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## **Holocene formation and evolution of coastal dunes ridges, Brittany (France)**

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1 **HOLOCENE FORMATION AND EVOLUTION**

2 **OF COASTAL DUNE RIDGES, BRITTANY (FRANCE).**

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13  
14  
15 **Abstract**

16 Holocene coastal dune formation under a continuously rising Sea-Level (SL) is an abnormal response  
17 to increasing storm frequency. The aim of this work is to understand the coastal sedimentary budget  
18 and the present-day sand starvation, controlled by climate and man. Dating in Brittany shows that  
19 aeolian deposition initiated from c.4000 cal BP, with the slowing-down of the SL rise. **Prehistorical**  
20 **dunes** appeared here from c.3000 cal BP, without SL regression. After, further building phases  
21 recycled the same stock of sands. **Historical dunes I** developed from c.350 AD. Major storms  
22 between 900 -1200 AD resulted in the construction of washover coastal ridges, the **Historical dunes**  
23 **II**. A part of the sand was evacuated offshore. From c.1350 AD, the pre-existing ridges are reworked  
24 forming the **Historical dunes III**, leading to a rapid coastal erosion and inland drift. Holocene dunes  
25 with a rising SL, constitute a temporary anomaly, mostly forced by man, soon erased by storms in  
26 Brittany.

27  
28 **Key words:** dunes, ,Holocene, climate, sand starvation, anthropic perturbation  
29

## 30 INTRODUCTION

31

32 Coastal dunes are connected to sea-level vicinity, and storminess, as a function of sedimentary supply  
33 (Einsele, 1993; Orford et al., 2000; Maüz et al., 2013). In that way, anthropic perturbations, such as  
34 agro-pastoral practices, may favour sand remobilisation on a regional scale (Pye and Tsoar, 2013).  
35 Most studies link the aeolian coastal deposits to regressive phases (Pye and Tsoar, 2013; Maüz et al.,  
36 2013), and only a few to a rising SL (Pye and Tsoar, 2013; Regnauld et al., 1996; Szkornik et al.,  
37 2008). A link between historical dune building and periods of limited marine regression (c. 50 cm) has  
38 been suggested (Lamb, 1995; Orford et al., 2000). Dunes formation in a context of rising Relative Sea-  
39 Level (RSL) results from the reworking or overstepping of the coastal foredune or storm ridge.

40 The history of the Holocene RSL on the North West European Shelf is a continuous rise followed by  
41 decelerating steps (Shennan and Horton, 2002; Goslin, 2014). An increased storminess is responsible  
42 for numerous episodes of sand drift and dune building along the western European coast, especially  
43 during the coolest part (AD 1570–1900) of the Little Ice Age (LIA, 1350-1880; Lamb, 1995; Barring and  
44 Fortuniak, 2009; Clarke and Rendell, 2009). The degree of preservation of dunes is largely  
45 constrained by the speed of the RSL rise and the wave energy regime, expressed here in terms of  
46 storm activity (Pye and Tsoar, 2013). The availability of sediment for dune building is controlled by  
47 sediment accumulation in the nearshore environment (<10 m deep; Einsele, 1993). Firstly, this  
48 requires low energy waves that allow an accumulation of sand on the beach profile and permit its drift  
49 in the form of a foredune (Short and Hesp, 1982). Secondly, it requires prevailing onshore winds to  
50 blow this sand inland. The source of available sands can be variable and include the reworking by  
51 RSL rise of past periglacial deposits, saprolites, or old marine deposits with some importation to the  
52 shore by river (Kelley et al., 2005). Additionally, large shelves, such as the shallow English Channel and  
53 North Sea, are generally excellent sediment suppliers, compared to the narrow Armorican platform  
54 surrounding the dune coastal ridges studied in the present paper.

55 From a general point of view, in summer, dissipative beaches present a wide foreshore, a low  
56 gradient, and fine sands that are less resistant to wind flow, and are more conducive for aeolian sand  
57 transport than the steeper reflective beaches (Hesp, 1999). Reflective beaches are much less  
58 favorable for aeolian transport (Hesp, 1999). The dune building process mostly results from the impact  
59 of recurrent storm periods that lower the beach profile, especially at the High Water Mark (HWM;

60 Hallégouët, 1981; Ruz and Meur-Ferec, 2004). The beach profile becomes dissipative as it was the  
61 case in Brittany in springs of 2010, 2013 and 2014: a thick foredune was formed in summer 2010 at  
62 Guisseny (Fig. 1a; Suanez et al., 2012) following a spring storm. Extreme storm events are  
63 responsible for erosion processes and over the course of a single extreme event, thick sediment  
64 deposition from the upper shoreface to the lower foreshore can occur (Houser et al., 2008, Fruergaard  
65 et al., 2013). They can also provoke erosive processes on the coast by offshore exportation of sand  
66 (Goff et al., 2004). This seems to be the case for western Brittany, after the long period of extreme  
67 waves in February 2014 (Fig. 2).Vegetation is also a major factor controlling the formation and  
68 morphology of coastal dunes (Hesp, 2002, Pye and Tsoar, 2013). Plant cover is responsible for  
69 roughness and reduction in the wind velocity, which increases the trapping of sands (Hesp et al.,  
70 2009). Climate and anthropogenic activities may thus influence dune formation.

71 Brittany is one of the most exposed coasts in France, characterized by a limited sand supply on a very  
72 flat polygenetic rocky platform, especially along the western and northern coasts. The coastal  
73 accumulations usually form ridges, topped with a thin dune, isolating partly (lagoon) or totally (marsh).  
74 depressions or valleys Today, the RSL keeps rising (Cazenave and Remy, 2011) and coastal retreat  
75 occurs at a rate of about 1m/yr in the bay of Audierne (1966 to 1988 ; Faye et al., 2007). Extreme  
76 storms mostly develop when the North Atlantic Oscillation (NAO) mode is negative on the decennial  
77 scale, although the NAO can be interrupted by shorter positive events, especially during a high Atlantic  
78 Multidecadal Oscillation mode (AMO; Van Vliet-Lanoë et al., 2014b). Since 2007, storms frequency is  
79 rising, reactivating the coastal retreat, with no marked drift of sands. The aim of this paper is to  
80 synthesize the conditions, timing and meaning of dune formation in Brittany.

81

## 82 **GEOLOGICAL AND GEOMORPHOLOGICAL SETTING**

83 From a geodynamical point of view, Brittany's peninsula is related to the post-rift subsidence of the  
84 Atlantic margin (Ziegler, 1992). The recent Holocene RSL curve established for Brittany (Goslin, 2014)  
85 indicates an estimated subsidence rate of ca. - 0.3 mm/year for the last 2000 years. Reconstructed  
86 Regional Relative Sea Level (RRSL) shows progressively a progressive slow-down of the rise, with  
87 clear inflexion points around 7000 cal BP (calibrated years before present), 6000 cal BP, 4500 cal BP  
88 and around the 3-2000 cal BP period, without any distinct oscillation or step-wise character (Goslin,  
89 2014). The tidal platform is mostly rocky, usually wide (one to several kilometres), and deepens very

90 regularly to -30 m offshore. Regional tidal regimes are mostly macrotidal. The offshore sedimentary  
91 cover is thin and limited, dominated by rock outcrops. Generally, terrigenous sediment supply by  
92 rivers is limited. Southern Brittany, especially to the East, is an exception due to important rivers and  
93 old marine formations that provide a larger sand supply. Soil erosion is the main provider for coastal  
94 sands via the rivers (Fan et al., 2004; Guillén et al, 2006). Slash and burn practices produced a limited  
95 forest clearance from c. 4000 cal BP (Early Bronze Age; Marguerie, 1992) exposing to interglacial  
96 rainfall a relictual periglacial topography (Van Vliet-Lanoë and Guillocheau, 1995). True agriculture  
97 developed regionally during the Iron Age, and the other main forest clearance epochs occurred in the  
98 Merovingian (VI-VIII<sup>th</sup> centuries) and XV-XVII<sup>th</sup> centuries. Damming of the rivers and estuaries  
99 developed from the XI<sup>th</sup> century, limiting the sediment supply to the coast.

100

## 101 **METHODOLOGY**

102 This work is mostly based on coastal section surveys (Figs. 1a, 1b) completed by vibrocores and  
103 drilling transects at Audierne Bay, Kermor-Tudy (Benodet Bay), Grand Loch de Guidel and Kerzine  
104 (Lorient), Le Conquet, Pors Milin (Brest), Le Vourch and Guisseny (Ploudalmézeau). Stratigraphic  
105 description with AMS-14C dates have been undertaken on these sections (Goslin, 2014; Van Vliet-  
106 Lanoë et al., 2014 a, b) and completed in March 2014. The stratigraphical data of Meurisse-Fort (2009)  
107 were used from Normandy and Picardy. In this study, 10 new AMS-14C dates (Poznan Radiocarbon  
108 Lab., Poland) have been obtained (Table 1), exclusively in connection with dune building phase, with a  
109 calibration using the CALIB 7.0. Software (Stuiver and Reimer, 2005) and the radiocarbon calibration  
110 (IntCal13; Reimer et al., 2013). Considering the regional scarcity in <sup>14</sup>C datable material, we used all  
111 available information existing in the literature. In this paper, we discuss 81 pertinent dating of dunes  
112 and coastal ridges from Brittany, Normandy and Picardy, directly compiled on Figure 1b.

113 Palaeo-storm events were identified through sedimentary fabrics (Buynevich et al., 2004). Palaeo-  
114 storminess traces have already been discussed and events were extracted from the Holocene prism  
115 stratigraphy (Van Vliet-Lanoë et al., 2014b). The RSL curve for Brittany (Goslin et al., 2013; Goslin,  
116 2014) was calibrated with the local tidal range, using a multi-proxy analysis based on the combined of  
117 geochemical, micromorphological and isotopic indicators.

118

## 119 **SEA-LEVEL AND STORMINESS MORPHOLOGICAL IMPACT**

120 The effects of storms on Holocene sedimentary sequences are particularly important since the mid-  
121 Holocene period, when the regional RSL reached a position close to the modern one. The  
122 sedimentary record of RSL rise and particularly the High Stands (HS) were perturbed by the increased  
123 strength of storm surges, mostly after Roman times (Meurisse-Fort, 2009). Large-scale (pluri-  
124 decimetric to metric) pseudo-oscillations observed in SL reconstructions (e.g. Morzadec, 1974); are  
125 the expression of disturbances of the sedimentary record induced by storms (Goslin et al., 2013; Van  
126 Vliet-Lanoë et al., 2014a). Extreme storms or several days' gales could be responsible for major  
127 morphological changes, in the former ridge and back-ridge zones. From our observations, pseudo  
128 "HS" seem to be perched notches preserved in sands dunes or depositional terraces, situated at 1-10  
129 m above the HWM, that may form as a result of dispersive swash action (McKenna et al., 2012) and  
130 commonly forming in lagoons perched washover fans. Low standing storm ridges result from run-up erosion  
131 of the crest, favouring breaching (Fig. 2). Storm-cut platforms develop in soft material down the ridge at the level  
132 of the average Low Water Mark (LWM; Retallack and Roering, 2012 ; Fig. 2). It allows to interpret "low  
133 surface" as erosion surface formed as the result of sediment export by storm (Fig. 2). Recurrent  
134 severe storms may accentuate the erosion. After the storm, the restoration of the normal beach profile  
135 and of the coastal ridge by swell and wind may take some time, following the sediment supply of the  
136 beach.

#### 137 **DUNES BUILDING PHASES: DATA**

138 Aeolian deposits are rarely resting directly on rock but commonly found on beach deposits, or resting  
139 on cultivated soils or peats. Stabilisation periods are often marked by humic soil or peat formation and  
140 these are often interrupted by thin aeolian sand sheets, or, more rarely, by thin colluvial loamy  
141 deposits (in the vicinity of cliffs). Convolute deformations can be observed in several sites. In  
142 washover fans, they are often associated with load casts (Lindström 1979), although in some places  
143 they result from cattle. It is debated whether the swash or animal treading hurts oversaturated sands  
144 (Allen, 1982). Today, in Ireland, cattle commonly visit the dunes and shores. In Picardy, the coast was  
145 pastured by the marsh little ox (Meurisse-Fort, 2009). For the Merovingian dunes of northern Brittany,  
146 sheep and goats are probably responsible for the small-sized trampling deformations.

147

#### 148 ***The pre-historical dunes, 3050 à 2300 cal BP*** (Fig. 1b)

149 The base of Penhat dune (Crozon, Fig. 1a), attest to the oldest sand drift (c. 5280 cal BP; Meurisse-  
150 Fort, 2009). At Audierne (Gwendrez; Fig.1a), the onset of dune accretion was later than 5000 cal BP

151 (< 4950 cal BP; Haslett et al.; 2000). In the Kermor marshes (Fig. 1a), a “brackish” sandy peat resting  
152 on a fresh water peat yields an age of c. 5122 cal BP at +0.7 m NGF, perhaps attesting to the breach  
153 of coastal ridges by storms with limited aeolian sand drift. At the Anse du Verger (NE Brittany), a date  
154 of 3600 cal BP was obtained for the onset of dune building (Regnauld et al., 1996).

155 After the construction of the first coastal ridge, peat began to accumulate in back-ridge depressions  
156 during the Halstatt period, as in the Bay of Audierne (c. 2450 cal BP; Carter et al. 1993) and also at  
157 Santec on the northern coast of Brittany (c. 2420 cal BP, Morzadec, 1974). The first well-recorded  
158 building of the dunes occurred between 2450-2350 cal BP at the Bay of Audierne (Van Vliet-Lanoë et  
159 al., 2014a). Here, a true storm ridge was topped with a dune dated to 2339 - 2487 cal BP (Van Vliet-  
160 Lanoë et al., 2014a) as also at the Anse du Verger (NE Brittany c. 2170 cal BP (Regnauld et al., 1996)

161

162 ***The historical dunes*** (Fig. 2)

163 *First generation, 350 AD- 800 AD*

164 Sand dune invaded the St Urnel cemetery (Bay of Audierne) in late Roman time (III<sup>d</sup> century; Giot and  
165 Monnier, 1977). Breaching of the coastal ridge and flooding reappear locally at the Bay of Audierne  
166 (Lescor's marsh and Troenoen lagoon) after 320 AD, in association with aeolian drift. A brief  
167 stabilization is recorded here between 620 and 680 AD, as also in SW and northern Brittany (Table 1,  
168 Fig. 1b).

169

170 *Second generation, 800 AD- 1200 AD.*

171 A second dune invasion was well documented between c. 800 AD and c.1000 AD at St. Urnel (Giot  
172 and Monnier, 1977), mainly during the second half of the 11<sup>th</sup> century. This burial place was re-  
173 abandoned in the late 12th century (Giot and Monnier, 1977) with a renewed dunes invasion. This  
174 period was marked by giant storms, well-recorded at 900 AD in southern Brittany (Van Vliet-Lanoë et  
175 al., 2014b). A limited stabilisation was observed from 1000 to 1200 AD, which was recorded in the  
176 form of humic soils or peaty layers in the region, although it was frequently interrupted by giant storms  
177 in the form of washover fans during the XI<sup>th</sup> century (Van Vliet-Lanoë et al., 2014b). Around Brittany,  
178 the ridges were often truncated and/or buried by sand drift or splay (Table 1; Fogéo: Visset and  
179 Bernard, 2006 Treffiat, la Torche and Pors Milin: Van Vliet-Lanoë et al., 2014a; Baie des Trépassés:  
180 Carter et al., 2003; Plouguerneau, Morzadec, 1974).

181

182 *Third generation, from 1350 AD*

183 From c.1350 AD to c.1500 AD, a first period of sand drift was recorded, ending with brief stabilisations  
184 marked by humic soils from c.1400 to c.1550 AD (Fig. 1a), which were better developed than during  
185 the Medieval Climate Optimum (MCO).

186 In the Bay of Goulven, Guisseny and Plouguerneau (Fig. 1a), dunes continued to migrate during the  
187 XVII-XVIII<sup>th</sup> centuries. Such landward dune migration also occurred at Audierne and other places,  
188 particularly in SE Brittany (Guilcher and Hallégouët, 1991) in Normandy and Picardy (Meurisse-Fort,  
189 2009). Several churches and villages in these regions, as well as in Brittany and Picardy, were buried  
190 by sands in the late XVII<sup>th</sup> century in association with major gales. After a period of relative  
191 quiescence, storms and sand drift again destroyed church and villages in the region, with sand drifts  
192 up to 5 km inland. Major storm events occurred in 1795, 1808 and 1824.

193

194

## 195 **DISCUSSION**

196

### 197 ***Stratigraphy:***

198 The onset of sand drift leading to **Prehistorical dunes** development in Brittany occurred very locally  
199 after 5000 cal BP. Sand drift with dune building appeared closer to 2750 cal BP, as a result of  
200 enhanced storminess driven by a major cooling event associated with the Homeric solar low (Van  
201 Vliet-Lanoë et al., 2014b). Since c. 2750 cal BP, dunes developed in Brittany, as on most of the  
202 European coasts (Wilson et al, 2004; Meurisse-Fort, 2009). In the Bay of Audierne, a second phase of  
203 sand drift seems to develop after the onset of La Tène Iron Age (c. 2425 cal BP), reworking the former  
204 deposits and splaying the sand locally inland (Giot and Monnier, 1977). This occurred in response to a  
205 brief climate degradation that corresponded to the Greek solar low (centered around 2300 cal BP).

206 The onset of dune building occurred in a similar time span after 4000 cal BP in Picardy (Meurisse-Fort,  
207 2009), Aquitaine (Clarke et al., 2009), Northumberland (Orford et al., 2000) and Denmark  
208 (Clemmensen et al., 2009), after 3500 cal BP in Belgium (Anthony et al., 2010) and the Netherlands  
209 (Jelgersma and Van Regteren Altena, 1969). We may consider the onset of the dune building to be  
210 clearly connected with the slowing down in the SL rise from c.4500 cal BP (e.g. Goslin, 2014). From



211 that time, the HWM reached the present-day LWM, allowing an easier accumulation of sediment in the  
212 upper beaches. This indicated the onset of the Holocene high stand. The sediment supply lowered  
213 mechanically due to a slower SL rise and more limited coastal erosion, mostly driven by storm activity,  
214 especially during cold events (Van Vliet-Lanoë et al., 2014b), but temporarily rose by soil erosion  
215 resulting from Bronze Age forest clearance.

216

217 **Historical dunes** tell another story: the dunes are preserved at the northern and western coast at the  
218 Roman time, but did not yet exist as a coastal ridge in the South. A first splay of sands from 350 to 600  
219 and from 700 to 800 AD is recorded in Brittany. The onset of the **historical dunes I** is well developed  
220 at a wider regional scale, in SW Cotentin (Fig. 1; Meurisse-Fort, 2009) or in the Scillies' Islands -(250 -  
221 330 AD Banerjee et al. 2001). Some storms were recorded around 540 - 600 AD and 680 - 720 AD in  
222 Brittany (Van Vliet-Lanoë et al., 2014b), separated by a brief stabilization (640 - 760 AD; Patterson et  
223 al., 2010), which was well-recorded in the entire region (Fig. 1b). The start of these Merovingian dunes  
224 seems rather synchronic at the scale of western Europe (Fig. 1b) .related with cold and stormy  
225 weather from 200 AD (McCormick et al., 2012; Patterson et al., 2010). Sand drift was recorded from c.  
226 260 - 300 AD, probably when the morphology of the beaches was sufficiently lowered to become  
227 dissipative and the sensible vegetation was destroyed by agro-pastoral activities developed by the  
228 Merovingian (Fig. 1b). A major point is the occurrence of frequent cattle trampling that coincided with  
229 the development of forest clearance and agro-pastoralism in Brittany, Cotentin and Picardy, which  
230 promoted instabilities in the sand cover: these destabilised dunes thus drifted further inland, with the  
231 largest splay of the whole dunes' generations. Villages were found in nearshore positions during the  
232 VII<sup>th</sup> century. It seems possible that, from that time, the sedimentary budget seriously lowered, partly  
233 due to regional anthropogenic practices and mostly inland sand drift. The climate also cooled from 536  
234 - 540 AD in response to a volcanic eruption (Gao et al., 2008) and to a first solar minimum between  
235 615 and 755 AD (Usoskin et al., 2007), fitting the Hegire period (Fig. 1b). The cooling from c. 700 to  
236 800 AD is related to a second solar low, the Viking minimum. Here, dunes continue to grow  
237 transversely, attesting to a progressive aggradation and regular Westerly winds only. The record in  
238 storminess attests to recurrent storm events, but no giant one. This generation of sand drift is not clear  
239 in southern Brittany, where the coastal budget and wind directions are normally more favorable and

240 the coastal ridge seems still vegetated. The Quiberon peninsula was still covered by forest in the XI<sup>th</sup>  
241 century.

242

243 The onset of the **historical dunes II** (Brittany: 800 - 1250 AD) occurred synchronously all over Europe  
244 (Jelgersma et al., 1995; Meurisse-Fort, 2009). The period from 950 to 1350 AD is often considered to  
245 be the European Medieval mild period (Hughes and Diaz, 1994). Rainy conditions existed all over  
246 Europe (Maruchek, 2010), promoting sand supply by rivers. Villages migrated inland as well in  
247 Brittany, Picardy and the Netherlands (construction during the VII<sup>th</sup> century); this migration was also  
248 connected with the Viking invasions. Centennial hurricanes were recorded in Brittany, the southern  
249 British Islands and also along the coast of western Cotentin (Fig. 1a; Van Vliet-Lanoë et al., 2014b).  
250 Hurricanes are recorded in northern France (890 AD, Meurisse-Fort, 2009), in Belgium, with the  
251 formation of the Zwin in 1134 AD, and in the Netherlands, easing the formation of the Zuiderzee (large  
252 storms in 838 AD, 1170 AD and 1240 AD, Buisman, 1965). These events were connected with the  
253 Oort solar minimum (1010 - 1050 AD; Usoskin et al., 2007). A very negative NAO, which was even  
254 recorded on Greenland (Kobashi et al., 2013), was responsible for very high sea surface temperatures  
255 in the NW Atlantic, which resulted from a warm intertropical ocean and a positive AMO (Van Vliet-  
256 Lanoë et al., 2014b). Here, the inland sand drift inland was more limited, due to heavy precipitation,  
257 filling mostly lagoons. Storm ridges, which were eroded to their back (Fig. 2), are found along the  
258 current coastline. The whole coasts of Brittany were subjected to a major morphological  
259 transformation. In Picardy, the shift from transverse dunes to parabolic is explained by a reduction in  
260 sand supply from the beach, a more extensive vegetation cover (high water table) and potentially  
261 harsher winds (Meurisse-Fort 2009). A quiet period for sand drift seemed to exist from 1250 to 1340  
262 AD (Fig. 1b) (Van Vliet-Lanoë et al, 2014b) which corresponds mostly to the MCO. The climate during  
263 this period was mild and the NAO mostly positive (Trouet et al., 2009) which resulted from a rise of the  
264 AMO in response to strong solar activity (1100 - 1250 AD; Usoskin et al., 2007).

265

266 The onset of the **historical dunes III** (Brittany: 1350 AD to present) coincides with the onset of the LIA  
267 in Europe; it shows the initiation and build-up of the recent dunes (1350 - 1750 AD), with a  
268 development, maximized during the LIA. Most of the LIA was dominated by giant storms and an  
269 unstable negative decennial NAO (Trouet et al., 2009), despite few positive AMO events. High

270 frequencies of SW winds were recorded in Britain (London) from 1340 to 1420 and from 1470 to 1550  
271 AD (Lamb and Fryedalh, 2005), corresponding to mild weather with regular, westerly gales, attesting  
272 to the prevailing positive winter NAO and fair weather optimal for building dunes. A first period of dune  
273 building occurred from 1350 to 1550 AD (Fig. 1b), a period of relative storm quiescence, especially  
274 from 1350-1530 AD on the North and Central Atlantic (prevailing positive decennial NAO with low  
275 AMO modes), which corresponded to peculiar weather (Van Vliet-Lanoë et al., 2014b) and AMOC  
276 patterns (Trouet et al., 2012). A first stormy period of the LIA occurred from c. 1460 to c. 1630, which  
277 was responsible for more important dune activity that corresponded to the Spörer solar minimum  
278 (1460 - 1550 AD) and a prevailing negative winter NAO. From 1600 AD, sea surface temperatures  
279 North of Iceland dropped (Bendle and Rosell-Mele, 2007), attesting to a low AMO mode. The  
280 prevailing winter NAO mode was negative and boosted by the Maunder Minimum (1645 – 1715 AD;  
281 Usoskin et al., 2007; Trouet et al., 2009). In the Scillies, an important sand drift has been dated AD  
282 1560 – 1680 (Banerjee et al. 2001). This is the second period for giant storms, this time with a  
283 meridian wind pattern (Van Vliet-Lanoë et al., 2014b) driven by unstable jet streams and brief positive  
284 NAO anomalies. Sand drift was major, burying churches and villages along the English Channel. The  
285 long Great Storm of 4-8 December 1703 crossed the English Channel and Brittany (Lamb and  
286 Fryedalh 2005). Similarly, the Christmas 1717 four-days storm affected most of Europe, North of the  
287 Gulf of Biscaye, while the 19-20<sup>st</sup> January 1735 and the 16<sup>th</sup> February 1736 events affected Brittany,  
288 Cotentin and the Scillies, (OSL dating:1700–1780, Banerjee et al., 2001). Superimposed storm-surge  
289 layers (Lindstrøm, 1979) exposed on the Keremma spit (Bay of Goulven) have been dated with OSL to  
290 1752 - 1776 and 1723 - 1751 AD (Van Heteren, 2002), and major exportation of sand to the offshore  
291 in 1703 AD (no dune field), which destroyed the former spit.

292 A third sand drift event can only be dated with archives and old maps. It took place mostly at the end  
293 of the XVIII<sup>th</sup> /early XIX<sup>th</sup> centuries, in relation to the Dalton Minimum (1790 - 1820). Again churches  
294 were buried on Batz Island (N Brittany) and Skagen (Jutland). Major storm events occurred regionally  
295 in 1795, 1808 and 1824 AD with dominant westerly winds. Dunes developed longitudinally at St.Anne-  
296 la-Palud and at Kerzine (Fig. 1a). In between these events, high frequencies of SW winds were  
297 recorded in Britain (London) from c. 1730, c. 1860 and 1900 - 1930 (Lamb, 2005), signaling positive  
298 NAO periods fitting the relative landscape stabilizations.

299

300 ***Dynamical context: dune disappearance in the near future***

301 When the stormy period ends, the beach is rapidly supplied by sands migrating gently from the  
302 subtidal accumulation (Fig. 2). The erosion notch is rapidly buried by dune collapse during the after-  
303 storm restoration of the beach. Additionally, when the climate warms up, water seepage further eases  
304 the fixation of drift sand. Firstly, a foredune is formed mostly from spring. Then, from late spring to late  
305 summer (water table lowering), drift sand is mobilized, climbing on the foredune and beginning the  
306 construction of the true dune. When the autumn's equinoctial storms occur, important drift may occur  
307 but also wave run-up may initiate interstratified dune / washover facies, as observed at Audierne,  
308 Guisseny and Goulven (Fig. 2). When this succession of events occurs within the same year,  
309 vegetation growth cannot impede the process.

310 Wind direction also has an important impact on dune formation. During positive NAO modes, regional  
311 winds are mostly westerlies (Pirazzoli et al., 2004). During negative NAO modes, the prevailing winds  
312 are meridian (Hénaff, 2008), driven by the important oscillations of the jet stream. This is the main  
313 reason for some regional differences in dune formation, as related to the coastal orientation.

314 When a period of low storm activity occurs for several years with a positive NAO and a high AMO  
315 mode, vegetation recolonization occurs rapidly after the storm due to wetter, but not necessarily  
316 warmer conditions, leading to a more stable coastline. In this case, ecological perturbation by tourism  
317 or by free pasture destabilizes the dune field, even if storminess is not particularly high. This is very  
318 clear with the post-1945 mobility of the dunes at the Bay of Audierne, which were also strongly  
319 perturbed by sand exploitation and tourism (Hallégouët, 1981). For the XVII<sup>th</sup> century, free pasture,  
320 vegetation clearance for agriculture on sand, and seaweed yield strongly perturbed the dunes in  
321 Brittany; this occurred in combination with reclamation of the upper tidal marsh areas in back ridge  
322 positions. This situation was accentuated since the Second World War by quarrying of the dune, and  
323 onshore and offshore sands exploitation, leading to a very negative sediment budget (Guilcher and  
324 Hallégouët, 1991).

325 Dunes have recycled the same stock of sediment, which was already limited in Brittany for geological  
326 reasons, with the slowing down since 3000 years of the transgression, although this has been  
327 somehow re-accelerated by the recent warming. The dissipative state of beaches underlying dune  
328 ridges, as in the Bays of Audierne, of Goulven and at Guisseny, signals a continuing longshore  
329 depletion of ridge sediment by erosion (Short and Hesp 1982). Inland sand drift was important during

330 the historical dune formations, but seem limited to local inland recycling since the LIA (dry storms).  
331 Giant LIA storms have resulted in the second major retreat of the coastline, despite some supply of  
332 sediments by forest clearance in Merovingian times River dam construction for water or tide mills  
333 activities limited the sand supply in Western Brittany from the XI<sup>th</sup> century. LIA dunes are less  
334 calcareous at the bay of Audierne or are richer in organics, as in Picardy, attesting to the reworking of  
335 the stabilized bodies. The existence of “dead” dunes perched on cliffs (Fig. 1a) also attests to a  
336 depleted sedimentary stock. A less negative budget along the South Brittany coast explains the latter  
337 preservation of coastal dunes (mostly formed after the XI<sup>th</sup> century), which are now endangered by  
338 both onshore (dune quarrying) and offshore sand exploitation.

339 As very important storms are associated with tall waves, up to 15 m high on the platform, sands are  
340 not only exported to the shallow nearshore (<10 m of depth), but are also reworked to a depth  
341 exceeding -30 m, leading to progressive sediment exportation by shelf currents to the platform edge  
342 (Fan et al., 2004, Guillen et al., 2006; Goff et al., 2004), a process particularly efficient with dry storm  
343 (Guillen et al., 2006). This suggests that there is, in many places and especially in Brittany, no large  
344 sediment volume available on the beach for a future period of dune building, as was already stressed  
345 for UK by Orford et al. (2000).

346

### 347 ***Climate global control***

348 During cold events on Europe, typically associated with negative NAO modes and solar lows,  
349 precipitation is usually reduced (Hurrell, 1995), whilst aeolian aggradation may result from moderate  
350 but frequent gales, thereby favouring the development of coastal dunes without or on former storm  
351 ridges. The extent of sea ice explains a more accentuated cooling of the western Atlantic Ocean, as  
352 occurred during the LIA (Miller et al., 2012) in association with a negative, decennial NAO mode  
353 (Trouet et al., 2009). Moreover, a sea-ice triggered cooling is consistent with a limited regression of a  
354 thermosteric nature ( $\leq 0.5$  m; Lamb, 1995). More frequent solar minima from the Roman time (Usoskin  
355 et al., 2007) resulted in a more frequent negative NAO mode, sea-ice extent and storminess.  
356 Additionally, dunes are strongly influenced by anthropic practices that artificially favour dune mobility,  
357 especially from the late Roman time. These practices induce sediment-supplying soil erosion with a  
358 rhexistasy dynamic of the coastal zone. We may thus suspect that within a context of rising SL, the  
359 occurrence of dunes is a man-made temporary and endangered anomaly of the Late Holocene HS.

360 This conclusion is similar but more obvious than in a high sand supply environment as in Denmark  
361 (Clemmensen et al., 2009).

362

### 363 **CONCLUSIONS**

364 Dune development in Brittany only occurred during the latter part of the Holocene stratigraphic record  
365 as a result of abnormal sand supply. Even though dunes appeared sporadically c. 4000 cal BP  
366 (although not earlier), the first real dune building occurred from 3-2.75 cal kyr BP in close connection  
367 with the slowing down of the Holocene transgression from 3 cal kyr BP and agriculture development..  
368 As a result, dune fields were limited along most Brittany coasts, and later in southern Brittany where  
369 the sand supply was higher. The favorable building conditions for dunes are recurrent gales  
370 associated with dominant negative NAO mode. Most parts of the so-called dune ridges are storm  
371 ridges along the southern coast of Brittany that are only topped by dunes, and formed mostly from 900  
372 - 1200 AD and during later periods of major storms driven by brief positive NAO event in a decadal  
373 NAO negative mode. Along the North coast, dunes have a similar timing as in Picardy and Normandy,  
374 although erosion by major storms at the transition of the XVI-XVII<sup>th</sup> centuries was responsible for the  
375 main storm ridge at the present coastline. Prior to the XX<sup>th</sup> century, dunes were represented regionally  
376 by thin sheets of sands, burying coastal relief and reworking mostly the top and the back of the coastal  
377 ridge. Many local dune fields have already disappeared. We think that within a context of rising SL, the  
378 occurrence of dunes is a man-made temporary anomaly of the Late Holocene, soon to be erased by  
379 both naturally and man-driven sediment starvation. This will result in the progressive disappearance of  
380 dunes with, consequently, higher risks for coastal submersion at these locales.

381

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386

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553

554 **Figures**

555 Fig. 1: location (A) and stratigraphy (B) of the dunes from Brittany a, Normandy and Picardy. For the  
556 data, see the text.

557

558 Fig. 2: Sketch of the barrier evolution in a limited sand supply environment, with both rising sea-level  
559 and storminess from 2400 BP to present..

560

561 Table 1: New dating from dunes bodies, Brittany. For location see Fig. 1

562