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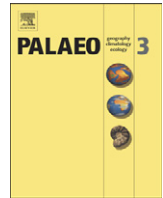
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# Climate control on late Holocene high-energy sedimentation along coasts of the northeastern Atlantic Ocean



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## ABSTRACT

Abundant sedimentological and geochronological data gathered on European sandy coasts highlight major phases of increased high-energy sedimentation in the North Atlantic Ocean during the late Holocene. Owing to an inconsistent use of the terminology, it is often difficult to determine whether studies have described storm-built or wave-built deposits. Both deposits can be identified by overall similar coarse-grained sedimentary facies, but may provide contradictory paleoenvironmental interpretations. The aim of this study is to address this issue, by analysing a set of published <sup>14</sup>C ages recovered from wave-built sediment bodies of the Pertuis Charentais (France). Integration of <sup>14</sup>C data highlights seven coarse-grained sedimentation pulses (CSPs) that reflect a synchronous increase in wave-induced sediment supply occurring around 2650, 2420, 1240, 970, 800, 650 and 450 cal. yr B.P. CSPs can be matched with geochronological data published on other exposed sandy coasts of the western Europe. In first order, CSPs were preserved during phases of decreased storm activity and thus limited coastal erosion in the North Atlantic Ocean from 2700 to 2000 and from 1200 to 600 cal. yr B.P. In second order, CSPs occurred during positive NAO and/or negative EA/WR peaks, which are known from previous studies to induce higher waves and to enhance wave-induced sediment transport in the Pertuis Charentais. Chronological boundaries of CSPs could be used as a diagnostic tool to differentiate storm deposits indicative of sudden, episodic very high-energy sedimentation from wave deposits resulting from the sustained action of above-average westerly winds blowing across the North Atlantic Ocean.

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## 1. Introduction

Sandy coasts represent an important proportion of the world's oceanic shorelines, typically occurring in energetic wave-dominated areas. Over timescales of hours to millennia, the morphological evolution of sandy coasts is determined by a dynamic equilibrium in the budget between sediment supply (resilience) and erosive events (destruction; Masselink and van Heteren, 2014). It is widely acknowledged that individual storm episodes can induce rates of coastal erosion far exceeding those observed during sustained fair weather conditions (Morton and Sallenger, 2003). Owing to the attractiveness of these landscapes, sandy coasts are often densely populated areas (Zhang and Leatherman, 2011). Forecasted acceleration of sea-level rise (Rahmstorf, 2007), combined with changes in wind and wave climate (Dobrynin et al., 2012), might modify

sediment budgets on these shorelines, thus putting more coastal populations at risk of storm-surge flooding (Chaumillon et al., 2017).

Abundant sedimentological and geochronological data gathered on European sandy coasts highlight major phases of storminess in the North Atlantic Ocean during the late Holocene. Disagreement between studies remains high, which is related to a great extent to the heterogeneity of sediment records involved. However, we also believe that the term “storminess” in itself is used inconsistently across publications. Some studies use “storminess” to designate the intensity of prevailing westerly winds blowing across the North Atlantic Ocean (e.g. Orme et al., 2015). Here, we use instead “storminess” in the meaning of e.g. Sabatier et al. (2012) or Sorrel et al. (2012), to designate the recurrence of extreme, sudden meteorological events lasting a few hours to days, associated with storm surge and wave runup that have strong potential for coast erosion. Storminess should be interpreted as a measure of the intensity and/or frequency of these morphogenic events that may fluctuate over a given period of time.

Following this definition, periods of increased storminess in the North Atlantic Ocean were shown to be tied to short-lived cooling

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events recorded as ice-rafted debris maxima (IRD; Bond et al., 2001; Sorrel et al., 2012). Temporal variability of the IRD time series displays three dominant oscillations of about 2400, 1450 and 1000 years (Debret et al., 2007). The 2400- and 1000-yr oscillations are associated with long-term changes in solar forcing. The 1450-yr cycle, which is expressed more strongly than the two former since about 6000 cal. yr B.P., is likely related to internal variability of the North Atlantic Ocean (Debret et al., 2007; Sorrel et al., 2012) and/or of the Arctic Ocean (Darby et al., 2012). This internal forcing likely drives fluctuations of the subpolar and subtropical gyres that modulate the strength and trajectory of storm tracks in the North Atlantic Ocean (Sorrel et al., 2012). It affects the occurrence of storm events on western European coasts, which have been grouped into five “Holocene Storm Periods” (HSP; Sabatier et al., 2012; Sorrel et al., 2012). The most recent HSP corresponds to the Little Ice Age (LIA), i.e. to the Bond cycle 0 (Bond et al., 2001). Steepening of the meridional temperature gradient during the LIA is frequently invoked as a plausible mechanism needed to trigger stronger storms in the North Atlantic Ocean at that time (Dezileau et al., 2011; Lamb and Frydendahl, 1991; Trouet et al., 2012), in possible conjunction with low-frequency changes in sea surface temperature driving tropical cyclogenesis (van Hengstum et al., 2015).

There is a fundamental dichotomy in the sedimentary expression of HSPs. Onshore, HSPs are associated with the widespread formation of massive aeolian dune fields and coversands stretching along the coasts of western Europe (Alexanderson and Bernhardtson, 2016; Bateman and Godby, 2004; Clarke et al., 2002; Clarke and Rendell, 2006; Clemmensen et al., 1996; Clemmensen and Murray, 2006; Clemmensen et al., 2009; Costas et al., 2013, 2012, 2016; Gilbertson et al., 1999; Jelgersma et al., 1995; Nielsen et al., 2016; Sommerville et al., 2007; van Vliet-Lanoë et al., 2016; Wilson and Braley, 1997; Wilson et al., 2004), also recorded as the deposition of thin wind-blown quartz layers over soils (Jackson et al., 2005) and peat bogs (Björck and Clemmensen, 2004; de Jong et al., 2006, 2007; Kylan-der et al., 2016; Orme et al., 2015, 2016; Sjögren, 2009; Tisdall et al., 2013). Aeolian activity was initiated during the last glacial termination (Costas et al., 2016) that gave rise to the periglacial “European Sand Belt” (Zeeberg, 2008), the most recent phase of dune formation being the LIA. In marine settings, the sedimentary expression of HSPs is more diverse. A dominant feature is the presence of discrete, millimetre to centimetre thick shelly sand to gravel layers embedded in back-barrier lagoonal successions (Degeai et al., 2015; Dezileau et al., 2011; Sabatier et al., 2008) or in marsh fine-grained sediments (Billeaud et al., 2009), interpreted as the imprint of barrier destruction and sand over wash (Chaumillon et al., 2017). These discrete coarse layers are also recognised offshore, in the wave-influenced outer section of estuaries (Baltzer et al., 2014; Sorrel et al., 2009). Another dominant feature is the detection of discrete erosional discontinuities in estuaries (Billeaud et al., 2009; Tessier et al., 2010) and lagoons (Ferrer et al., 2010), indicative of prolonged phases of sediment remobilisation and/or erosion.

Owing to an inconsistent use of the terminology, it is often difficult to determine whether these studies have described storm or wave deposits. Both have overall similar coarse-grained sedimentary facies, but may provide contradictory palaeoenvironmental interpretations. Storm deposits resulting from sudden meteorological events may be indicative of coastal destruction. Inversely, wave deposits resulting from the sustained action of above-average westerly winds may be indicative of coastal progradation. Accurate stratigraphical and geochronological data, correlated across coasts within the same climatic zone, are therefore needed to better constrain these discrepancies. As described above, the sedimentary expression of HSPs is illustrated by abundant data, but less is known in contrast about the evolution of European sandy coasts between HSPs, in a context of weakened storm intensity and/or frequency. The aim of this study is to address these two issues, by analysing a set of  $^{14}\text{C}$  data obtained on

coarse-grained sediment bodies of the Pertuis Charentais regressive coastal environment (France), and by comparing results with similar sand bodies in western Europe.

## 2. Study area

The Pertuis Charentais area was chosen because it has received much attention over recent decades, with abundant stratigraphical, sedimentological and geochronological data (Allard et al., 2008, 2010; Bertin et al., 2008; Bertin and Chaumillon, 2006; Billeaud et al., 2005; Chaumillon et al., 2008, 2004; Chaumillon and Weber, 2006; Poirier et al., 2011; Weber et al., 2004a,b). Previous studies have demonstrated the vulnerability of the Pertuis Charentais to storm events (Baumann et al., 2017a,b; Breilh et al., 2014), and its ability to record climate changes of the past centuries to decades (Allard et al., 2008; Poirier et al., 2011, 2017).

### 2.1. Geological setting

The study area is located along the Atlantic Coast of France (Fig. 1A), in Charente Maritime (46° N, 01° W), and corresponds to the northern boundary of the Aquitaine Basin, at the contact with the Armorican Massif (Fig. 1B; Biteau et al., 2006). Anticlines and synclines formed in the northern part of the Aquitaine basin during the late Cretaceous and Paleocene, in response to compressive deformation of the crystalline basement related to Pyrenean orogeny (Sibuet et al., 2004). Differential erosion of Mesozoic to Cenozoic loose marls and sandstones in synclines during the Pleistocene contributed to the formation of NW–SE incised valleys, which provided a large accommodation space for deposition of Holocene marine and continental sediments (Fig. 1B; Chaumillon et al., 2008; Chaumillon and Weber, 2006; Weber et al., 2004a,b).

### 2.2. Geomorphology

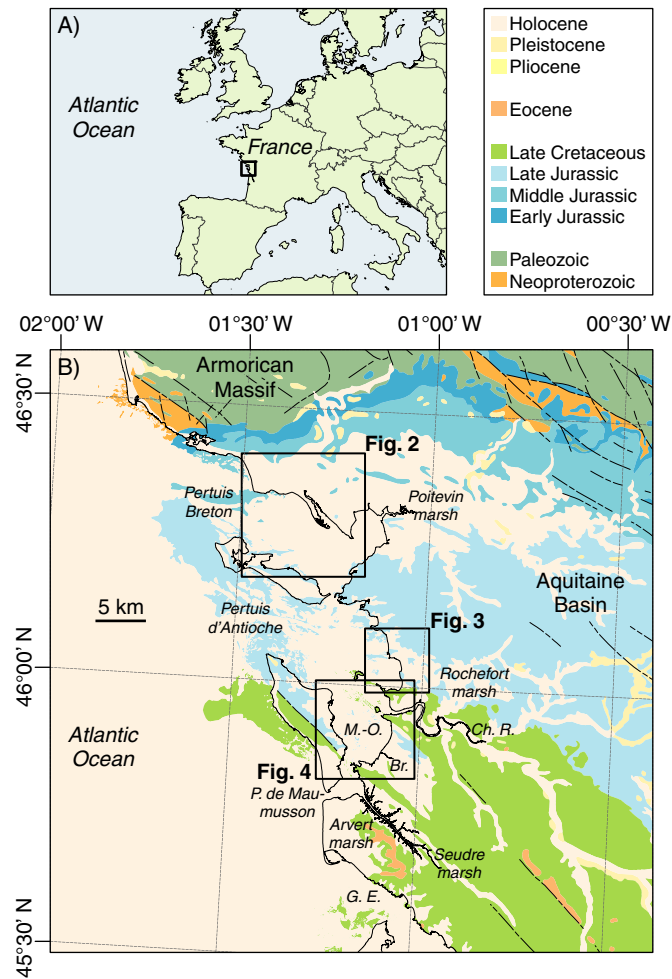
The study area is referred to as the “Pertuis Charentais”. The word “pertuis” locally designates the outer marine segment of three main incised valleys (Chaumillon et al., 2008), which extend inland into large low-lying coastal marshes (Breilh et al., 2013). They include, from north to south (Fig. 1B):

- The Pertuis Breton (260 km<sup>2</sup>) and Poitevin marsh (980 km<sup>2</sup>), which correspond to the paleo-valleys of the Sèvre Niortaise, Vendée and Lay rivers (Chaumillon and Weber, 2006; Weber et al., 2004a),
- The Pertuis d’Antioche (450 km<sup>2</sup>) and Rochefort marsh (240 km<sup>2</sup>), which correspond to the paleo-valley of the Charente River (Chaumillon and Weber, 2006; Weber et al., 2004b),
- The Pertuis de Maumusson and Arvert marsh (170 km<sup>2</sup>), which correspond to the paleo-valley of the Seudre river (Chaumillon et al., 2008). The Pertuis de Maumusson, unlike the two former bounded by rocky shores, is a 1.5 km wide sedimentary tidal inlet (Bertin et al., 2004).

The Pertuis Charentais seafloor is shallow, with more than 90% of its total area between 0 and –20 m NGF (French reference vertical datum, zero being mean sea level at Marseille), and 65% between 0 and –10 m. Mesozoic bedrock outcrops in the marshes to an altitude of  $+6 \pm 2$  m NGF on average (from +2 up to +20 m NGF), compared to an average marsh elevation between +1.6 and +3.4 m NGF (Breilh et al., 2013).

### 2.3. Wave climate

The area is affected by semi-diurnal tides ranging from less than 2 m (neap tides) to more than 6 m (spring tides), and by waves



**Fig. 1.** A, Map of Europe, showing the location of the Pertuis Charentais. B, Simplified continuous land-sea geological map of the area, showing the location of the three study areas. Labels in italics correspond to toponyms cited in the text. M.-O., Marennes-Oléron Bay; Br., Brouage Marsh; Ch. R., Charente River; G. E., Gironde Estuary.

originating from the North Atlantic Ocean. Two main wave climate categories can be distinguished: (1) low to moderate wave conditions (height  $H_{s1/4} = 0.8\text{--}2.5$  m, period  $T_{p1/4} = 6\text{--}12$  s, direction  $\text{Dir}_{p1/4} = 274\text{--}292^\circ$ ) more frequent during summer and representing 58–69% of the annual wave climate and (2) energetic wave conditions ( $H_{s1/4} = 2.5\text{--}9.4$  m,  $T_{p1/4} = 11\text{--}15$  s,  $\text{Dir}_{p1/4} = 265\text{--}280^\circ$ ) more frequent in winter and representing 15–27% of the annual wave climate (Bertin et al., 2008). Owing to complex hydrodynamic and bathymetric interactions within the Pertuis, wave energy along the coast is decayed by almost one order of magnitude relative to offshore conditions (Allard et al., 2008).

At the annual to decadal time scale, the position, strength and trajectory of low-pressure systems across the North Atlantic Ocean is controlled by Northern Hemisphere atmospheric circulation patterns, the most prominent being the North Atlantic Oscillation (NAO; Barnston and Livezey, 1987; Rogers, 1997). The NAO atmospheric circulation pattern, along with the East Atlantic (EA), East Atlantic–West Russia (EA/WR) and Scandinavian (SCAN) patterns, indirectly affects wave height, period and direction in the North Atlantic Ocean (Martínez-Asensio et al., 2016, and references therein). Recent (1948–2014) nearshore wave climate and resulting wave-induced longshore sediment transport have been

computed from a high-resolution wave hindcast along the Arçay sand spit (Fig. 3A; Poirier et al., 2017). Within the Pertuis Breton, the NAO and EA/WR patterns respectively account for 25.2 and 20.6% of the winter (December to February) longshore sediment transport variability, while the contribution of EA pattern is minor (3.6%) and that of SCAN is not significant. Longshore sediment transport increases with positive NAO and negative EA/WR conditions (Poirier et al., 2017), both being associated with higher offshore and nearshore waves in the area (Martínez-Asensio et al., 2016).

#### 2.4. Holocene evolution

Internal architecture, sedimentology and timing of deposition of the Holocene sediment infilling of the outer marine Pertuis Charentais have been extensively investigated with very high-resolution seismic surveys ground-truthed by sedimentary cores and  $^{14}\text{C}$  dating (Chaumillon et al., 2004; Chaumillon and Weber, 2006; Weber et al., 2004a,b), with particular emphasis on the Marennes-Oléron Bay (Allard et al., 2010; Billeaud et al., 2005; Poirier et al., 2011). Inland, Holocene sediment infilling of the coastal marshes has been described from sedimentary cores, with a focus on the record of relative sea-level changes in the Poitevin Marsh (Clavé et al., 2001; Gruet and Sauriau, 1994; Sauriau and Gruet, 1988; Visset, 1987; Visset et al., 1990). A large array of boreholes has been retrieved in the marshes for geotechnical or hydrological studies, and provide additional descriptions of the marsh sediments (Carbonel et al., 1998; Decker et al., 2001; Weber et al., 2004b).

At the millennial scale, sediment infilling of the incised valleys was dominantly coarse-grained (Chaumillon and Weber, 2006). Stratigraphy was primarily controlled by rapid sea-level rise during the early Holocene (ca.  $9\text{ mm yr}^{-1}$ ; Lambeck, 1997; Stéphan and Goslin, 2014), which is similar to other sediment-starved incised valleys of the French Atlantic coasts (Chaumillon et al., 2008, 2010). Coarse-grained sediment infilling of the Pertuis Charentais is capped by a silt drape (ca.  $820\text{ km}^2$  large, 1 to 1.5 m thick on average) that lies unconformably on older sand deposits (Billeaud et al., 2005; Chaumillon et al., 2004) and formed since about the 18th century (Poirier et al., 2011). Fine-grained sediment supply and trapping increased as a result of deforestation on catchments (Poirier et al., 2011), coastal marsh reclamation (Allard et al., 2008) and oyster farming (Bertin and Chaumillon, 2006).

#### 2.5. Sediment sources

Sources of fine-grained sediments in the Pertuis Charentais include (1) coastal rivers flowing directly into the area, the largest being the Charente river (Fig. 1B), (2) the Gironde estuary that is located 35 km southwards (Dabrin et al., 2014; Parra et al., 1998), (3) Mesozoic marls and limestones outcropping along the coast, and (4) coastal marsh clay minerals (Parra et al., 1998).

By contrast, sources of coarse-grained sediments are poorly known. Mineralogical composition of sandy sediments in the Pertuis Charentais is markedly different from that of nearby Cenomanian sandstones or remnant Pleistocene fluvial terraces (Barusseau, 1967). This indicates the importance of hydrodynamical sorting of particles since the beginning of the Holocene marine transgression, and also suggests that much of the coarse-grained sediments in the area are not derived from ancient continental outcrops. Volumes of coarse-grained sediment infilling the Pertuis Breton are larger than those infilling the Pertuis d'Antioche. Given that both incised valleys are subjected to similar tide and wave regimes, and are connected to similarly-sized rivers, Chaumillon and Weber (2006) have concluded that the northern Pertuis Breton acted as a trap for marine sediments derived from the southward-oriented littoral drift. From these observations (Barusseau, 1967; Chaumillon and Weber, 2006), it

appears that coarse-grained particles in the study area are therefore predominantly of marine, not continental, origin.

### 3. Materials and methods

The study relies on a compilation of both existing and new  $^{14}\text{C}$  ages determined on marine mollusc shells retrieved from coarse-grained sediment bodies of the Pertuis Charentais. Three study areas were defined (Fig. 1B), including from north to south, (1) the inner Pertuis Breton and western Poitevin marsh, (2) the Rochefort marsh, and (3) the Marennes-Oléron bay and Brouage marsh, which make up a smaller system at the transition between the Charente and Seudre incised valleys (Allard et al., 2010).

#### 3.1. $^{14}\text{C}$ data compilation

##### 3.1.1. Existing data

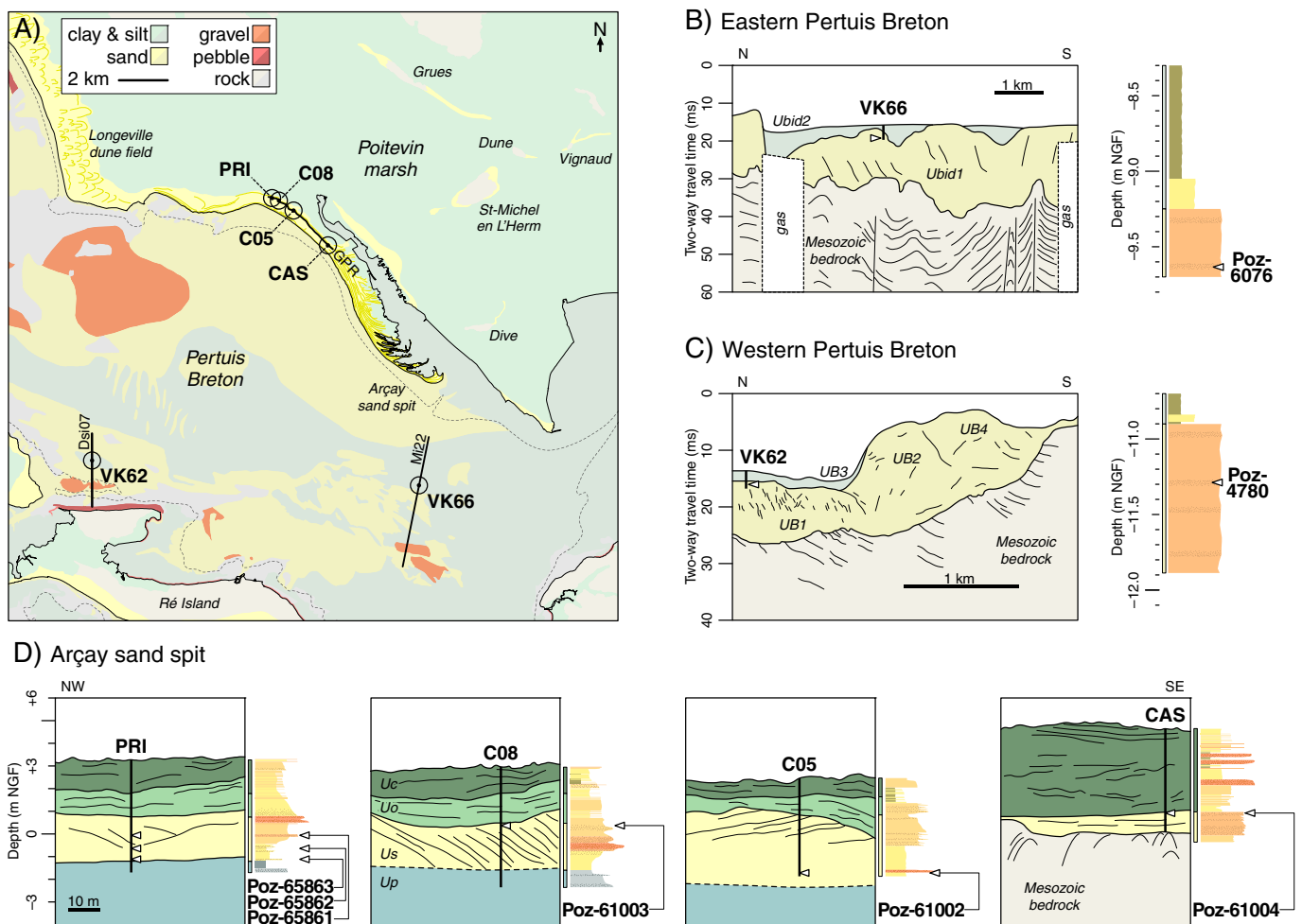
Existing  $^{14}\text{C}$  ages were published in regional monographs (Gabet, 1981; Regrain, 1980), in radiocarbon laboratory reports (Delibrias et al., 1974, 1982) and in peer-reviewed articles (Allard et al., 2010; Chaumillon et al., 2004; Chaumillon and Weber, 2006; Poirier et al., 2011).

Works carried out during the 1970's and 1980's provided mostly qualitative information about the stratigraphical context in which  $^{14}\text{C}$  samples were retrieved, but descriptions were sufficiently detailed to ensure the provenance of these samples.  $^{14}\text{C}$  measurements involved the scintillation method that yielded standard errors typically ranging between 90 and 100 years.

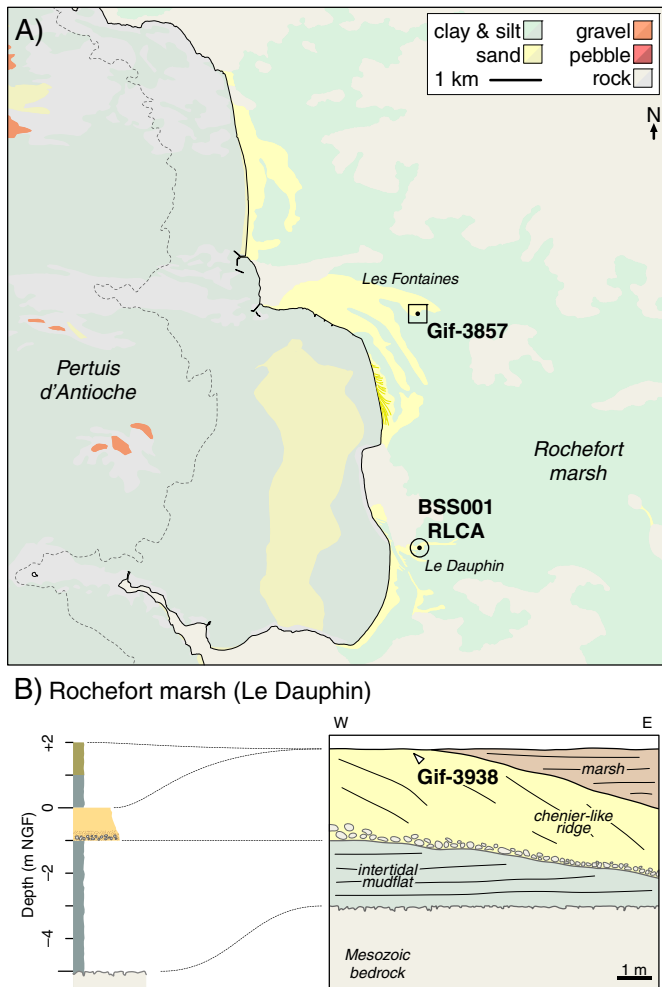
Works carried out since the 2000's involved extensive geophysical surveys of the Pertuis Charentais combined with abundant sedimentological and geochronological data, providing a precise control on the stratigraphic position of  $^{14}\text{C}$  samples. Measurements involved the AMS method that yielded standard errors not greater than 30 years.

##### 3.1.2. New data

The  $^{14}\text{C}$  database was completed with new ages obtained on four sedimentary cores retrieved in 2013 with a vibro-corer in the Arçay sand spit (study area 1; Fig. 2A). Cores were positioned along Ground Penetrating Radar (GPR) profiles. GPR survey of the spit (40 km of profiles) was carried out with a GSSI SIR-3000 acquisition unit, equipped with a 400 MHz antenna and a GPS (Tessier et al., 2013). Post-acquisition processing included enhancement of



**Fig. 2.** A, Map of study area 1, Pertuis Breton and Poitevin Marsh. Labels in italics correspond to features cited in the text. Circle symbols indicate the location of sediment cores in which  $^{14}\text{C}$  samples listed in Table 1 have been recovered. Cores have been positioned along geophysical profiles represented as thick black lines. B, Stratigraphy of the eastern Pertuis Breton, illustrated by seismic profile Mi22 and sedimentary log of core VK66 (redrawn from Chaumillon and Weber, 2006). C, Stratigraphy of the western Pertuis Breton, illustrated by interpreted seismic profile Dsi07 and sedimentary log of core VK62 (redrawn from Chaumillon et al., 2004). D, Stratigraphy of the Arçay sand spit, illustrated by interpreted Ground Penetrating Radar profiles and sedimentary logs of cores PRI, C08, C05 and CAS (this study). Along each sedimentary log,  $^{14}\text{C}$  samples are positioned by white arrows labelled with corresponding laboratory codes.



**Fig. 3.** A, Map of study area 2, Pertuis d'Antioche and Rochefort Marsh. Labels and symbols as in Fig. 2. Square symbol indicates the location of a  $^{14}\text{C}$  sample for which a detailed description of the stratigraphical context is not available. B, Stratigraphy of Le Dauphin chenier-like ridge, interpreted from Regrain (1980) photograph description of a trench dug 450 m eastwards of sediment core BSS001RLCA. Dashed lines correlate sediment facies recognised in the trench and the core.  $^{14}\text{C}$  sample Gif-3938 is positioned on the interpreted stratigraphic section with a labelled white arrow.

signal-to-noise ratio with a Karhunen-Loève filter (Zhao et al., 2005), time-to-depth conversion based on a variable velocity model (Allroggen et al., 2015), and topographic migration (Dujardin and Bano, 2013).

Sediment facies in the cores were visually described, and marine mollusc shells were sampled for  $^{14}\text{C}$  age determination (AMS method; Poznań Radiocarbon Laboratory, Poland). In order to prevent dating of reworked material, only fully preserved remains, belonging to species ecologically compatible with the depositional environment were chosen. When applicable, thin-shelled infaunal bivalves were preferred, because they are indicative of a short post-mortem residence at the water-sediment interface, and are thus expected to record more accurately the true timing of sediment deposition (Poirier et al., 2010). These selection criteria were also followed for  $^{14}\text{C}$  samples reported by Allard et al. (2010) and Poirier et al. (2011), but it is unclear whether they were followed as well in the other works used to build the database.

### 3.2. $^{14}\text{C}$ data processing

Processing of the  $^{14}\text{C}$  database (existing and new ages) was performed with *Bchron* package implemented in statistical analysis

software R (Haslett and Parnell, 2008; Parnell et al., 2008). First,  $^{14}\text{C}$  ages were calibrated against Marine13 reference curve (Reimer et al., 2013). The regional reservoir offset value  $\Delta R$ , which is here  $-28 \pm 23$ , is the inverse-error weighted average of 4 measurements carried out on mollusc shells of the Pertuis Charentais ( $-36 \pm 40$ ,  $-34 \pm 60$ ,  $-32 \pm 39$ ,  $+7 \pm 60$ ; Tisnérat-Laborde et al., 2010).

Function *BchronDensity* was then applied to the whole  $^{14}\text{C}$  database, in order to combine the calibrated age distributions into a single, average age distribution. Instead of summing age probabilities, *BchronDensity* fits a mixture of a user-specified number  $G$  of normal distributions (here  $G = 64$ ). The function relies on a stochastic algorithm (Markov Chain Monte Carlo) that produces slightly different results at each run. *BchronDensity* was therefore iterated 1000 times to improve reproducibility, and output was finally averaged.

## 4. Results

### 4.1. Origin of samples

Before describing the output of the *BchronDensity* function, this preliminary section provides a description of the geographical and stratigraphical context in which both existing and new  $^{14}\text{C}$  samples have been retrieved from coarse-grained sediment bodies of the Pertuis Charentais. Although this section partly deals with published material, it is intended to serve as a guide to the description of  $^{14}\text{C}$  results. Inland, these sediment bodies consist of thin, bedrock-attached chenier-like ridges that mark the position of former coastlines. They are depicted on fine-scale geological maps of the area (Bourgueil et al., 1976a,b, 1972; Hantzpergue, 1988; Platel et al., 1976; Verger et al., 1975). Local toponyms in the Poitevin Marsh ("Dune") and elsewhere in the area ("La Sablière", "La Gravelle") are consistent with the presence of sand or gravel-rich subsurface deposits that contrast with dominant clayey silt sediment infilling of the marshes. Within the Pertuis Charentais, Holocene sediments are buried under the large silt drape deposited since the 18th century. Coarse-grained sediment bodies outcrop in hydrodynamically active areas, where the silt drape is absent (Figs. 2A, 3A, 4A).

#### 4.1.1. Study area 1: Pertuis Breton and Poitevin marsh

The sediment infilling of the Pertuis Breton is predominantly composed of marine sands and gravels, derived from the southward-oriented littoral drift. Subtidal sand outcrops (Fig. 2A) correspond to the top of back-stepping progradational wedges deposited in the area in response to Holocene sea-level rise (Weber et al., 2004a). In the eastern Pertuis Breton (Fig. 2B),  $^{14}\text{C}$  sample Poz-6076 was recovered from core VK66 at a depth of  $-9.60$  m NGF, in order to determine the age of the sand wedge Ubid1 (Chaumillon and Weber, 2006). In the western Pertuis Breton (Fig. 2C),  $^{14}\text{C}$  sample Poz-4780 was recovered from core VK62 at a depth of  $-11.30$  m NGF, in order to determine the age of the sand wedge UB1 (Chaumillon et al., 2004).

New  $^{14}\text{C}$  samples were recovered from the Arçay sand spit, which is composed of four stratigraphical units (Fig. 2D), described from base to top in the following. Unit Up has a transparent to low-amplitude horizontal radar facies correlated with blue-grey silty sands, interpreted as the spit platform (in the meaning of Allard et al., 2008). Unit Us displays high-amplitude, high-angle reflectors dipping southeastwards, in the direction of spit progradation. Us is composed of orange medium sands intercalated with discrete, centimetre-thick coarse shelly sand layers. It is interpreted as the main spit unit. Above, units Uo and Uc have medium amplitude, sub-horizontal or channelised reflectors. Uo consists of homogeneous fine sands containing abundant millimetre-thick laminations of dark heavy minerals, while such laminations disappear in Uc. Uo is interpreted as an exposed, upper beach environment, while Uc

corresponds to a closed back-barrier tidal lagoon that formed along the northwestern Arçay sand spit, in response to human interventions during the 1970's (Poirier et al., 2017).  $^{14}\text{C}$  sample Poz-61004 was recovered from core CAS at a depth of +0.92 m NGF, in order to determine the age of the spit platform unit Up. Five other  $^{14}\text{C}$  samples were retrieved from spit unit Us, including Poz-65681, 65682 and 65683 in core PRI (−0.05, −0.65, −1.15 m NGF respectively), Poz-61002 in core C08 (+0.37 m NGF) and Poz-61002 in core C05 (−1.70 m NGF).

#### 4.1.2. Study area 2: Rochefort marsh

Chenier-like ridges occurring at the seaward margin of the Rochefort marsh (Fig. 3A) were qualitatively described and sampled for  $^{14}\text{C}$  age determination by Regrain (1980). Sample Gif-3857 was taken in Les Fontaines at an approximate depth of 0 m NGF, and sample Gif-3938 was taken in Le Dauphin at an approximate depth of +1.8 m NGF.

Internal architecture of Le Dauphin marsh was illustrated in Regrain (1980) by a photograph of a trench dug in the marsh, which shows a sand body lying between about −1 and +2 m NGF above a former intertidal mudflat, and eventually topped by marsh sediments (Fig. 3B). The description is confirmed by the borehole BSS001RLCA (Anonymous, 1997), which was drilled 450 m westward of the trench. Grey sands and gravels (3–4 mm) with abundant shell debris were observed between 0 and −1 m NGF, hence confirming the probable presence of extensive chenier-like ridges in this area, as depicted on the local geological map (Bourgueil et al., 1972).

#### 4.1.3. Study area 3: Marennes–Oléron bay and surrounding marshes

Similar subsurface coarse-grained deposits were identified and sampled for  $^{14}\text{C}$  age determination in the Charente estuary and Brouage marsh (Fig. 4A) by Regrain (1980). They include the Soumard (Gif-4497, +3.6 m NGF) and Lupin (Gif-4498, +2.4 m NGF) chenier-like ridges along the Charente estuary, the Quadoré (Gif-3856, +2.8 m NGF) and Nancras (MC-2158, +0.9 m NGF) chenier-like ridges, and a deep subtidal sand body lying directly over the bedrock in Brouage (Gif-3757, −20 m NGF; Gif-3758, −23 m NGF). To the west, Gabet (1981) described a large set of chenier-like ridges in the Salines marsh (Oléron Island, Fig. 4A).  $^{14}\text{C}$  ages listed in a radiocarbon laboratory report (Delibrias et al., 1982) include Gif-3382 (+2 m NGF), Gif-4393 (+1.5 m NGF) and Gif-4395 (+2.5 m NGF).

The Holocene sediment infilling of the Marennes–Oléron bay has been extensively studied with very high resolution seismic profiles and  $^{14}\text{C}$ -dated sedimentary cores. To the west (Fig. 4B), three short sister cores penetrating into the top of a large progradational sand wedge recovered three  $^{14}\text{C}$  ages (Poz-26302 in VC34, −7.1 m NGF; Poz-26303 in VC35, −6.5 m NGF; Poz-26304 in VC33, −8.7 m NGF), used for age determination of seismic unit UT3 (Allard et al., 2010; Billeaud et al., 2005). To the east (Fig. 4C), core UC01 provided a continuous record of sedimentation from units UT3 to UT4.2 (Poirier et al., 2011). Samples Poz-31120 (−5.30 m NGF) and Poz-31121 (−4.15 m NGF) were recovered from sandy unit UT3 to confirm age determination of its western counterpart.

#### 4.2. Definition of coarse-grained sedimentation pulses (CSPs)

The compiled database includes a total of twenty-four  $^{14}\text{C}$  ages retrieved from coarse-grained sediment bodies of the Pertuis Charentais (Table 1). Two main age populations are recognised, ranging from  $700 \pm 90$  (Gif-4395) to  $1640 \pm 30$  uncal. yr B.P. (Poz-61004), and from  $2650 \pm 100$  (Gif-4497) to  $2880 \pm 100$  uncal. yr B.P. (Gif-3382). Similar  $^{14}\text{C}$  ages are found in much different geographical and stratigraphical contexts. For instance, samples Gif-4395 and Poz-61002 were recovered from a chenier-like ridge in the Salines marsh (Fig. 4A) and from the Arçay sand spit unit Us (Fig. 2D) respectively,

but both yielded equivalent ages of  $700 \pm 90$  and  $730 \pm 30$  uncal. yr B.P.

The 24 calibrated  $^{14}\text{C}$  ages (Fig. 5A) were supplied to the *BchronDensity* function. Averaged output is a complex, multimodal age distribution (Fig. 5B) with 7 well-defined peaks of age probability centered on two distinct periods, from about 300 to 1400 cal. yr B.P. and from about 2300 to 2900 cal. yr B.P. We define each age peak as a coarse-grained sedimentation pulse (CSP), assuming that formation of independent, disconnected coarse-grained deposits reflects a synchronous event occurring in the whole Pertuis Charentais area. The multimodal age distribution was decomposed into a subset of individual normal distributions in order to determine the age ranges of each CSP. Decomposition was carried out by a density estimation algorithm implemented in R package *mclust* (Fraley and Raftery, 2002). CSPs are labelled A to G, from the youngest to the oldest, and have ages of  $445 \pm 50$ ,  $649 \pm 64$ ,  $797 \pm 47$ ,  $968 \pm 62$ ,  $1240 \pm 53$ ,  $2422 \pm 54$  and  $2646 \pm 62$  cal. yr B.P., respectively (Table 2).

#### 4.3. Recognition of CSPs along European coasts

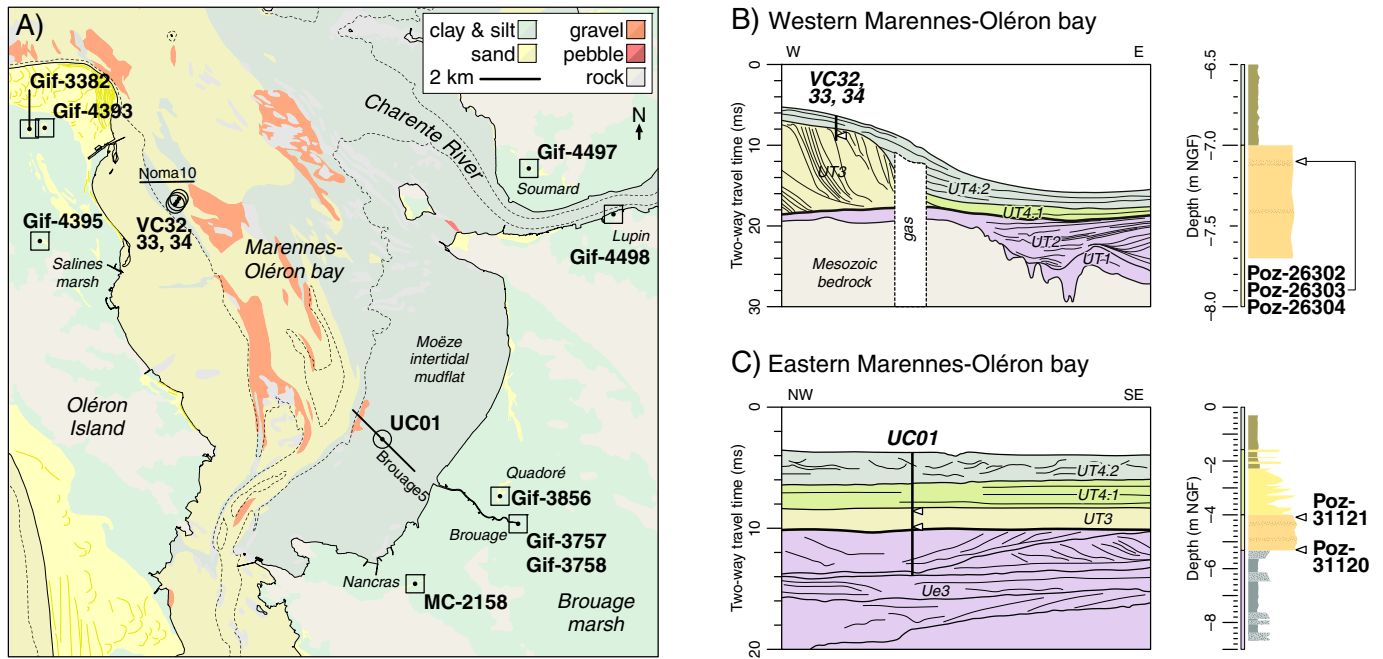
An additional dataset of 39  $^{14}\text{C}$  and OSL ages obtained on wave-influenced environments of western Europe was built (Table 3), in order to determine whether CSPs identified in the Pertuis Charentais reflect a local or regional signal. Dated deposits include spits, beaches (including unconsolidated sands and beachrocks) and ridges (including cheniers and plains) from the exposed coasts of Germany, United Kingdom, France, Spain and Portugal (Fig. 6A). When publications already reported calibrated age ranges, they were recalculated to ensure a consistent processing of the dataset, using an up-to-date calibration curve (Marine13) and  $\Delta R$  values determined from the on-line “Marine Reservoir Correction” database (Reimer and Reimer, 2006). The *BchronDensity* function was not applied to this dataset, which is more heterogeneous in terms of sample provenance.

For latitudes between  $55^\circ$  (Sylt, Germany) and  $43^\circ$  N (Punta Gallin, Spain), two main age populations are distinguished. The most recent one ranges from about 300 to 1300 cal. yr B.P., matching the  $2\sigma$  boundaries of CSPs A to E, and the oldest one ranges from about 2100 to 3100 cal. yr B.P., matching the  $2\sigma$  boundaries of CSPs F and G.  $^{14}\text{C}$  ages obtained on spits and beachrocks of the Cadix Gulf (southern Spain and Portugal), around  $37^\circ$  N, range from about 400 to 3000 cal. yr B.P. and do not match this overall dichotomy (Fig. 6B). Maximum probability age of some samples falls precisely within, or very close to, the CSP age ranges (Fig. 6B; Tables 2, 3). This is the case e.g. for  $^{14}\text{C}$  sample KIA-31638 from Sylt spit, Germany (562–261 cal. yr B.P., equivalent to CSP A), for OSL samples of the Dungeness beach ridge plain, United Kingdom (1053–856 cal. yr B.P., equivalent to CSP D), or for  $^{14}\text{C}$  sample CNA-1053 from Punta Gallin beach, Spain (907–675 cal. yr B.P., equivalent to CSP C).

Other samples, such as CNA-1052 (643–468 cal. yr B.P.) from Punta Gallin beach, fall in between two CSPs (here A and B), or have large calibration ranges which make the connection with a CSP more questionable (e.g. UQ-2058 in Cordon de Richard chenier, France; 3091–2465 cal. yr B.P., possibly equivalent to CSP G). The lowest agreement is found for  $^{14}\text{C}$  ages of the Cadix Gulf, for which only 5 samples out of 19 can be associated with CSPs. Poor agreement also exists for  $^{14}\text{C}$  ages obtained on beachrocks (Gif-1100 in Plage de la Torche, France; IRPA-20056 and Beta-185788 in Armação de Pêra, Portugal), which are out of the CSPs  $2\sigma$  age ranges (Fig. 6B).

#### 5. Discussion

The basic assumption of this study is that CSPs in the Pertuis Charentais reflect a regional shift towards more energetic marine conditions. While the contribution of relative sea-level changes to the occurrence of CSPs cannot be excluded, it is probably minor in the context of the steady, slow sea-level rise recorded along



**Fig. 4.** A, Map of study area 3, Marennes-Oléron bay and surrounding marshes. Labels and symbols as in Figs. 2 and 3. B, Stratigraphy of the western Marennes-Oléron bay, illustrated by seismic profile Noma10 and sedimentary log of core VC34 (redrawn from Allard et al., 2010 and Poirier et al., 2011). C, Stratigraphy of the eastern Marennes-Oléron bay, illustrated by seismic profile Brouage5 and sedimentary log of core UC01 (redrawn from Poirier et al., 2011).

French Atlantic coasts during the late Holocene (Lambeck, 1997; Stéphan and Goslin, 2014). In this section, the external climate drivers involved in the occurrence of CSPs are discussed, by comparing CSP age ranges with time series of the North Atlantic Ocean climate since 3500 cal. yr B.P. (Fig. 7).

### 5.1. Impact of storminess

A key finding of this study is that CSPs do not coincide with the two last phases of increased North Atlantic storminess previously identified in various studies from about 2000 to 1200 cal. yr B.P. and from about 600 to 150 cal. yr B.P. (Fig. 5B; HSAP, “high storm activity

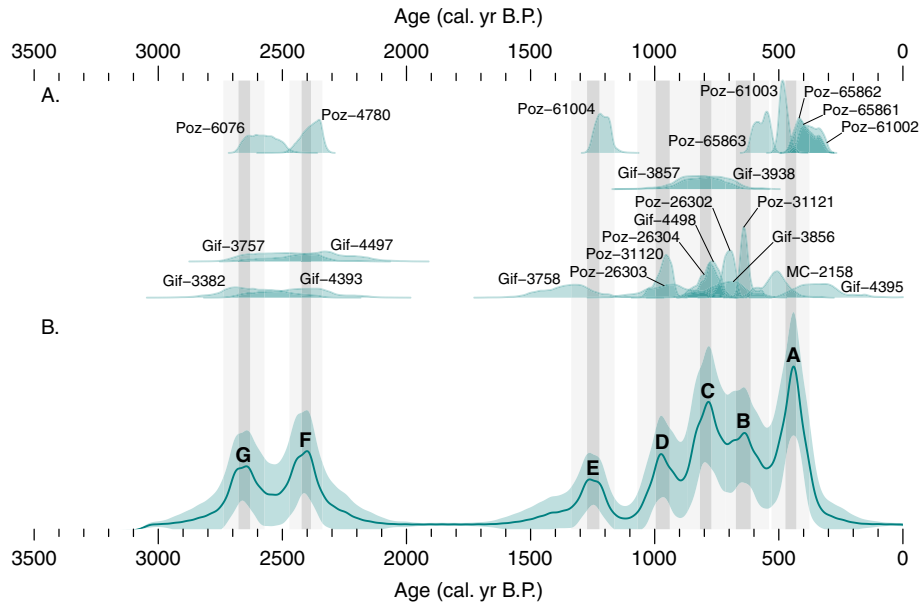
period” in Sabatier et al., 2012; HSP, “Holocene Storm Period” in Sorrel et al., 2012; van Vliet-Lanoë et al., 2014; SP, “storm periods” in Degeai et al., 2015; Costas et al., 2016 and references therein).

Inversely, CSPs coincide with decreasing or minima values in the 1450-yr wavelet reconstruction of the IRD time series (Fig. 7C; Bond et al., 2001), i.e. during periods of decreased North Atlantic storminess (Sorrel et al., 2012). The same observation applies for a clay mineralogy record of lagoonal sediments in the northwestern Mediterranean Sea (Sabatier et al., 2012), for which CSPs coincide with above-average ( $> 1.2$ ) values in the smectite/(illite + chlorite) ratio, interpreted by the authors as a proxy of reduced storm activity (Fig. 7D). Wavelet reconstruction of this clay mineralogy time

**Table 1**  
<sup>14</sup>C database (Pertuis Charentais).

Lab reference	<sup>14</sup> C age (uncal. yr B.P.)	Study area	Toponym	Publication reference	Type	2 $\sigma$ range (cal. yr B.P.)	1 $\sigma$ range (cal. yr B.P.)
Gif-4395	700 ± 90	3	Arceau	Delibrias et al., 1982	Chenier-like	518–185	452–289
Poz-61002	730 ± 30	1	Pointe d'Arçay	This study	Spit	472–307	453–358
Poz-65861	750 ± 30	1	Pointe d'Arçay	This study	Spit	487–319	473–386
Poz-65862	755 ± 30	1	Pointe d'Arçay	This study	Spit	490–324	477–394
Poz-65863	850 ± 30	1	Pointe d'Arçay	This study	Spit	548–440	521–473
MC-2158	900 ± 70	3	Le Grand Nancras	Regrain, 1980	Chenier-like	650–430	601–487
Poz-61003	975 ± 30	1	Pointe d'Arçay	This study	Spit	646–523	621–551
Poz-31121	1065 ± 30	3	Moëze tidal flat	Poirier et al., 2011	Subtidal (marine)	721–590	681–627
Gif-3856	1150 ± 90	3	Quadoré	Regrain, 1980	Chenier-like	910–590	819–647
Poz-26302	1165 ± 30	3	Rade des Trousses	Allard et al., 2010	Subtidal (marine)	821–660	765–687
Gif-3938	1230 ± 100	2	Le Dauphin	Regrain, 1980	Chenier-like	1012–630	900–708
Poz-26304	1235 ± 30	3	Rade des Trousses	Allard et al., 2010	Subtidal (marine)	899–721	865–762
Poz-26303	1245 ± 30	3	Rade des Trousses	Allard et al., 2010	Subtidal (marine)	904–729	875–776
Gif-3857	1280 ± 90	2	Les Fontaines	Regrain, 1980	Chenier-like	1039–672	934–748
Gif-4498	1390 ± 90	3	Lupin	Regrain, 1980	Chenier-like	1174–763	1081–872
Poz-31120	1420 ± 30	3	Moëze tidal flat	Poirier et al., 2011	Subtidal (marine)	1085–912	1037–949
Poz-61004	1640 ± 30	1	Pointe d'Arçay	This study	Spit	1295–1155	1269–1200
Gif-3758	1790 ± 100	3	Brouage marsh	Delibrias et al., 1982	Subtidal (marsh)	1594–1172	1480–1275
Gif-4497	2650 ± 100	3	Soumard	Regrain, 1980	Chenier-like	2682–2137	2567–2267
Poz-4780	2695 ± 30	1	Pertuis Breton	Chaumillon et al., 2004	Subtidal (marine)	2575–2324	2469–2349
Gif-4393	2710 ± 100	3	La Moulinade	Delibrias et al., 1982	Chenier-like	2723–2241	2608–2335
Gif-3757	2770 ± 100	3	Brouage marsh	Delibrias et al., 1982	Subtidal (marsh)	2751–2301	2682–2420
Poz-6076	2815 ± 30	1	Pertuis Breton	Chaumillon and Weber, 2006	Subtidal (marine)	2714–2480	2692–2561
Gif-3382	2880 ± 100	3	La Moulinade	Delibrias et al., 1982	Chenier-like	2878–2359	2776–2512





**Fig. 5.** Definition of the coarse-grained sedimentation pulses (CSPs) described in the text. A, Calibrated  $^{14}\text{C}$  ages of the Pertuis Charentais coarse-grained sediment bodies listed in Table 1. B, Output of the *BchronDensity* function. Thick green line corresponds to the mean age distribution after 1000 *BchronDensity* iterations. Light green shading corresponds to the  $2\sigma$  envelope.

series for the 1450-yr cycle is in phase with that obtained for the IRD time series (Fig. 7C). The occurrence of CSPs is therefore likely conditioned by a decrease in the frequency and/or intensity of North Atlantic storms. Such conditions are believed to allow the deposition and long-term preservation of coarse-grained sediments in the Pertuis Charentais. It is likely that coastal barriers in the study area repeatedly switched between phases of destruction during HSPs (ca. 3500 to 2700, 2000 to 1200, and 600 to 150 cal. yr B.P.) and resilience between HSPs (2700 to 2000 and 1200 to 600 cal. yr B.P.)

## 5.2. Impact of wave climate

According to the present-day wave climate studies described above (Martínez-Asensio et al., 2016; Poirier et al., 2017), wave-induced sediment transport in the study area increases with positive NAO and negative EA/WR conditions. Several reconstructions of low- to high-frequency changes in the NAO index are available for the late Holocene to historical periods, with differences in temporal coverage and resolution (Fig. 7E; Baker et al., 2015; Olsen et al., 2012; Ortega et al., 2015; Proctor et al., 2000; Trouet et al., 2009). The EA/WR atmospheric circulation pattern has received less attention, with a focus mostly on its impact on temperature and precipitation in western Europe and in the Mediterranean region (Ionita, 2014; Krichak and Alpert, 2005; Lim, 2015, and references therein). To our knowledge, no reconstruction of the late Holocene EA/WR variability exists yet. Given that a positive correlation between EA/WR and

precipitation rates is observed across Asia (Barnston and Livezey, 1987), with negative EA/WR conditions inducing a drier climate, we use a record of late Holocene summer (JJAS) precipitation from lake Ngamring Tso, southern Tibet (Conroy et al., 2017) as an indirect proxy of the long-term EA/WR variability (Fig. 7F).

CSPs A to E (i.e. 450 to 1250 cal. yr B.P.) coincide with dominantly positive NAO conditions prevailing from about 500 to 1900 cal. yr B.P. (Fig. 7E; Baker et al., 2015; Olsen et al., 2012), and with dominantly negative EA/WR conditions from about 400 to 1700 cal. yr B.P. (Fig. 7F; Conroy et al., 2017). Although the  $1\sigma$  age ranges of CSPs A to E coincide with minor, slightly positive EA/WR peaks occurring within the overall negative trend (Fig. 7F), they also closely match positive NAO peaks (Ortega et al., 2015; Trouet et al., 2009), or periods of decreasing NAO after these peaks (Olsen et al., 2012), depending on the reconstructions (Fig. 7B). It is therefore very likely that CSPs A to E reflect periods of increased deposition of coarse-grained sediments in the Pertuis Charentais, induced by a more energetic wave climate. This interpretation partly applies for CSPs F and G (2400 and 2650 cal. yr B.P.), as they closely match the likely most negative EA/WR peaks reached since the last 3500 years, but also moderately to strongly negative NAO peaks (Fig. 7E,7F). Such climate conditions have no present-day analogue, and it is therefore difficult to determine to which extent they contributed to a more energetic wave climate as for CSPs A to E.

## 5.3. Climate control on CSPs along European coasts

Additional  $^{14}\text{C}$  and OSL ages obtained on wave-influenced environments of western Europe (Fig. 6; Table 3) provide some clues about the broader geographical and hydrodynamical context in which CSPs have been recorded. Most  $^{14}\text{C}$  and OSL ages from northern Europe (above  $43^\circ\text{N}$ ) could be related to CSPs identified in the Pertuis Charentais database with fair (e.g. UQ-2058) to excellent agreement (e.g. SacA-23973; Table 1). Conversely, agreement is poor or non-existent for  $^{14}\text{C}$  ages from southern Spain and Portugal (around  $37^\circ\text{N}$ ). Spit growth in this area may not only depend on wave climate variability, but also indirectly on progradation of

**Table 2**  
Chronological boundaries of coarse-grained sedimentation pulses (CSPs).

CSP	$2\sigma$ range (cal. yr B.P.)	$1\sigma$ range (cal. yr B.P.)	Normal distribution (cal. yr B.P.)
A	526–362	466–420	$445 \pm 50$
B	753–543	676–616	$649 \pm 64$
C	874–719	817–773	$797 \pm 47$
D	1070–866	995–937	$968 \pm 62$
E	1328–1152	1263–1213	$1240 \pm 53$
F	2510–2333	2445–2395	$2422 \pm 54$
G	2748–2544	2673–2615	$2646 \pm 62$

**Table 3**  
<sup>14</sup>C database (Europe).

Reference	Lab code	Age (uncal. yr B.P.)	Method	Location	Latitude	Depositional environment	2σ range (cal. yr B.P.)	CSP
Lindhorst et al., 2010	KIA-31638	775 ± 25	<sup>14</sup> C	Sylt, Germany <sup>a</sup>	54° 54,7' N	Spit	562–261	A
Lindhorst et al., 2010	KIA-31639	1350 ± 30	<sup>14</sup> C	Sylt, Germany	54° 54,7' N	Spit	1121–725	D
Roberts and Plater, 2007	several <sup>b</sup>	1005 ± 50	OSL	Dungeness, United Kingdom	50° 55,9' N	Ridge (plain)	1053–856	D
van Vliet-Lanoë et al., 2014	SacA-23972	565 ± 30	<sup>14</sup> C	Plage de la Torche, France <sup>c</sup>	47° 50,3' N	Beachrock	297–178	None
Giot, 1998	Gif-891	1100 ± 90	<sup>14</sup> C	Plage de la Torche, France	47° 50,3' N	Beach (unconsolidated)	876–548	B
van Vliet-Lanoë et al., 2014	SacA-23973	1390 ± 30	<sup>14</sup> C	Plage de la Torche, France	47° 50,3' N	Beach (unconsolidated)	1037–920	D
van Vliet-Lanoë et al., 2014	Poz-36728	1435 ± 30	<sup>14</sup> C	Plage de la Torche, France	47° 50,3' N	Beach (unconsolidated)	1088–948	D
van Vliet-Lanoë et al., 2014	Poz-37202	1460 ± 30	<sup>14</sup> C	Plage de la Torche, France	47° 50,3' N	Beach (unconsolidated)	1129–972	D
van Vliet-Lanoë et al., 2014	Poz-36729	1600 ± 30	<sup>14</sup> C	Plage de la Torche, France	47° 50,3' N	Beach (unconsolidated)	1262–1159	E
van Vliet-Lanoë et al., 2014	Poz-34212	1605 ± 30	<sup>14</sup> C	Plage de la Torche, France	47° 50,3' N	Beachrock	1264–1164	E
van Vliet-Lanoë et al., 2014	Poz-31327	1620 ± 30	<sup>14</sup> C	Plage de la Torche, France	47° 50,3' N	Beach (unconsolidated)	1271–1174	E
Giot, 1981	Gif-1100	2670 ± 110	<sup>14</sup> C	Plage de la Torche, France	47° 50,3' N	Beachrock	2701–2163	F and/or G
Pontee et al., 1998	n.a. <sup>d</sup>	1421 ± 162	<sup>14</sup> C	Cordon de Richard, France <sup>e</sup>	45° 29,3' N	Ridge (chenier)	1292–686	D
Clavé, 2001	UQ-1983	1600 ± 135	<sup>14</sup> C	Cordon de Richard, France	45° 29,3' N	Ridge (chenier)	1460–915	E
Pontee et al., 1998	n.a.	2575 ± 120	<sup>14</sup> C	Cordon de Richard, France	45° 29,3' N	Ridge (chenier)	2647–2005	F?
Clavé, 2001	Beta-102696	2590 ± 70	<sup>14</sup> C	Cordon de Richard, France	45° 29,3' N	Ridge (chenier)	2493–2117	F?
Clavé, 2001	Beta-102695	2850 ± 90	<sup>14</sup> C	Cordon de Richard, France	45° 29,3' N	Ridge (chenier)	2819–2377	G
Clavé, 2001	UQ-2058	2975 ± 120	<sup>14</sup> C	Cordon de Richard, France	45° 29,3' N	Ridge (chenier)	3091–2465	G?
Feal-Pérez et al., 2014	CNA-1052	1048 ± 35	<sup>14</sup> C	Punta Gallín, Spain <sup>f</sup>	43° 33,4' N	Beach (unconsolidated)	643–468	None
Feal-Pérez et al., 2014	CNA-1053	1347 ± 36	<sup>14</sup> C	Punta Gallín, Spain	43° 33,4' N	Beach (unconsolidated)	907–675	C
Zazo et al., 1994	R-2207	1440 ± 50	<sup>14</sup> C	El Rompido, Spain <sup>g</sup>	37° 13,0' N	Spit	933–549	None
Zazo et al., 1994	R-2179	1460 ± 50	<sup>14</sup> C	El Rompido, Spain	37° 13,0' N	Spit	953–560	None
Zazo et al., 1994	R-2180	1875 ± 50	<sup>14</sup> C	El Rompido, Spain	37° 13,0' N	Spit	1369–941	E?
Zazo et al., 1994	R-2203	2605 ± 50	<sup>14</sup> C	El Rompido, Spain	37° 13,0' N	Spit	2270–1732	None
Moura et al., 2007	IRPA-20056	710 ± 20	<sup>14</sup> C	Armação de Pêra, Portugal	37° 05,9' N	Beachrock	280–0	None
Moura et al., 2007	Beta-185788	2280 ± 40	<sup>14</sup> C	Armação de Pêra, Portugal	37° 05,9' N	Beachrock	1840–1351	None
Zazo et al., 1994	R-2204	1490 ± 50	<sup>14</sup> C	Doñana, Spain	36° 49,7' N	Spit	986–594	C
Zazo et al., 1994	R-2187	1790 ± 50	<sup>14</sup> C	Doñana, Spain	36° 49,7' N	Spit	1296–882	D
Zazo et al., 1994	R-2188	1850 ± 50	<sup>14</sup> C	Doñana, Spain	36° 49,7' N	Spit	1340–924	None
Zazo et al., 1994	R-2185	1860 ± 50	<sup>14</sup> C	Doñana, Spain	36° 49,7' N	Spit	1350–929	E?
Zazo et al., 1994	R-2210	2010 ± 50	<sup>14</sup> C	Doñana, Spain	36° 49,7' N	Spit	1535–1078	E
Zazo et al., 1994	R-2205	2185 ± 50	<sup>14</sup> C	Doñana, Spain	36° 49,7' N	Spit	1729–1273	None
Rodríguez-Polo et al., 2009	AERO	1190 ± 80	<sup>14</sup> C	Valdelagrana, Spain	36° 32,2' N	Spit	695–328	None
Rodríguez-Polo et al., 2009	ESCA	1250 ± 70	<sup>14</sup> C	Valdelagrana, Spain	36° 32,2' N	Spit	773–417	None
Rodríguez-Polo et al., 2009	TORVC-4	1590 ± 60	<sup>14</sup> C	Valdelagrana, Spain	36° 32,2' N	Spit	1109–671	None
Zazo et al., 1994	R-2186	2120 ± 50	<sup>14</sup> C	Valdelagrana, Spain	36° 32,2' N	Spit	1674–1226	None
Zazo et al., 1994	R-2181	2270 ± 50	<sup>14</sup> C	Valdelagrana, Spain	36° 32,2' N	Spit	1826–1340	None
Zazo et al., 1994	R-2182	2320 ± 50	<sup>14</sup> C	Valdelagrana, Spain	36° 32,2' N	Spit	1882–1386	None
Zazo et al., 1994	R-2208	3145 ± 50	<sup>14</sup> C	Valdelagrana, Spain	36° 32,2' N	Spit	2864–2345	G

<sup>a</sup> ΔR = −23 ± 92; average of values Nos. 73, 74 and 75 (see on-line “Marine Reservoir Correction” database for details; Reimer and Reimer, 2006).

<sup>b</sup> Average of samples 73BH-7/1; 73BH-9/1,2,3; 73BH-10/1,2,3. OSL ages were reported in years before 2000 CE and were therefore offset by 50 years for comparison with <sup>14</sup>C expressed in cal. yr B.P.

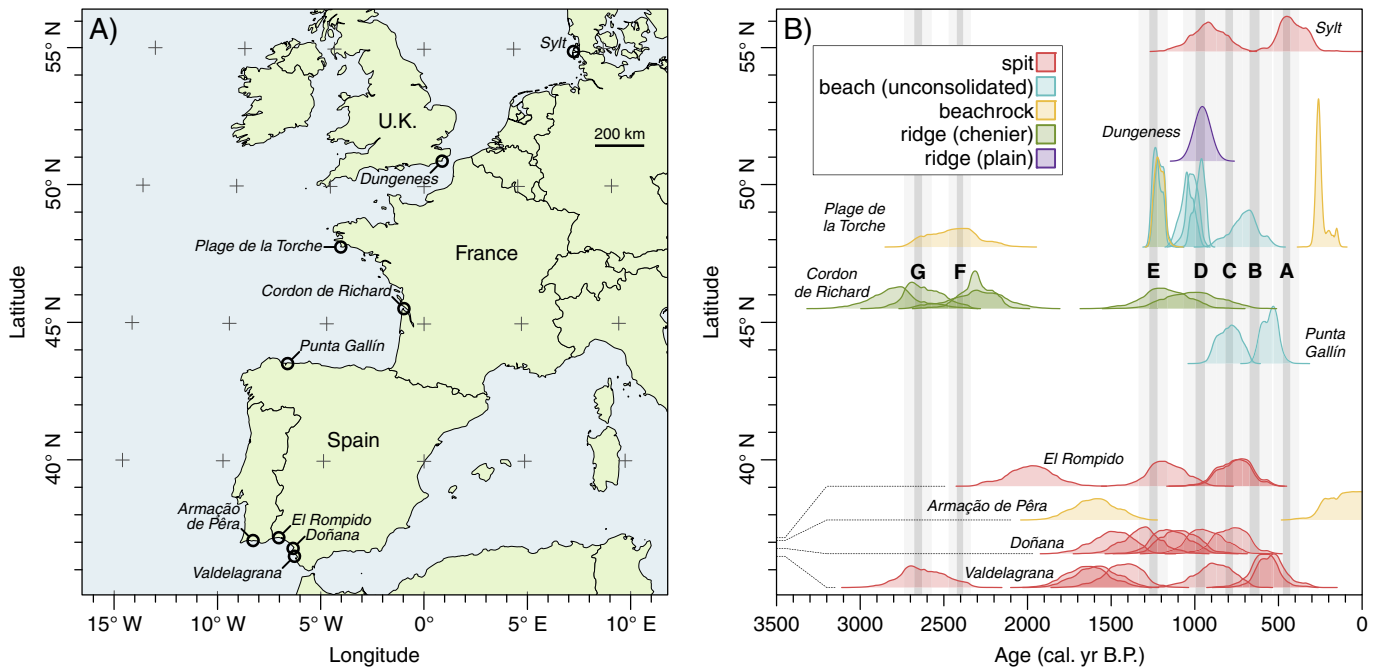
<sup>c</sup> ΔR = −40 ± 23; value No. 1075.

<sup>d</sup> n.a., not applicable.

<sup>e</sup> ΔR = −34 ± 60; value No. 1574.

<sup>f</sup> ΔR = +101 ± 65; average of values Nos. 132, 1553 and 1554.

<sup>g</sup> ΔR = +253 ± 110; average of values Nos. 133 to 144 and 146.



**Fig. 6.** Recognition of CSPs in wave-influenced depositional environments of the exposed coasts of western Europe. A, Map of Europe showing the location of the studied environments. B, Calibrated age distributions of the  $^{14}\text{C}$  ages listed in Table 3. Ages are ordered vertically by latitude. Background light and dark grey shading correspond to the CSP  $2\sigma$  and  $1\sigma$  age ranges, respectively (Table 3).

adjacent deltas (e.g. Guadiana and Guadalquivir) driven by human activities and changes in precipitation regimes (Lario et al., 1995).

Local effects may indeed play a role in the Cadix Gulf, as well as in other areas considered here, but the overall difference between northern and southern Europe (Fig. 6) is more likely explained by spatial variability in wave climate across the North Atlantic Ocean. Spatially-explicit correlations between the NAO index and wave height show a marked north-south dipole pattern. Transition area of zero correlation occurs at the northwestern corner of Spain, around  $43^\circ\text{ N}$  (Fig. 6A; Martínez-Asensio et al., 2016). Southwards of this limit, for instance in the Cadix Gulf, wave height decreases with positive NAO conditions. The combined influence of low-frequency storminess and high-frequency NAO variability, which likely drives the occurrence of CSPs in the Pertuis Charentais and elsewhere in northern Europe, is therefore not valid for this area. This opposite north/south pattern does not exist for the EA/WR index (Martínez-Asensio et al., 2016).

#### 5.4. Uncertainties and perspectives

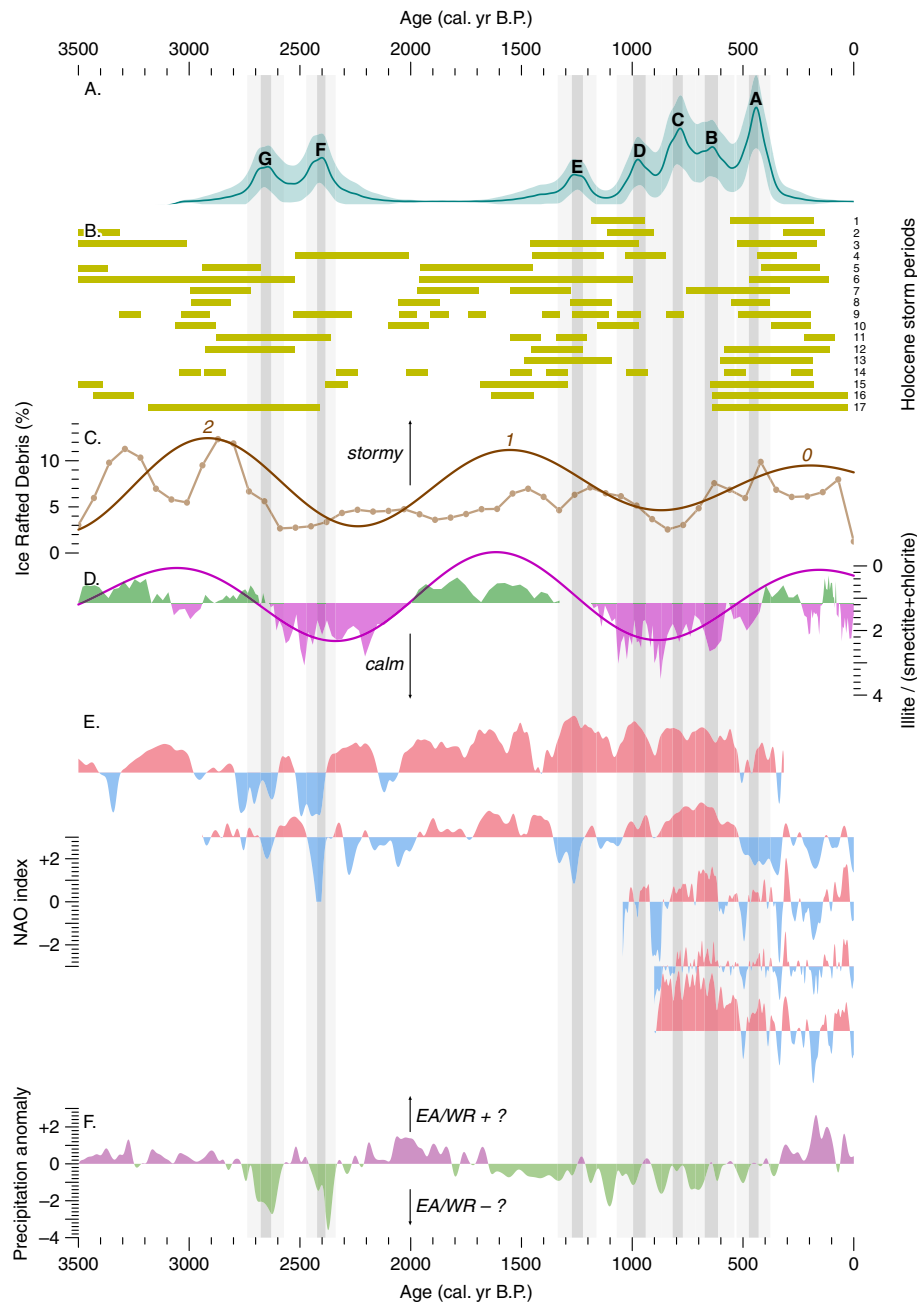
The present study raised a number of questions that would merit further consideration. As shown above, the EA/WR atmospheric circulation pattern seems to be an important driver of the occurrence of CSPs. We used (Conroy et al., 2017) lake record of summer (JJAS) precipitation rates over southern Tibet as an indirect proxy of the long-term EA/WR variability, but the influence of EA/WR on wave climate of the Pertuis Charentais predominates in winter (DJF; Poirier et al., 2017). With a sampling resolution of 25 years, it could be expected that this lake record provides a smoothed, long term-averaged reconstruction of the EA/WR circulation pattern. Further work is however needed to determine to which extent it can be reliably used as a proxy of the winter EA/WR during the late Holocene. Sediment records, speleothems or tree ring data recovered

from the EA/WR poles of action, in western Europe and central Asia (Barnston and Livezey, 1987), might be useful to check this hypothesis.

Reservoir age of the water masses on the northern Icelandic shelf ( $65^\circ\text{ N}$ ) varied by  $\pm 150$  years since about 1300 cal. yr B.P., depending on the strength of the North Atlantic Current (NAC; Wanamaker Jr et al., 2012). Feedbacks between the NAC and the NAO atmospheric circulation pattern have also influenced  $\Delta R$  along French Atlantic coasts between 1885 and 1950 CE by 90 to 170 years (Tisnérat-Laborde et al., 2010). In the present study, such changes in the  $\Delta R$  parameter were not considered for calibrating the  $^{14}\text{C}$  ages (Table 2), which could have an impact on the chronological boundaries of CSPs. The overall good agreement between CSPs and late Holocene climate changes in the North Atlantic Ocean suggests that this impact is probably minor, but additional data would help to raise this uncertainty.

Definition of CSPs F and G in the Pertuis Charentais mainly relied on  $^{14}\text{C}$  dates with a large dating error (scintillation method; Table 1). New data may help to evaluate more precisely the chronological boundaries of CSPs that could have occurred during the penultimate period of decreased storminess, from about 2000 to 2700 cal. yr B.P. (Fig. 5).

Additional geochronological studies should also be carried out along the coasts of western Europe, in order to better constrain the spatial and temporal extent of the CSPs evidenced in the Pertuis Charentais. Dating of beachrocks should be avoided, as carbonate cementation involved in their formation has complex, multifactorial causes controlled by water temperature, pH, salinity, dissolved ions, organic matter and bacteria, to name but a few (Voudoukas et al., 2007). This could explain the overall low agreement between CSP age ranges and  $^{14}\text{C}$  dates obtained on beachrocks in Plage de la Torche (France) and Armação de Pêra (Portugal,  $37^\circ\text{ N}$ ), the latter being moreover located in the negative NAO-wave height correlation area.



**Fig. 7.** Coarse-grained sedimentation pulses with respect to late Holocene climate change in the North Atlantic Ocean since 3500 cal. yr B.P. A, Mean age distribution of integrated  $^{14}\text{C}$  data, as in Fig. 5B. B, Periods of increased Holocene storminess (1–17, redrawn from Costas et al., 2016, see references therein). C, Ice-rafted debris stack record with 1450-year wavelet reconstruction (Bond et al., 2001). Numbers in italics indicate the corresponding Bond cycles. D, Clay mineralogy record of NW Mediterranean lagoonal sediments with 1450-year wavelet reconstruction (Sabatier et al., 2012). Note the inverted y-scale, with large values corresponding to decreased storminess. E, Reconstructions of the North Atlantic Oscillation index, including from top to bottom, Olsen et al., 2012; Baker et al., 2015; Proctor et al., 2000; Ortega et al., 2015; Trouet et al., 2009. F, Precipitation anomalies over the Tibetan Plateau (Conroy et al., 2017), used as an indirect proxy of the East Atlantic/West Russia index. All time series are scaled and smoothed with a robust cubic spline. Background light and dark grey shading correspond to the CSP  $2\sigma$  and  $1\sigma$  age ranges, respectively (Table 3).

## 6. Conclusions

Compilation of existing  $^{14}\text{C}$  data performed on coarse-grained sediment bodies of the Pertuis Charentais helped to better understand the temporal trends in high-energy marine sedimentation along coasts of the northeastern Atlantic Ocean, between the so-called Holocene Storm Periods. CSPs are defined as periods of increased accumulation of coarse-grained sediment particles identified in the study area, and possibly in other wave-exposed

environments of western Europe, above  $43^\circ\text{N}$ . In first order, the occurrence of CSPs is likely controlled by the 1450-yr cycle of North Atlantic storminess. Decreased frequency and/or intensity of erosive storm events is interpreted to allow the deposition and long-term preservation of coarse-grained sediment deposits. In second order, the occurrence of CSPs is likely controlled by changes in the North Atlantic wave climate, driven by low-frequency variability in the NAO and EA/WR atmospheric circulation patterns. Combination of positive NAO and negative EA/WR conditions is known to induce

more energetic waves across the North Atlantic Ocean. Such conditions are therefore expected to increase transport of coarse-grained sediments to the coast, contributing to the formation of coastal barriers. Although spatially restricted, our data highlight the complex climate control on sediment supply and preservation on the edification of marine coastal barriers. Our results confirm that the Pertuis Charentais have the potential to record climate changes that occurred during the late Holocene with reasonable accuracy. Results also suggest that the chronological boundaries of CSPs, as opposed to that of HSPs, could be used as a diagnostic tool to differentiate storm deposits indicative of sudden, episodic high-energy sedimentation, from marine sediment bodies resulting from the sustained action of higher-than-average wave-induced sediment transport. They could also provide additional support in the interpretation of late Holocene coastal paleoenvironments. Integration of existing and new geochronological data obtained on coarse-grained sediment bodies of western European coasts may help to better constrain CSPs in space and time.

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