we have. The same anti-correlation pattern between these two taxa has been reported in the Armorican domain over the mid-Holocene and has been related to human impact (Joly and Visset, 2009). At PM, the absence of anthropogenic taxa through the PM1 core leads us to consider an alternative hypothesis and to examine more deeply the possibility of climate forcing. On the other hand, it is well known that several cold millennial-scale events, or Bond events, have been recorded in the North Atlantic throughout the Holocene and are

attributed to variability in solar activity and/or internal ocean-atmosphere mechanisms (Bond et al., 2001; Giraudeau et al., 2010; Mayewski et al., 2004; Moros et al., 2004; Nesje et al., 2004; Wanner et al., 2008). These major periods of drift ice measured in deep-sea sediment cores (Bond et al., 2001) are also the basis of significant reduction of North Atlantic Deep Water production (Bond et al., 2001; Mayewski et al., 2004). Furthermore, palaeohydrological conditions reconstructed from peat bogs in Brittany (Langdon et al., 2003) suggest that Holocene Bond events were synchronous with humidity increases and associated humification in the peat record. As for investigated areas in Southern Europe, repeated Mediterranean Forest collapses during the Holocene have been observed at multi-centennial timescales in the Iberian margin (Chabaud et al., 2014) and the Alboran Sea (Fletcher et al., 2010), reflecting repeated dryness and/or cold conditions at multi-centennial timescales related to Bond events. They were interpreted as decreases in the North Atlantic subtropical gyre sea surface temperature (SST) driven by freshwater inputs and thermohaline circulation slowdown. We therefore also observe in Western Brittany the impact of the Holocene North Atlantic SST on the coastal arboreal vegetation through our observed *Quercus* drops at PM and increases in humidity. Furthermore, we also find that short-term *Quercus* contractions–*Corylus* expansions coincide with major Holocene storm events reported for Northern Europe (Sorrel et al., 2012) and Western Brittany at the Holocene scale (Van Vliet-Lanoë et al., 2014a) (Figure 6). According to Sorrel et al. (2012), storm events at that time may have been induced by a global reorganization of North Atlantic oceanic and atmospheric configurations, resulting in a southward shift of the subtropical gyre and in a major change in the track and strength of the westerlies. This would also be consistent with our observed vegetation and faunal changes as mentioned above.

The time resolution of our palynological record during the period between 6200 and 5000 cal. yr BP (70 years on average) allows us to describe more precisely the two specific shifts centred on 6000 and 5400 cal. yr BP (Figure 7). We then identify contractions of *Quercus* synchronously with SST decreases and sea ice cover increases North of Iceland (Solignac et al., 2006). We can therefore argue that the significant and recurrent contractions of *Quercus* during the millennial climatic cold event 6–5 kyr BP would be attributed to more humid, colder conditions and more frequent storms at that time (Figure 7). Our data would therefore suggest that *Quercus*–*Corylus* trends recorded at PM over the mid-Holocene are not an anthropic signal (Joly and Visset, 2009) but instead result from climate shifts that prevailed over the Northern Hemisphere, implying atmospheric and oceanic reorganizations.

Land use over the Late Holocene (Bronze Age to Middle Ages)

Major vegetation changes in PM can be observed at the transition between mid- and Late Holocene (PMp1-PMp2 limit around 300 cm, also equivalent to the Sub-Boreal-Sub-Atlantic limit, Figures 5 and 6). This change is characterized by a shift from a wooded landscape dominated by *Corylus*–*Quercus* to a cleared landscape (PMp2, Gallo-Roman period; Figures 5 and 6). Until the end of PMp2, any signal of cereals stays relatively weak as suggested by low percentages of *Cerealia* and *Humulus/Cannabis*. The good representation of *Plantago lanceolata* during PMp2-3 (Figures 5 and 6) probably marks both compaction and nitrogen enrichment of soil by increasing livestock activities. The persistence of a well-developed forest landscape at the beginning of the Bronze Age (4500 cal. yr BP) at PM (end of PMp1 palynozone, Figure 5) is in good agreement with previous studies carried out in the Armorican domain, suggesting the late apparition of

agricultural activities (Gaudin, 2004), as we observe just before 750 cal. yr BP (cf. PMp3c; Figures 5 and 6).

Then, a regional decrease of agro-pastoral activities is observed from about 1800 to 1653 cal. yr BP at PM, together with a slight but significant forest recovery (*Corylus*–*Quercus*) accompanied by alluvial trees (*Alnus*). This partial abandonment of agricultural practices has previously been observed in the Armorican domain (Barbier and Visset, 1997; Visset, 1994) and has been related to an economic decline all over Europe during the Roman Empire (beginning of the 3rd century AD). Climatically, the 3rd century is also reported as being colder and drier in Western Europe (McCormick et al., 2012) as also marked by the onset of historical dune development in Western Brittany (Van Vliet-Lanoë et al., 2014a). These climate variations disrupted food production over decades and arboreal vegetation was restored during these dark periods.

After this agricultural regression observed at PM, a major new clearing event is observed after 1653 cal. yr BP (start of PMp3 palynozone, Figure 5) on the watershed, with a significant decrease of *Corylus*–*Quercus* marking the start of the Middle Age (Figure 5). This major forest drop is followed by the decrease of *Alnus* around 200 years later and the anthropization reached its maximum before 750 cal. yr BP (i.e. around the 12th–13th century AD) with a maximum of *Cerealia* and *Cannabaceae* recorded at PM (PMp3c; Figures 5 and 6).

Impact of clearance events on the insect fauna

Regarding the Sub-Atlantic period, the decrease of *Alnus* at PM is mainly related to clearing events associated with human settlement, including (1) direct cutting in order to develop farming activities on alluvial plains and (2) increases in water supply caused by deforestation and agricultural use of the surrounding dry land areas (Barthelmes et al., 2010). Several studies around Europe have previously shown the relationship between *Alnus* declines and human settlement during the late Sub-Atlantic period in England (Brown, 1988), Finland (Sarmaja-Korjonen, 2003) and in the eastern Baltic sea (Saarse et al., 2009).

Simultaneous faunal declines associated with waterlogged forests, such as *B. modesta* (Cranston et al., 1983), are evidence that the floodplain deforestation by cultivators, and its transformation into humid meadow by drainage, lead to faunal habitat loss. Disappearances of insects related to vegetation changes have been observed several times, allowing for the detection of human impact (Andrieu et al., 1997; Ponel et al., 2007). A previous insect-based study carried out in Northern France on peat bogs evidenced a disappearance of tree-dependent insects from 4000 cal. yr BP (Gandouin and Ponel, 2010). Major ecological changes related to large-scale forest clearance have also been attributed to the spread of cultivation and pastoralism during the Neolithic period. At Saint-Omer (Northern France), pollen data also show evidence of deforestation post 4000 cal. yr BP (Gandouin et al., 2009) while, before 4000 cal. yr BP, the coleopteran record did not contain any species associated with cultivated grounds. On the contrary, several coleopteran species typical of pristine, undisturbed primeval forests were identified (Ponel et al., 2007). These results suggest that insects can be used as clearing event indicators. In the case of PM, we suggest that *B. modesta*, which is reported to prosper in woods, can also be used as an indicative species for the development of undisturbed alluvial forests.

Faunal changes: General evolution from the mid-Holocene to present

Chironomids are sensitive to several factors such as temperature, oxygen, trophic level and precipitation. At PM, chironomid

changes are not directly related to temperature, since quantitative reconstructions show that there is no significant correlation between chironomid distribution and temperature. In floodplain areas, according to Gandouin et al. (2005), some chironomids can be qualitatively assigned to different ecological conditions related to current speed (lentic versus lotic conditions), and hence allow for reconstruction of hydrodynamic conditions. At PM, variations of lotic- and lentic-based taxa show that the level of connection of the studied site to the river has probably impacted faunal assemblages. During the mid-Holocene, from about 6900 to 6600 cal. yr BP, high percentages of lotic taxa such as *B. modesta*, *Chaetocladius* and *Micropsectra* spp. (Figure 6), synchronously with low percentages of *Limnophyes* which presently occurs in very shallow water (Hofmann, 1998) characterized by low precipitations (Hofmann, 1998; Massafero and Brooks, 2002), indicate that the site was humid and that river run off was high at that time. Later, from about 6000 to 5700 cal. yr BP, higher percentages of lentic taxa such as *C. plumosus*-type and *M. pedellus*-type, associated with a slight decrease of *B. modesta* percentages may suggest a slight decrease of river run off, probably related to lower precipitation as suggested by the slight increase of *Limnophyes*. This hypothesis is confirmed by the decrease of *Corylus* (Figures 5 and 6). Many of the changes observed in chironomid assemblages can be also related to eutrophic conditions, as reported for *C. plumosus*-type and *P. nubeculosum*-type. Between 6000 and 5700 cal. yr BP, lentic taxa increases such as *C. plumosus*-type percentages and ubiquitous taxa such as *P. nubeculosum*-type could then be related to eutrophic changes. However, changes in vegetation observed at that time, illustrated by a decrease of the humid taxa *Corylus*, exclude the trophic level as a trigger factor.

Regarding the upper core, the period from 1800 to 1000 cal. yr BP is marked by a collapse of lotic taxa, especially *B. modesta* (Figures 4 and 6), associated with an increase of lentic taxa such as *Limnophyes* and ubiquitous taxa such as *P. nubeculosum*-type. This suggests a probable decrease of river run off related to agricultural activity, as suggested by the increase of anthropogenic taxa such as *Plantago*, *Rumex* and *Cannabis* (Figures 5 and 6). Between 1000 and 750 cal. yr BP, the increase of *P. nubeculosum*-type associated with the disappearance of several chironomid taxa (Figure 4) is contemporaneous with the expansion of agricultural activity in the region as suggested by the increase of *Cerealia* and *Cannabis* (Figures 5 and 6). The chironomid signal detected throughout PM4 then indicates that human disturbance is present and has certainly impacted faunal assemblages. Changes of current speed observed during this period may then directly be related to the development of agricultural activities; natural areas have been embanked and drained, inducing a loss of chironomid habitats.

Conclusion

This present work represents the first study using combined Holocene chironomid and pollen analysis in a coastal marsh environment in Brittany (PM studied site, Northwestern France). We demonstrate the great potential of this sedimentary context to record widespread climatic variation over the mid-Holocene (7–4.2 cal. kyr BP) as well as anthropization forcing on the Late Holocene (from 4.2 kyr BP to 750 cal. yr BP). Dense arboreal mixed forests, composed of thermophilous taxa (*Corylus–Quercus*), clearly prevailed over the mid-Holocene with a clear dominance of *Corylus*, related to the humid oceanic conditions prevailing at PM. Furthermore, superimposed on the long Holocene climate trend, the well-dated and resolved pollen results between 6 and 5 kyr BP reveal a short-term anti-correlation between slight *Corylus* expansions and *Quercus* contractions at 6, 5.8 and 5.4 cal. kyr BP, with a probable signature of oceanic and atmospheric reorganizations at that time. Concerning chironomid

records, our data show variations attributable to river flooding and temperature fluctuations, probably related to climate changes over the mid-Holocene. Regarding the late Holocene (Sub-Atlantic), starting with the late Bronze Age, vegetation and chironomid changes appear to be related to human activities as suggested by synchronous high abundances of pollinic anthropogenic taxa and decline in chironomids associated with alluvial forest.

Acknowledgements

Much of the core dating was obtained, thanks to National ARTEMIS radiocarbon laboratory facilities. We also would like to thank the *National Botanical Conservatory* for their valuable data concerning vegetation around Porsmilin, and the reviewers for their careful reading and valuable improvements they provided to the manuscript.

Funding

This study was supported by the French Research Programme ANR COCORISCO, as well as the programme PHILTRE funded by the Brittany Region.

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