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1 **Correlating three centuries of historical and geological data for the marine deposit**  
2 **reconstruction of two depositional environments of the French Atlantic coast**

3  
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11 **Abstract**

12 This paper details a high-resolution record of French Atlantic coast extreme wave events  
13 using a multi-proxy analysis of dated sedimentary deposits. Two lagoons 1) the Petite Mer de  
14 Gâvres and 2) the Traicts du Croisic were chosen to identify damaging storm events from the  
15 last 300 years with Beeker sampling, <sup>210</sup>Pb and <sup>137</sup>Cs dating and sedimentary analysis. Using  
16 two new geochemical proxies in the French Atlantic coast, Sr/Fe and Ca/Ti, shows that  
17 several storminess events are reported in the nine cores drilled. By correlation with historical  
18 archives, seven major storms are confirmed: 1924 AD, 1940 AD, 1972 AD, 1977 AD, 1990  
19 AD, 1999 AD, and an 1896 AD highly damaging event. Four other XIX<sup>th</sup> and XVIII<sup>th</sup> century  
20 extreme wave event correlations are also proposed from this multi-proxy analysis: 1775 AD,  
21 1811 AD, 1838 AD and 1876 AD. Societal and natural impacts caused by these coastal floods  
22 are revealed using our dense and varied historical archives.

23  
24 **Keywords:** French Atlantic coast, storm events, geochemical ratios, historical archives, 1896  
25 event.

26  
27 **Highlights**

28 Good sedimentological and historical correlation for the last three centuries

29 Sr/Fe and Ca/Ti are two proxies useful for detecting recent washover in the French Atlantic  
30 coast

31 Eleven extreme events recorded in French Atlantic coast sediments

32

## 33 **1. Introduction**

34 Since the 1990s, there has been a major increase in paleostorm studies, particularly in North  
35 America, which is the most studied continent for the geomorphological reconstruction of past  
36 storms (Bennington and Farmer, 2014; Boldt et al., 2010; Das et al., 2013; Horwitz and  
37 Wang, 2005; Liu and Fearn, 2000, 1993; Mann et al., 2009; Parris et al., 2009). These  
38 researches help coastal American societies to better understand the past stormy dynamics of  
39 their area. This knowledge is needed to face damaging events and build a more resiliency  
40 coastal system as it seems the global coastal population will increase (Chaumillon et al., 2017;  
41 Lutz and Samir, 2010; Naylor et al., 2017). By contrast, only a few recent sedimentological  
42 paleostorm studies have focused on the French coasts, and most of them concern the  
43 Mediterranean coastline. Sabatier et al., 2008 reconstructed three stormy events from the last  
44 250 years, while Degeai et al., 2015 attempted to find a storminess periodicity in the last 3000  
45 years in the north-western Mediterranean Sea, where the tide amplitude is very low with only  
46 a few centimeters. Along the French Atlantic coast, the tidal regime is much higher and cliff  
47 top deposits have mainly been used to reconstruct recent historical storm variations (Fichaut  
48 and Suanez, 2011; Suanez et al., 2009). From a sedimentological analysis, different types of  
49 recent marine deposits on the south-western coastline have been distinguished (Baumann et  
50 al., 2017). However, Anthropocene storm analysis is still mainly based on statistics and wave  
51 modeling (Bardet et al., 2011; Bertin et al., 2014; Breilh et al., 2013). As several storms have  
52 recently hit western French coasts, such as Xynthia in 2010 (Breilh et al., 2014; Regnaud,  
53 1999; Regnaud and Kuzucuoglu, 1992; Ruin et al., 2008; Suanez and Cariolet, 2010; Vinet et  
54 al., 2012), we focused our study on central western France to detect recent damaging Atlantic  
55 storms and analyze their impact by a comparison with historical records.

56 Recent works have proved that grain size is not the only foolproof proxy for extreme wave  
57 events (Goto et al., 2012; Szczuciński et al., 2016) as it can be affected by backflow erosion.  
58 Thus, geochemistry seems to be a better tool to detect these events (Chagué-Goff et al., 2017).  
59 In the absence of previous attempts to define geochemical indicators of past storms for the  
60 European Atlantic coast, our objective was to test geochemical proxies testifying to marine  
61 conditions in two coastal depositional environments. These proxies will provide a 300-year  
62 high-resolution record of extreme wave events from dated sedimentary deposits. Combined  
63 with our dense historical resources, these strong events will be associated with the precise  
64 date of past storms that impacted the French Atlantic coast, with details about the damage  
65 caused by these events.

## 66 **2. Material and methods**

### 67 **2.1. Study area**

68 Two study sites were selected based on three criteria : i) back barrier coastal depositional  
69 environments; ii) not impacted by man for at least 300 years, with a constant natural  
70 evolution; iii) in an area threatened by coastal flooding.

71 Appropriate sites were chosen after a GIS chronological analysis based on IGN (French  
72 National Geographic Institute) data. Historical maps were combined with recent aerial  
73 photographs to evaluate the evolution of urbanization and the landscape (Pouzet et al., 2015).  
74 A topographic analysis was carried out to assess the most relevant back barrier depositional  
75 environments. Finally, two of these were selected, directly exposed to coastal flooding on the  
76 central western French coast (Le Roy et al., 2015). This comparison revealed that the Traicts  
77 du Croisic (central Pays-de-la-Loire region) and the Petite Mer de Gâvres (southern Brittany)  
78 lagoons have been well preserved during the last three hundred years. They seem to be  
79 appropriate depositional environments for a reconstruction of storminess.

80 The Petite Mer de Gâvres (southern Brittany) and the Traicts du Croisic (central Pays-de-la-  
81 Loire) are two coastal marshes with a high morphogenic activity (Fig. 1). These two back  
82 barrier lagoons are separated from the sea by a sandy barrier so are useful to detect recent past  
83 storms (Baldock et al., 2008; Pierce, 1970; Sabatier et al., 2010; Switzer and Jones, 2008;  
84 Zecchetto et al., 1997). They correspond to two different types of lagoon. First, the Petite Mer  
85 de Gâvres, near the city of Lorient, is located in a protected natural area. It is a well-formed  
86 lagoon, where the barrier beach was already built in the mid-XIX<sup>th</sup> century (Fig. 1). Based on  
87 the sedimentological surface study realized by the Service Hydrographique et  
88 Océanographique de la Marine (SHOM) which is available on the database at *data.shom.fr*  
89 (*modified*), the Petite Mer de Gâvres can be divided in three distinct sedimentological  
90 sections. The western part which is open to the sea is mainly composed of sands, due to its  
91 direct tidal connection with the Atlantic Ocean, whereas the eastern back section is more  
92 isolated, and shows sediments that are mainly of mostly clayey type. A silty surface offers a  
93 slight transition between these two distinct sediment types (Fig. 2A). After a preliminary core  
94 test, we chose to sample two different sections of the barrier beach to detect potential  
95 differences in the record of storminess between a thin (cores LA1 and LA2) and a thick (cores  
96 LB1 and LB2) high protecting dune barrier, in the clayey dominated section (Fig. 1, Fig. 2B).  
97 On the other hand, the Traicts du Croisic, situated 100 km west of Nantes, is an open lagoon,  
98 which is closing, separated from the sea by a coastal spit that has been growing for centuries:  
99 this site corresponds to an actively morphogenic area, also located behind a high protecting  
100 dune. The two main channels bring sandy sediments from the ocean by the south-western  
101 inlet which rapidly transited by a silty, then clayey type dominating sediment by moving  
102 away until the back protected section (Fig. 2A). A longitudinal transect was made of five  
103 different cores, behind the thinner part of the barrier and far from the channel's influence,  
104 mainly located in a silty soil. Starting from T1 near the dune up to T5 in the center of the  
105 marsh, we wanted to recover homogeneous and continuous deposits. A large channel  
106 remobilizes sediments in this lagoon, but the first aerial photograph taken in 1948 (from the

107 IGN) shows that it has not moved in the last 70 years (Fig. 1, Fig. 2B). This channel is  
108 unlikely to have an impact on the sediment archives.

109 The French Atlantic coast has a semi-diurnal tidal regime; the highest tidal ranges of the two  
110 sites are around 6 to 7 meters (according to the SHOM). In our area, waves reach higher  
111 heights but shorter periods than in southern France. With main WSW and WNW directions,  
112 wintery waves can reach nearly 2.2 meters at l'Ile d'Yeu, located at 50km south from the  
113 Traicts du Croisic, whereas they approximately reach 1.45 meters during the summer (Butel  
114 et al., 2002). Considering that protecting dunes reach nearly 10 meters NGF (Nivellement  
115 General de France, 0 meter NGF is the French topographical reference for the Mean Sea  
116 Level, linked to the Mean Sea Level of Marseille, France), only past storms that matched the  
117 high tide can be observed. Exposed to extratropical storms that present a mean duration of 4.5  
118 days, events mainly come from the ocean during the winter, with a trajectory coming from the  
119 SW (Lozano et al., 2004). In the whole Europe, the number and the wind speed of these  
120 strong winter events seem to have increased over several decades (Zappa et al., 2013)

## 121 **2.2. Sampling and sediment analysis**

122 Nine short sediment cores were collected in August 2016 using an Eijkelpkamp© gravity corer,  
123 50 mm in diameter and 100 cm in maximum length, to sample into a humid clayey or silty  
124 soil. A plastic hammer was used to penetrate the ground, and then a piston avoided  
125 compression during the extraction of each humid core. Trimble Differential Global  
126 Positioning System (DGPS) was used to survey core positions. All locations were linked to  
127 geo-referenced IGN benchmarks and leveled with respect to the NGF datum. Each core was  
128 longitudinally sliced and each half-section photographed and described. High-resolution  
129 elemental analyses of split sediment cores were carried out using an Avaatech© XRF core  
130 scanner. Element intensities normalized by the total intensity (count per second of each  
131 spectrum: cps) (Bouchard et al., 2011; Martin et al., 2014), and element ratios (Chagué-Goff,  
132 2010; Sabatier et al., 2012) were considered. To complement the sedimentological  
133 description, the Scopix© system was used to take X radiographs (Migeon et al., 1998);  
134 lightness was estimated by colorimetric analyses (Debret et al., 2011; Polonia et al., 2013)  
135 with a Minolta© Cm-2600d spectrometer, as a positive correlation between lightness and  
136 carbonate content has already been demonstrated (Mix et al., 1995). The magnetic  
137 susceptibility of each centimeter of the nine different cores was measured with an MS2E-1©  
138 Bartington-type (Bloemendal and deMenocal, 1989; Wassmer et al., 2010), which has been  
139 previously used with success in other studies (Begét et al., 1990; Buynevich et al., 2011; Roy  
140 et al., 2010). Then sediment cores were sampled every 0.5 cm for dating, and every 1 cm for  
141 grain size, which was measured by a Malvern Mastersizer 2000© laser beam grain sizer  
142 (Parsons, 1998; Yu et al., 2009).

## 143 **2.3. Dating**

144 The age-depth models of cores LB1 and T1 were established from a combination of two  
145 short-lived radionuclides. First,  $^{210}\text{Pb}$  is a naturally-occurring radionuclide that is incorporated  
146 rapidly into the sediment from atmospheric fallout and water column scavenging. This  $^{210}\text{Pb}$ ,  
147 referred to as  $^{210}\text{Pb}$  in excess ( $^{210}\text{Pb}_{\text{xs}}$ ), decays in sediment over time, according to its half-life  
148 ( $T_{1/2} = 22.3$  years). On the other hand,  $^{137}\text{Cs}$  ( $T_{1/2} = 30$  years) is an artificial radionuclide,  
149 which has well-known pulse inputs related to the atmospheric nuclear weapon tests in the  
150 early sixties (maximum atmospheric fallout in 1963 in the northern hemisphere) and, to a  
151 lesser extent, to the Chernobyl accident in April 1986.

152 Core descriptions were used to select samples for dating, excluding the sand layers that are  
153 not appropriate for  $^{210}\text{Pb}$  determination. The activities of  $^{210}\text{Pb}$ ,  $^{226}\text{Ra}$  and  $^{137}\text{Cs}$  were  
154 determined at the University of Bordeaux on 2.5-4 g of dried sediment by gamma  
155 spectrometry, using a well-type, high efficiency low background  $\gamma$  detector equipped with a  
156 Cryo-cycle (CANBERRA©). The detector was calibrated using certified reference materials  
157 (IAEA-RGU-1; IAEA-IAEA135). Activities are expressed in mBq g<sup>-1</sup> and errors based on 1  
158 standard-deviation counting statistics.  $^{210}\text{Pb}_{\text{xs}}$  was determined by subtracting the activity  
159 supported by its parent isotope,  $^{226}\text{Ra}$ , from the measured  $^{210}\text{Pb}$  activity in the sediment. For  
160 the two cores investigated in this work, sediment accumulation rates were calculated from the  
161 sedimentary profiles of  $^{210}\text{Pb}_{\text{xs}}$ , plotted against depth. The deposition time (in years) of the  
162 sediment layer was obtained by dividing the depth per unit area by SAR. The deposition year  
163 for each sediment layer was subsequently estimated based on the 2016 sampling date for the  
164 sediment-water interface.

## 165 **2.4. Historical archives**

166 As explained above in the introduction, extreme storms recently hit the western French coast.  
167 These hazards highlighted the need for an efficient historical reconstruction through the  
168 analysis of past storms and marine submersion over the last centuries. Unlike the Netherlands  
169 (Gottschalk, 1977, 1975, 1971) or Britain (Bailey, 1991; Hickey, 1997; Lamb and  
170 Frydendahl, 1991), research on the history of storms in France is very recent, mostly dating  
171 from the past 7 years (Chaumillon et al., 2014; Noël, 2014; Péret and Sauzeau, 2014;  
172 Sarrazin, 2012). Although the historical method can be helpful in the sedimentary approach  
173 and the study of past storms and sea floods, multidisciplinary approaches, like the one  
174 proposed in this paper, are not very widespread and often integrate the historical data rather  
175 superficially (Breilh et al., 2014; Van Vliet Lanoe et al., 2014).

176 The historical research is mainly based on ancient documents: i) ancient maps, ii) narrative  
177 sources (chronicles, diaries, memories etc.) and iii) documents (books of accounts, records of  
178 repairs, surveys conducted after a disaster, barometric observations, newspapers etc.)  
179 preserved in libraries and in municipal, departmental, and national archives. These documents  
180 contain observational and descriptive data on past extreme weather hazards (descriptions of

181 the storm and the damage caused), as well as impacts on societies and their reactions and  
182 adaptation. For the period studied in this paper, we also considered instrumental data such as  
183 barometric information and data from Météo France. In order to cover and reconstruct the  
184 history of storms and sea flooding that occurred on the central western French coast over the  
185 last 300 years, we consulted more than 398 documents, of which only 264 contained data on  
186 past storms and coastal floods.

187 Before being used to reconstruct the history of storms and sea flooding over a relatively long  
188 period, these data had to be studied, analyzed, criticized and included in databases to produce  
189 cross-checking. To consider a written document (and its data) reliable, details about the  
190 writing of the document, i.e. who was the author, if he/she witnessed (or not) the event, what  
191 was the institutional framework and so on, had to be defined (Athimon and Maanan, 2018).  
192 Moreover, when possible, it was necessary to cross-check the hazard testimonies with several  
193 sources. The aim was to have a more precise and exhaustive view of the event in order to  
194 characterize it, spot potential errors more easily and reconstruct the history of storms within a  
195 defined temporal and spatial frame. Like any method, there are some limitations of the  
196 historical reconstruction of storms and sea floods (Athimon and Maanan, 2018): the most  
197 important is probably the loss of countless documents and data, especially during the French  
198 Revolution and wars like the Second World War. However, this does not prevent the  
199 historical climatologist from identifying and characterizing important storms and sea floods of  
200 the past.

## 201 **2.5. Statistical analysis**

202 Multivariate statistical analysis was used to investigate the geochemical structure (continental  
203 or marine context data) of the sediments quantitatively, and to extract the geochemical  
204 markers characterizing an extreme event of marine origin. Calculations were performed on  
205 606 sediment samples, 357 from the Traicts du Croisic and 249 from La Petite Mer de  
206 Gâvres, using statistical analysis according to the recommendation of van Hattum et al., 1991.  
207 Based on the Pearson correlation coefficient, each potential stormy proxy was correlated to  
208 each other. A Principal Component Analysis has been made using R© software to sort these  
209 elements into two groups (Yamasoe et al., 2000), testifying to two different types of deposit  
210 origin: lagoonal and allochthonous (marine) elements. The sorting have been automatically  
211 made by the software after a dendrogram summarization of the ACP, using libraries “*vegan*”  
212 and “*cluster*” of the software. The most opposed elements were then used to test geochemical  
213 ratios that could potentially testify to oceanic conditions. These ratios helped to determine the  
214 stormy layers specific to the French Atlantic coast, in these two specific environments.

## 215 **3. Results and discussion**

### 216 **3.1. Dating and age-depth modeling**

217 At the Traicts du Croisic (TC), the lower parts of the five cores are mostly composed by sand.  
218 The upper layers consist mainly of silty clay, but a gradual decrease in its thickness, from 30  
219 cm in core T1 to nearly 10 cm in core T3, is noticeable with the distance from the coastline  
220 (Fig. 2C). Cores T4 and T5, both extracted the furthest from the high protecting dune, show a  
221 high composition of sands, with a thin 5-cm silt horizon in the upper layers and an increasing  
222 sand grain size downcore. There are no earthworms or air holes, which mean that bioturbation  
223 can be excluded in all Croisic cores.

224 In the Petite Mer de Gâvres (PMG), the cores extracted at two different locations present two  
225 different stratigraphic profiles (Fig. 2C). In the LB area, the top of each core starts with fine-  
226 grained sediment, mainly composed of clay or silt. Deeper, from about 35 to 50 cm (LB1) or  
227 20 to 60 (LB2), there is a coarser-grained layer, which presents a high variability in grain size  
228 (fine sand to a 6-cm diameter pebble) testifying to a difference in sediment origin. The base of  
229 the PMG-LB cores again presents fine-grained sediment. In PMG-LA cores, there is a  
230 sandy/silt main variation after a thin 10-cm fine-grained sediment top layer. The end of these  
231 two cores (last five centimeters) is also finer than the dominant sands. In the same way as in  
232 the Traicts du Croisic marsh, no bioturbation marker is observed in all four PMG cores.

233 Based on the core description, we selected one core per site for dating. At the Traicts du  
234 Croisic, core T1 presents the thickest clayey top layer (nearly 30 cm) and appears the most  
235 appropriate for radionuclide determinations. In the Petite Mer de Gâvres (PMG), LB1 is the  
236 finest-grained core with an intermediate layer between 35 and 50 cm consisting of coarse sand  
237 and pebbles. This layer was considered a hydrodynamic event and was not sampled for  
238 radionuclide determination.

239 The profile of  $^{210}\text{Pb}_{\text{xs}}$  with depth in core T1 is rather classic, with activities decreasing  
240 exponentially to reach negligible levels below 20 cm (Fig. 3, A). A mean sediment  
241 accumulation rate of  $0.24 \text{ cm yr}^{-1}$  was estimated. The  $^{210}\text{Pb}$  chronology indicates that core T1  
242 ranges from  $1916 \pm 13$  to 2016. This estimate is supported by the sedimentary  $^{137}\text{Cs}$  profile;  
243  $^{137}\text{Cs}$  activities disappear rapidly to negligible levels below a deep peak at about 12-13 cm,  
244 which corresponds to 1963 according to the  $^{210}\text{Pb}$  dating.

245 In the Petite Mer de Gâvres (PMG), core LB1 presents lower activities of radionuclides,  
246 which could be related to a higher sedimentation rate and coarser sediments (Fig. 3, B).  
247  $^{210}\text{Pb}_{\text{xs}}$  presents the same decreasing trend with depth in the sediment as already observed for  
248 core T1. In addition, low levels of  $^{210}\text{Pb}_{\text{xs}}$  were measured below the sand layer. Mean  
249 sedimentation accumulation rates are about  $0.37 \text{ cm yr}^{-1}$ . The  $^{210}\text{Pb}$  chronology indicates that  
250 the base of the sand layer is about  $1896 \pm 10$ . Although at low levels, the  $^{137}\text{Cs}$  profile  
251 supports this chronology.



252 For horizons beyond the timescale covered by  $^{210}\text{Pb}$ , we extrapolated the ages by assuming  
253 that the mean sedimentation rate determined for each site,  $0.4 \text{ cm yr}^{-1}$  (PMG) and  $0.2 \text{ cm yr}^{-1}$ ,  
254 (TC) was constant.

## 255 **3.2. Cored sediments characteristics**

### 256 *3.2.1. Development of extreme event indicators*

257 A statistical correlation analysis was carried out to sort the correlated elements into two  
258 different groups, testifying to two distinct types of sediment: continental and allochthonous.  
259 Part of the American massif, the watershed is an association of “two mica” leucogranites:  
260 magnesium peraluminic and alkali granites rich in potassium (Capdevila, 2010). Continental  
261 major layers will thus present high proportions of metal elements. Our statistical results show  
262 a high opposition of two elements, Ca and Sr, (also well correlated to each other with a  
263 correlation coefficient cc. of 0.96, Table 1) with all other elements including those found in  
264 the watershed (Fig.4, Fig.5). Si is the only exception isolated alone as it can be found in both  
265 continental and marine sediments. Thus, three groups can be observed with analysis of the  
266 correlation coefficient and the automatized sorting function of the dendrogram : i)  
267 allochthonous and marine elements: Ca and Sr; ii) continental elements, and particularly  
268 lacustrine, for this study site: Br, Cl, Co, Cu, Fe, K, Pb, Rb, Ti and Zn (cc. around 0.5 and  
269 more), and secondarily Al, K, Ni, and Zr (cc. between 0.2 and 0.5); iii) Si, which can be found  
270 in both environments. Finally, Mn and S are the two only elements with no correlation with  
271 another. PCA shows that Mn can be regrouped with marine elements, whereas S is closer than  
272 the continental group. Ca and Sr can provide a good extreme wave event signature from  
273 marine carbonate, where high radioactivity can be found into shells debris (Bozzano et al.,  
274 2002; Chagué-Goff et al., 2017; Degeai et al., 2015; Raji et al., 2015; Sabatier et al., 2010;  
275 Szczuciński et al., 2005). Strontium is also used into some paleotsunami studies, proving that  
276 it could be a significant proxy of sea saltwater sediment incomes (Cuven et al., 2013; Nichol  
277 et al., 2007). As these two seem to be very distinct from the other elements, and particularly  
278 those corresponding to the watershed, we tested Ca/Ti and Sr/Fe ratios for the first time in the  
279 European Atlantic coastline.

### 280 *3.2.2. Traicts du Croisic*

281 All five cores show two different systems with a base of coarser grain sized, and generally  
282 more marine geochemical elements (Fig. 6). The 20-30 cm upper part of the cores shows  
283 lower morphogenic activity, with mostly silt or clayey sediment and lower Sr/Fe, Ca/Ti and  
284 lightness with higher MS values, testifying to more continental inputs. This large difference  
285 between these two systems is due to the evolution of the sandy spit, which became thicker  
286 with time (Fig. 1, Fig. 6), thus isolating this north-western part of the coastal marsh from the  
287 sea. This is why more storminess is identified in the coarser base of the core than in the upper

288 clayey layer: as the spit became thicker during the last decade, the upstream marsh became  
289 more protected from the sea. Storms cannot disturb this environment now as much as when  
290 the dune was thinner.

291 All five cores show correlations of proxies increase between grain size, Sr/Fe and Ca/Ti  
292 ratios, lightness and a decrease in magnetic susceptibility. The tenth decile is also used as a  
293 new stormy proxy here. As it represents only 10 percent of the finest fraction of each sample,  
294 a high D10 shows overall coarse sediment (at least for 90 percent of its composition). T1  
295 shows this clear multiple correlation near cm. 35 (coarse sandy layer with increase in Sr/Fe  
296 and Ca/Ti from 0 to 0.3 and 0 to 3), with a peak in lightness (45 to 50%) and a fall in MS (10  
297 to 8 SI) indicating an allochthonous marine layer. As erosion can affect storm markers, we  
298 also report the large increase in the two geochemical ratios at cm. 61 in this core, even though  
299 the grain size stays constant. These two storm markers are also seen in the T2 core, which  
300 testifies to the most impacted area because five other marine allochthonous layers are  
301 observed. Three of them are very noticeable at cms. 40, 35 and 30 with a high grain size and  
302 geochemistry peaks. The last two are slighter storminess events observed at cms. 17 and 10.  
303 T3 presents four probable storminess events observed at cms. 17, 29, 43 and 61 with high  
304 proxy variations, testifying to huge differences with the surrounding finer grained layers. T4  
305 and T5 are similar with two marine layers observed at cms. 31 and 17 but with two last  
306 marine intrusion observed only in the T4 core at cms. 7 and 59, and one last in the T5 core at  
307 cm. 5 (Fig. 6).

### 308 3.2.3. *Petite Mer de Gâvres*

309 In the Petite Mer de Gâvres, the well-formed basin studied has been closed and isolated from  
310 the sea for centuries. Therefore, only a unique sedimentological profile can be detected here,  
311 in contrast to the Traicts du Croisic sedimentological analysis (Fig. 7). This profile is defined  
312 by fine grain sized sediments (silt or clay), with low Sr/Fe, Ca/Ti, lightness with a high MS  
313 for an area affected by the continent and well isolated from the sea. In the same way as in the  
314 Croisic analysis, storminess can be detected by coarser grain sized sediments coming from  
315 marine washovers, with an increase in these two geochemical ratios and lightness, and a  
316 possible decrease in MS.

317 Two different sites were drilled, "LA" and "LB", because our preliminary core tests showed  
318 that an important storminess variation is recorded behind a thick (LB) and a thin (LA) dune  
319 barrier (Fig. 1, Fig. 7). First, an important storminess is recorded near cm. 50 in the LB area,  
320 with coarse pebbles detected between two clayey layers. A 6-cm diameter pebble was  
321 extracted from the core. These pebbles come from the mixed sandy/pebbly beach on the other  
322 side of the dune barrier (photograph I, Fig. 7), confirming the washover origin of this layer.  
323 Furthermore, the nearshore sediment surface is also composed by pebbles, thus demonstrating  
324 their marine origin (Fig. 2A). In our core analyses, no pebble is observed in the LA

325 environment although we think that it was impacted as much as LB, as shown by the  
326 sedimentology comparisons and dating carried out in these two sites. In the LA area, we can  
327 assume that this significant event breached the dune barrier where the vegetation is less dense,  
328 and that the wave backflow evacuated these coarser deposits. Geochemical ratios show that  
329 storminess is also recorded in the LA area, without these pebbles. In the LB environment, it is  
330 the opposite: the thicker sandy barrier caught the pebbles in the marsh, explaining why they  
331 were found during drilling. According to sediment observations and analysis results, this  
332 storminess corresponds to the marine input at 45-50 cm depth of the LA area. The fall in the  
333 Ca/Ti ratio is due to measurement disturbances made by a hole where a marine shell was  
334 removed before analysis, and with its correlation with the low MS values and increase of  
335 lightness and Sr/Fe ratio, proves the marine input for this section.

336 Moreover, with the method previously described, other significant allochthonous layers are  
337 reported: sedimentological analyses show another marine intrusion at cm. 35 for LA1; at cms.  
338 10, 15, 25 and 35 for LA2; at cms. 5 and 35 for LB1; and at cms. 5, 15, 25 and 35 for LB2  
339 (Fig. 7).

### 340 **3.3. Historic records of extreme events**

#### 341 *3.3.1. Coupling with historical data*

342 Our searches found 149 storms, including twenty sea floods, recorded in historical documents  
343 from the middle of the XVIII<sup>th</sup> century to today. From historical archives, eleven marine  
344 floods correlating with stormy conditions have been recorded in the XX<sup>th</sup> century, six in the  
345 XIX<sup>th</sup> century, and three in the second part of the XVIII<sup>th</sup> century. Into these twenty events,  
346 fourteen of them reports damage in the two study areas, whereas the six others only impacted  
347 the Croisic study area (Pays-de-la-Loire region) and didn't damaged the Gâvres site (Brittany  
348 region). Since the middle of the XVIII<sup>th</sup> century, storms appear much more extreme in the  
349 Northern Atlantic (Hickey, 1997; Lamb and Frydendahl, 1991), and from the second part of  
350 the 19<sup>th</sup> century, they seem more numerous (Desarthe, 2013). However, it is necessary to be  
351 careful: historical documentation is more available for the XVIII<sup>th</sup> - XX<sup>th</sup> centuries than for  
352 earlier periods. Moreover, the development of modern meteorology since the second part of  
353 the XIX<sup>th</sup> century and the use of relatively recent technology such as satellite views may  
354 distort researchers' observations and interpretations.

#### 355 *3.3.2. Extreme event reconstruction*

356 From the sedimentological analysis, periods attesting to allochthonous layers coming into  
357 these two clayey lagoons were extracted. By correlation with the historical archives, we found  
358 a precise extreme wave event date for each of these layers reported. No notable tsunami has  
359 been identified in the historical records for the last 200 years in our area (Dawson et al., 2004;

360 Karnik, 1971), so we assume that these marine layers come mainly from stormy conditions.  
361 The French Atlantic coast experiences high tidal ranges; we conclude that stormy events have  
362 to combine with high tides to disturb these natural environments. Consequently, marine layers  
363 observed in these cores are overwashes due to stormy events combined with high tide  
364 conditions. As  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$  activities stop near 1890 AD, we kept only XX<sup>th</sup> century dates  
365 as high certainty events. For the earlier ones assessed by extrapolation of the sedimentation  
366 rate, we allowed only the estimated geological periods as a result. From the sedimentology,  
367 we extracted seven main storminess post 1896 dates and four high probable earliest  
368 hypothesis. The historical archives enabled us to have a more precise dating. We know that all  
369 the events were from Atlantic depressions, with mostly southerly or southwesterly high  
370 winds, and some with known high tide coefficients. They also provide clues about the  
371 environmental and societal destruction, to assess the real impact of these extreme wave  
372 events.

373 Overall, results demonstrate a good correlation between historical archives and  
374 sedimentological results. From the twenty marine flooding dates recorded into historical data,  
375 eleven have been identified in our nine sedimentological cores. The nine others that have not  
376 been identified are explained by a sedimentological storm record limit, and by the precision of  
377 historical data and their damage location details. First, we cannot record successive storms in  
378 sediment archives. With a mean sedimentation rate of 0.25cm/yr, a centimeter depth of a core  
379 does correspond to a four year sedimentation period. If successive marine flooding occurs in  
380 less than a five-years period, only one marine layer can be recorded (Chaumillon et al., 2017;  
381 Liu and Fearn, 1993; Pouzet et al., 2018). This can be the case for the 1987 AD and 1990 AD  
382 events in the study site. Moreover, an important historical limit cannot allow the building of a  
383 complete correlation. Some past storms, as the very devastating 1760 AD event, recorded a  
384 high marine flooding at Bouin, just 50 kilometers south from the Traicts du Croisic  
385 (Departmental Archives of Vendée: 8 B 32). This event has been taken into account in the  
386 database as a destructive event for the Croisic area, as damages were identified near the study  
387 site. However, we cannot be sure that this marine flooding also occurs in our cored area, since  
388 the very old reference that mention this storm, while being precise, does not necessarily report  
389 all the damages made everywhere by this storm. From our sedimentological results, the non-  
390 presence of marine input in the Croisic cores confirms that it may not have impacted the area  
391 as well as the Bouin site. If the coupling of historical and sedimentological archives allows us  
392 to confirm sedimentological results, the sedimentology can also increase the flawed  
393 knowledge of some past storms.

394 The great majority of storms are not violent enough to affect societies and ecosystems  
395 dramatically. Since only the most extreme events are recorded in sediments, once these data  
396 are coupled with historical observations, meteorological characteristics and descriptions of the  
397 damage caused, we can refine the knowledge of some important hazards. This makes the  
398 combination of different methods introduced in this paper relevant, because as the coastal

399 population is expected to increase during the next decades (Lutz and Samir, 2010), the  
400 damages enhanced by coastal flooding will undoubtedly follow these dynamics (Chaumillon  
401 et al., 2017). With a better knowledge on past stormy dynamics, coastal societies directly  
402 exposed to this hazard will be prepared to face it, and consequently be less vulnerable to their  
403 induced damages. Past storm historical chronologies are essential to assess extreme events  
404 recurrence intervals and to subsequently prepare society more reliably to face the future storm  
405 and coastal flooding hazards (Goslin and Clemmensen, 2017). Therefore, for their wide  
406 source of historical information, palaeodata have to be included in risk assessment to better  
407 prepare coastal societies and enable them to develop a more resilient way of life (Naylor et  
408 al., 2017).

#### 409 i) Traicts du Croisic cores

410 T1, located just behind the sandy barrier, only records a pre-XX<sup>th</sup> century storm. Its location  
411 too near the sandy barrier probably prevented later overwash deposits (Fig. 1, Fig. 6). Just two  
412 overwashes are recorded there, when the coastal split was thinner. From T2 to T5, numerous  
413 marine flooding markers are recorded, with a growing signature gradient from the barrier to  
414 the center of the lagoon: the core located nearest the coastline records the most storminess,  
415 while the three others have only four potential markers. With the five cores retained, four  
416 main certain and accurate dates for the XX<sup>th</sup> century can be determined from our historical  
417 research: 26<sup>th</sup> February 1990 (cm. 5 for T4 core), 11<sup>th</sup> January 1978 (cm. 7 for T5 core), 13<sup>th</sup>  
418 February 1972 (cm. 10 for T2 and T5 cores) and 17<sup>th</sup> November 1940 (cm. 15-20 for T2, T3,  
419 T4 and T5 cores). From historical records, three different storms crossed the study area in  
420 1990, including its strongest that crossed a 104 high tide coefficient (SHOM) on February 26-  
421 28, 1990. The three storms caused 100 fatalities over the whole country, with winds reaching  
422 176 km/h maximum in western France and many reports of flooded houses and broken dikes  
423 (<http://tempetes.meteofrance.fr/Daria-le-25-janvier-1990.html>, <http://tempetes.meteofrance.fr/Herta-le-03-fevrier-1990.html>,  
424 <http://tempetes.meteofrance.fr/Viviane-du-26-au-28-fevrier-1990.html>;  
425 Municipal Archives of Nantes, 23 Z 355; 24 PRES 152, 05/02/1990 and 24 PRES  
426 152, 27 and 28/02/1990, Departmental Archives of Vendée, 1856 W 38). The second date  
427 from found in sedimentology is 1977. From historical archives, the two different events of  
428 December 2, 1976 or January 11, 1978 can be related. As in the first case the tide coefficient  
429 was very low, ca. only 50, and it reached 109 in the second (SHOM), the second date is  
430 therefore more likely. With ten deaths and fatalities reported, the 1978 storm crossed a large  
431 part of the country with damage notified from Dunkerque to the Gironde estuary (numerous  
432 shipwrecks and marine flooding reported in Le Marin 1595, MetMar 101 and (Steers et al.,  
433 1979) for other English damages). Historical records show that these two last earlier storms of  
434 1972 and 1940 created a wind speed of 200 km/h that uprooted trees, damaged bell towers,  
435 toppled cranes, destroyed dikes, boats and roofs with many coastal floods. While the second  
436 one mostly hit western France (<http://tempetes.meteofrance.fr/Tempete-du-13-fevrier-1972.html>;  
437 Municipal Archives of Nantes, 1038 W 327; Departmental Archives of Vendée,

438 78/31 1953-1975 – tempête du 13 février 1972), the first affected the whole country for three  
439 days, destroying whole forests and leading to nearly 30 deaths  
440 (<http://tempetes.meteofrance.fr/Tempete-du-16-au-17-novembre-1940.html>); Departmental  
441 Archives of Loire-Atlantique, 75 W 274 –31/12/1940, 75 W 274 – 18/02/1941, 75 W 274 –  
442 12/05/1941; Departmental Archives of Vendée, BIB B 1036/1-2).

443 Four other extreme wave events are recorded with sedimentation rate extrapolation at around  
444 1890 AD (cm. 30-35 for all five cores), 1880-75 AD (cm. 35 for T2), 1840-35 AD (cm. 40-45  
445 for T2 and T3), 1810-1800 AD (cm. 50 for T2), and around 1775-1770 AD (cm. 55-60 for T1,  
446 T2, T3 and T4). From historical records matches, they correspond to the high impacting  
447 storms of 31<sup>st</sup> December 1876 – 1<sup>st</sup> January 1877 AD, creating nearly 25 kilometers of  
448 breaches into the Croisic dikes, with three millions Francs (more than 500 000 \$) total  
449 damage estimated (Departmental Archives, 575 S 1, 7 S 181, Journal L'Union Bretonne –  
450 11/01/1877 (numerisation)); to the 24<sup>th</sup>/25<sup>th</sup> February 1838 AD event, creating “*considerable*  
451 *damages*” according to the former home secretary (Journal de la Charente Inférieure,  
452 01/03/1838-04/04/1838; Municipal Archives of Nantes, 7 PRES 15 – 25/02/1838; (Brunet,  
453 1994) Bibliothèque Mazarine, 8° 94560-1 and 8° 94560-2, p. 552); to the 26<sup>th</sup> February 1811  
454 AD storm that totally flooded the island of Bouin, located at 50 kilometers south from the  
455 Croisic area (Municipal Archives of Nantes, 55PRES21 03/03/1811; Tardy P., 2000); and to  
456 the October 1775 AD intense storm, with a report mentioning that “*the sea goes over the*  
457 *roads, overturns and drives a bridge*” (Debresme, 1922). The last 1900-1895 AD marker,  
458 impacting all the area, is mentioned in the following section about Petite Mer de Gâvres.

459 There are various consequences of the Croisic extreme events recorded in the historical  
460 documents, according to the intensity and recurrence of the hazard. Damages are mostly  
461 human, economic, and material. The event of January 1877 is well documented. An extreme  
462 storm hit the west of France, in particular the studied area. Strong west-south-west winds  
463 coupled with a strong tidal coefficient generated a phenomenon of overtide. Breaking with  
464 power, the sea crashed onto the land causing significant damage: 25 kilometers of dykes at  
465 Croisic were completely destroyed, the salt marshes of Guerande were submerged by the sea,  
466 public health was compromised by stagnant water, the loss of salt production was estimated at  
467 between 25 and 50% and the amount of money to repair the infrastructure was exorbitant  
468 (Departmental Archives, 575 S 1, 7 S 181, Journal L'Union Bretonne – 11/01/1877).

#### 469 ii) Petite Mer de Gâvres cores

470 The combination of proxies revealed three main dates observed for Croisic of 1990 (cm. 10 of  
471 LA2), 1972 (cm. 15-20 for LB2 and LA2) and 1940 (cm. 25-30 for LB2 and LA2) (Fig. 7).  
472 As they disturbed two different lagoons 100 km apart, these three storms deeply impacted a  
473 large part of the French Atlantic coast. Moreover, two main other storminess events are seen  
474 in several Gâvres cores. Using historical archives, these were precisely dated to 9<sup>th</sup> January

475 1924, and 26<sup>th</sup>/27<sup>th</sup> December 1999. These two different dates testify to two destructive  
476 storms. In 1924 (storminess observed at cm. 30-35 in all four cores), a 100 km/h wind speed  
477 combined with a 100 tidal coefficient event hit all the Atlantic coasts and drowned ten people  
478 (Météo France: <http://tempetes.meteofrance.fr/Tempete-du-8-au-9-janvier-1924.html>; Journal  
479 Ouest Éclair, 10/01/1924; Journal La Vendée Républicaine, 12/01/1924; Journal L'Etoile de la  
480 Vendée, 13/01/1924; Municipal Archives of Nantes, 304 PRES 838; Departmental Archives  
481 of Loire-Atlantique, 109 S 167, 05/11/1927). In 1999 (cm. 5 in LB), all the country was hit  
482 and nearly a hundred dead were reported during these two series of storms reaching 200 km/h  
483 wind speeds (<http://tempetes.meteofrance.fr/Martin-les-27-et-28-decembre-1999.html>; 24  
484 PRES 270, 30/12/1999; 24 PRES 271, 06/01/2000).

485 The last important marker was dated circa 1895–1900, which brought the 6-cm diameter  
486 pebble into the LB environment (Fig. 7). As a clayey layer was dated underneath the pebble  
487 horizon, our dating estimates the overwash near 1896. In addition, our dating on top of this  
488 layer is estimated at near 1915, so it would have taken nearly twenty years to re-stabilize the  
489 environment after this highly damaging event. From historical archives, we know that the  
490 storm hit the whole country on 4<sup>th</sup> December 1896, and that numerous breaches were  
491 reported, which makes the Gâvres breach hypothesis very likely. This information was  
492 extracted from a dozen sources, including a visual testimony. A tsunami might have brought  
493 this pebble layer, but the region is rarely hit by this kind of hazard (Dawson et al., 2004;  
494 Karnik, 1971). Furthermore, this date does not correspond to any tsunami record in the  
495 archives, which is why we favor the powerful storm hypothesis. This event caused 33 deaths  
496 in France during flooding created by the storm that combined with a high tide coefficient of  
497 95 according to the SHOM (Météo-France: <http://tempetes.meteofrance.fr/Tempete-du-4-decembre-1896.html>; Journal de la Charente Inférieure, 09/12/1896; Departmental Archives  
498 of Loire-Atlantique, 575 S 1; 7 R 1/1509; 3 Z 195; Departmental Archives of Vendée, 1 M  
499 558). We propose the hypothesis that this damaging event affected a large part of the French  
500 Atlantic coast as a Croisic hypothesis is set at around 1890 (Fig. 6). Markers found in the  
501 Gâvres cores may correspond to this Croisic hypothesis, reported in all nine cores of this  
502 study. As the upper contact with the clayey layer is dated around 1915 AD, we estimated the  
503 resilience of the Gâvres lagoon system to be nearly twenty years after this high impacting  
504 event.  
505

#### 506 **4. Conclusion**

507 Coupling historical and sedimentological archives helps to date recent marine deposits and  
508 obtain information about extreme wave events. We detected three main impacting storm dates  
509 found in the two different sites: 1990 AD, 1972 AD and 1940 AD. Three other stormy events  
510 also disturbed one of the two lagoons: 1924 AD, 1977 AD and 1999 AD, with four other 19<sup>th</sup>  
511 and XVIII<sup>th</sup> century extreme wave event hypotheses reported in the central western French

512 coast: 1775 AD, 1811 AD, 1838 AD and 1876 AD. Moreover, we propose that an important  
513 storm event completely disturbed a part of the French Atlantic coast in 1896 AD.

514 Based on statistical analyses, we also tested two new geochemical ratios never previously  
515 used in the French Atlantic coast: Sr/Fe and Ca/Ti. Coupling these ratios with other  
516 sedimentological analyses showed their usefulness in detecting recent storms. Historical  
517 archives proved that these storm hypotheses agree with sedimentological storminess dates,  
518 particularly due to these two new geochemical ratios. Further work must now be done to  
519 extend this European Atlantic storm analysis earlier to confirm pre-XX<sup>th</sup> century dates with  
520 the large historical French archive collection available.

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Table 1. Geochemical correlation matrix

	Al	Br	Ca	Cl	Co	Cu	Fe	K	Mn	Ni	Pb	Rb	S	Si	Sr	Ti	Zn	Zr	
Al	1.00	0.44	-0.12	0.01	0.28	0.29	0.50	0.85	-0.03	0.17	0.46	0.64	0.06	0.25	-0.11	0.57	0.43	0.35	Al
Br		1.00	-0.20	0.55	0.69	0.54	0.83	0.49	0.02	0.26	0.58	0.58	0.33	-0.35	-0.15	0.75	0.76	0.29	Br
Ca			1.00	-0.27	-0.09	-0.11	-0.15	-0.28	0.12	-0.03	-0.18	-0.46	0.31	-0.06	0.96	-0.18	-0.10	-0.22	Ca
Cl				1.00	0.70	0.38	0.70	0.36	-0.05	0.19	0.37	0.45	0.54	-0.82	-0.28	0.66	0.73	0.42	Cl
Co					1.00	0.51	0.86	0.45	0.08	0.19	0.43	0.48	0.59	-0.57	-0.07	0.81	0.83	0.50	Co
Cu						1.00	0.57	0.34	0.05	0.22	0.40	0.37	0.30	-0.26	-0.11	0.53	0.56	0.23	Cu
Fe							1.00	0.63	0.12	0.26	0.60	0.59	0.57	-0.53	-0.13	0.95	0.93	0.46	Fe
K								1.00	-0.13	0.18	0.49	0.84	0.22	-0.03	-0.28	0.69	0.60	0.46	K
Mn									1.00	-0.14	0.04	-0.25	0.12	-0.02	0.10	0.09	0.11	-0.07	Mn
Ni										1.00	0.19	0.15	0.17	-0.12	-0.02	0.26	0.23	0.15	Ni
Pb											1.00	0.51	0.16	-0.16	-0.16	0.56	0.55	0.27	Pb
Rb												1.00	0.07	-0.11	-0.42	0.60	0.57	0.42	Rb
S													1.00	-0.63	0.26	0.55	0.61	0.33	S
Si														1.00	-0.04	-0.46	-0.58	-0.22	Si
Sr															1.00	-0.17	-0.10	-0.22	Sr
Ti																1.00	0.90	0.55	Ti
Zn																	1.00	0.48	Zn
Zr																		1.00	Zr
	Al	Br	Ca	Cl	Co	Cu	Fe	K	Mn	Ni	Pb	Rb	S	Si	Sr	Ti	Zn	Zr	



Figure 1. Historical presentation of the two studied sites

Figure 2. Sedimentological presentation of the two studied sites, with the SHOM sedimentological map (A), the precise core location (B) and the presentation of the nine extracted cores (C)

Figure 3.  $^{210}\text{Pb}_{\text{xs}}$  profile with depth and  $^{137}\text{Cs}$  profile with age along the cores in the Traicts du Croisic (T1, A) and the Petite Mer de Gâvres (LB1, B)

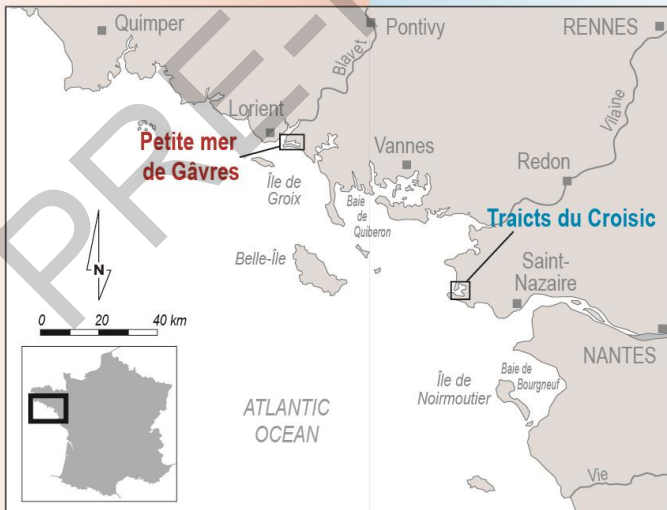
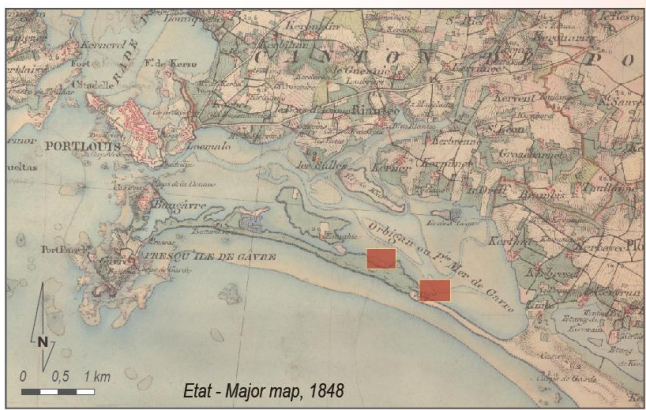
Figure 4. Geochemical elements dendrogram

Figure 5. PCA summarization with automatized group-sorting (blue : marine elements, pink : continental elements, yellow : mixed element)

Figure 6. Detection of Traicts du Croisic paleoevents

Figure 7. Detection of Petite Mer de Gâvres paleoevents

PRE-PRINT



Petite mer  
de Gâvres

Traits du Croisic

Petite mer  
de Gâvres

Traits du Croisic

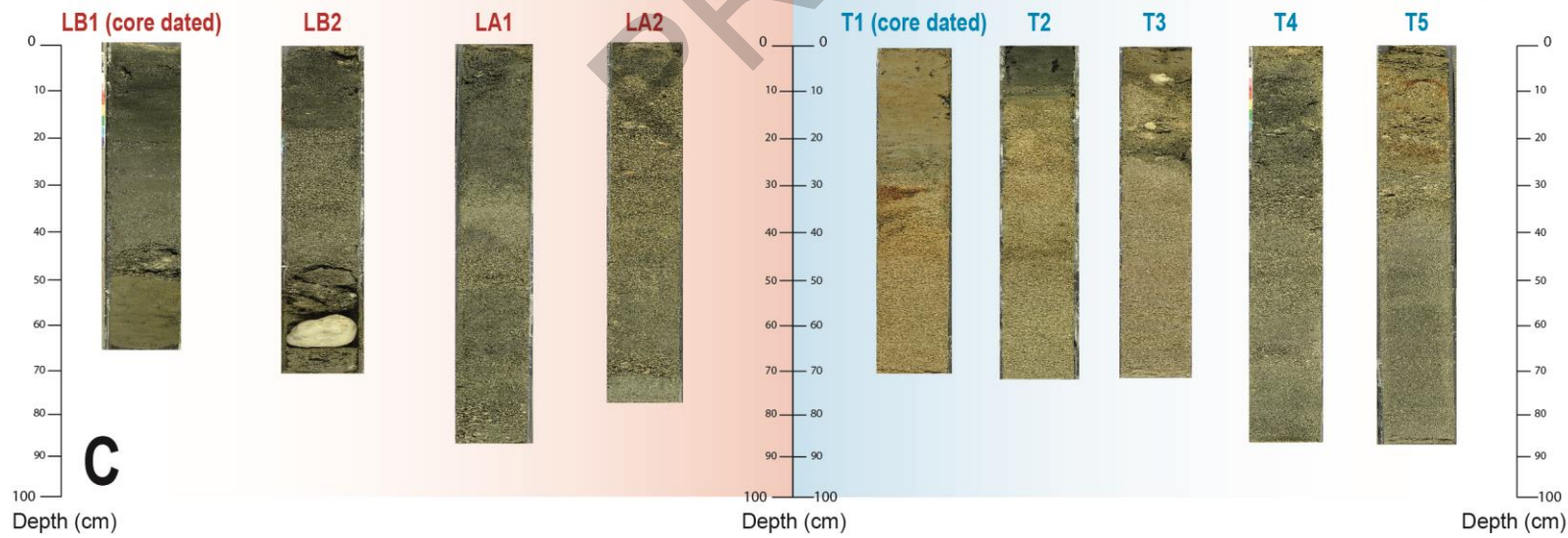
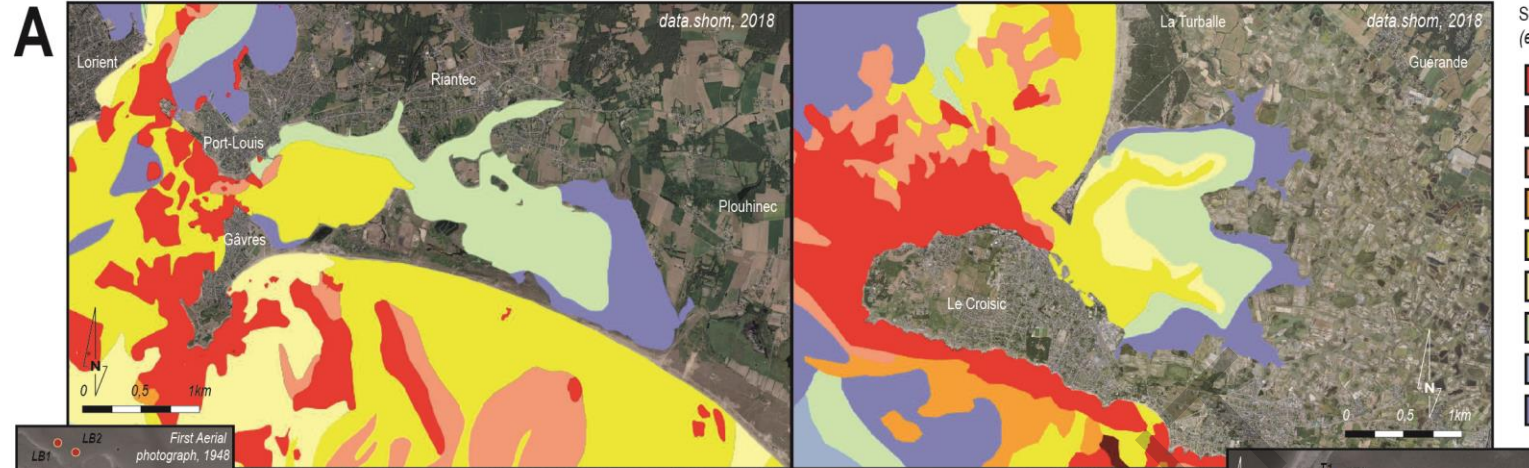


## Petite mer de Gâvres

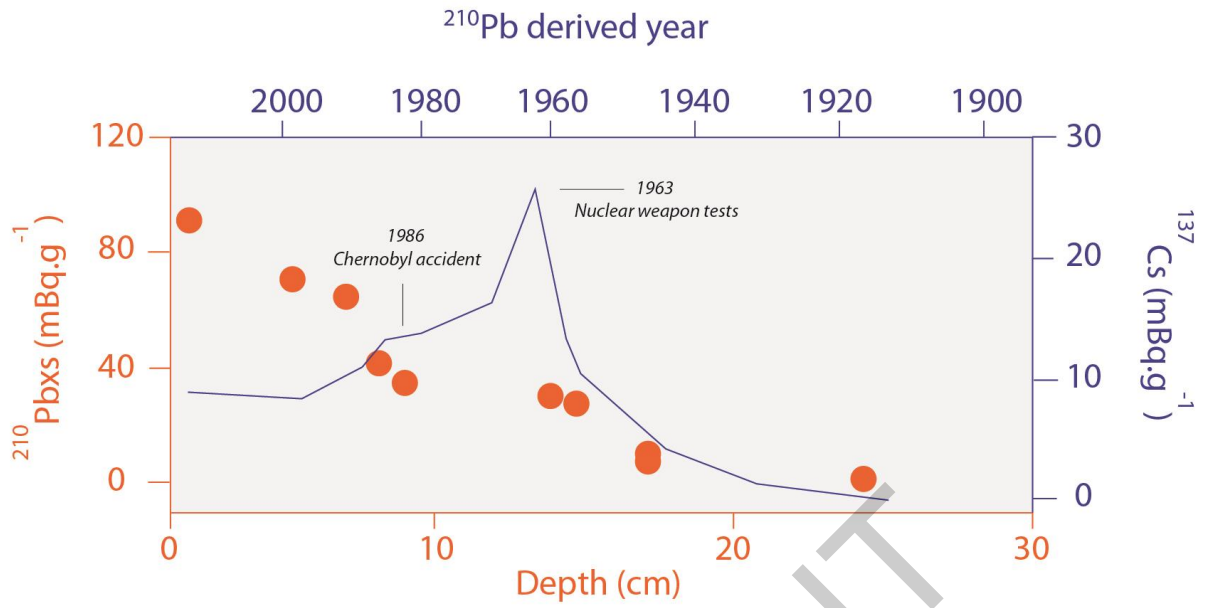
## Traits du Croisic

Sedimentological map  
(extracted from the SHOM database)

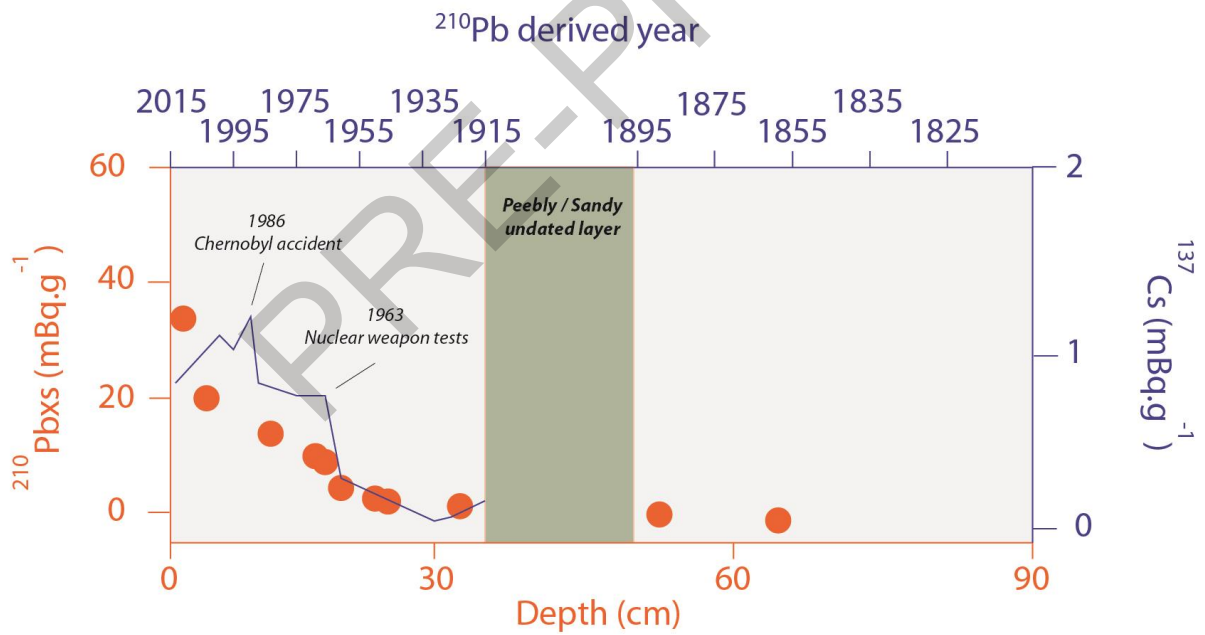
- Rock
- Coarse pebble
- Pebbles
- Coarse sand
- Sand
- Fine sand
- Silt
- Silty clay
- Clay

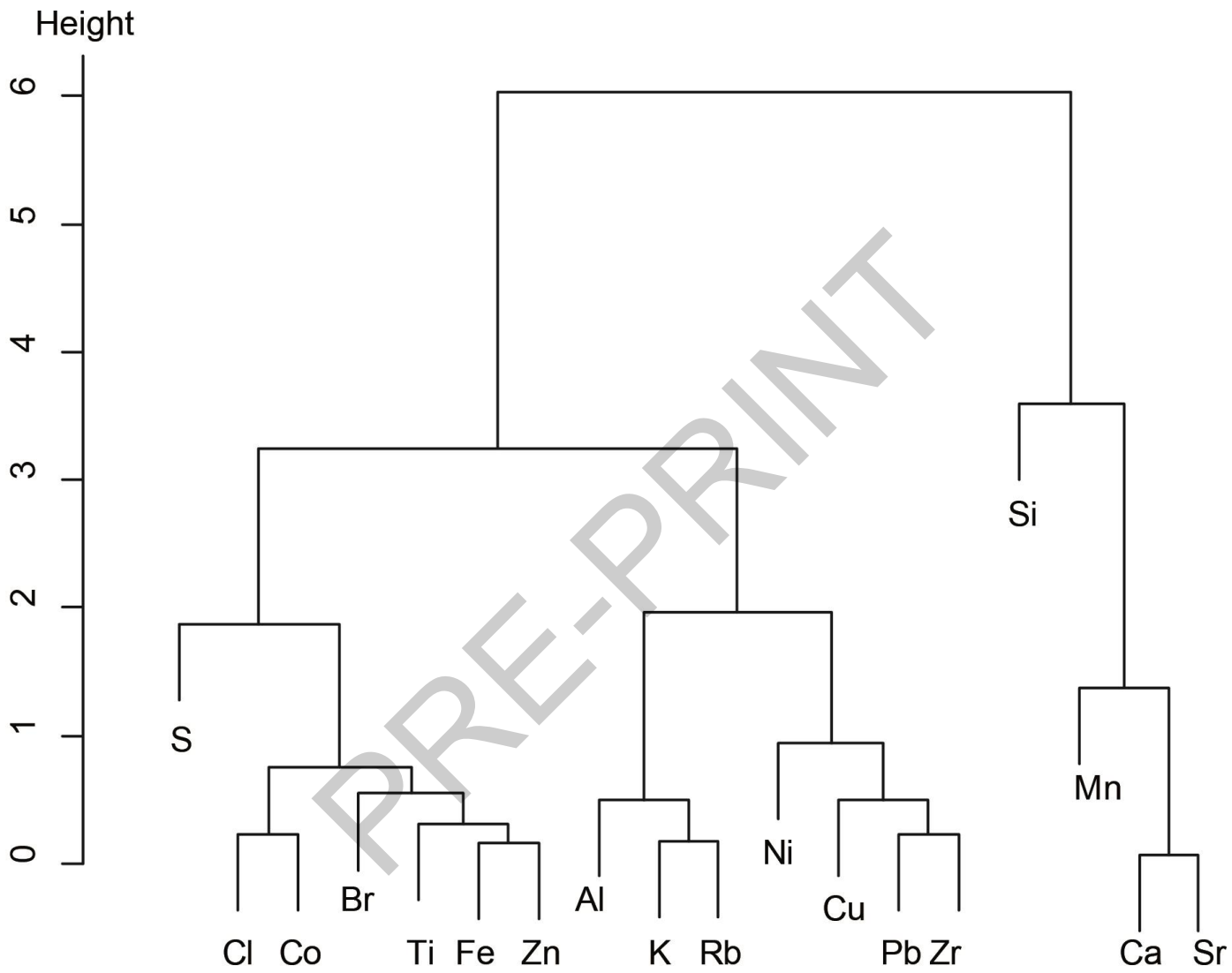


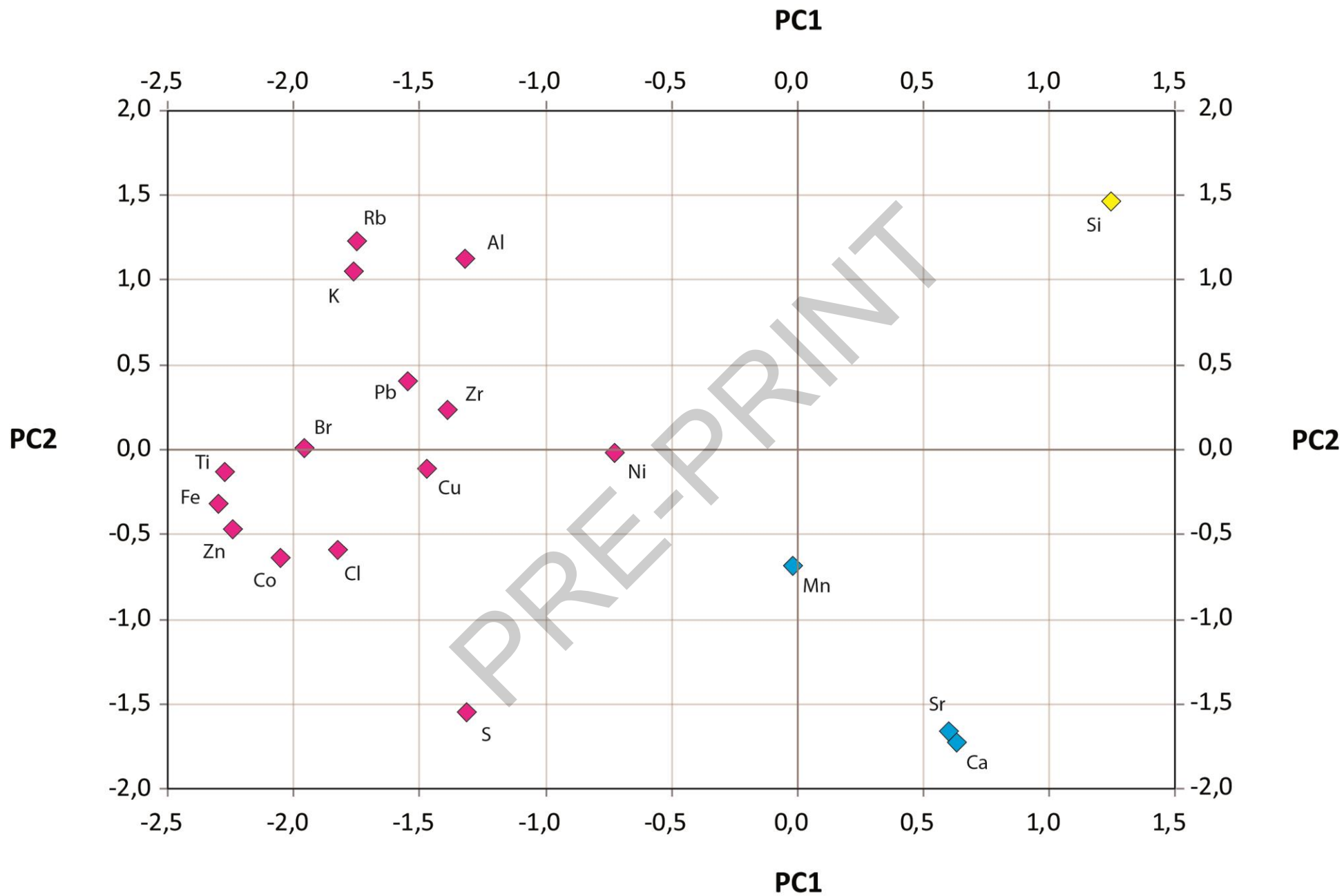
## A. Traicts du Croisic (T1)



## B. Petite mer de Gâvres (LB1)

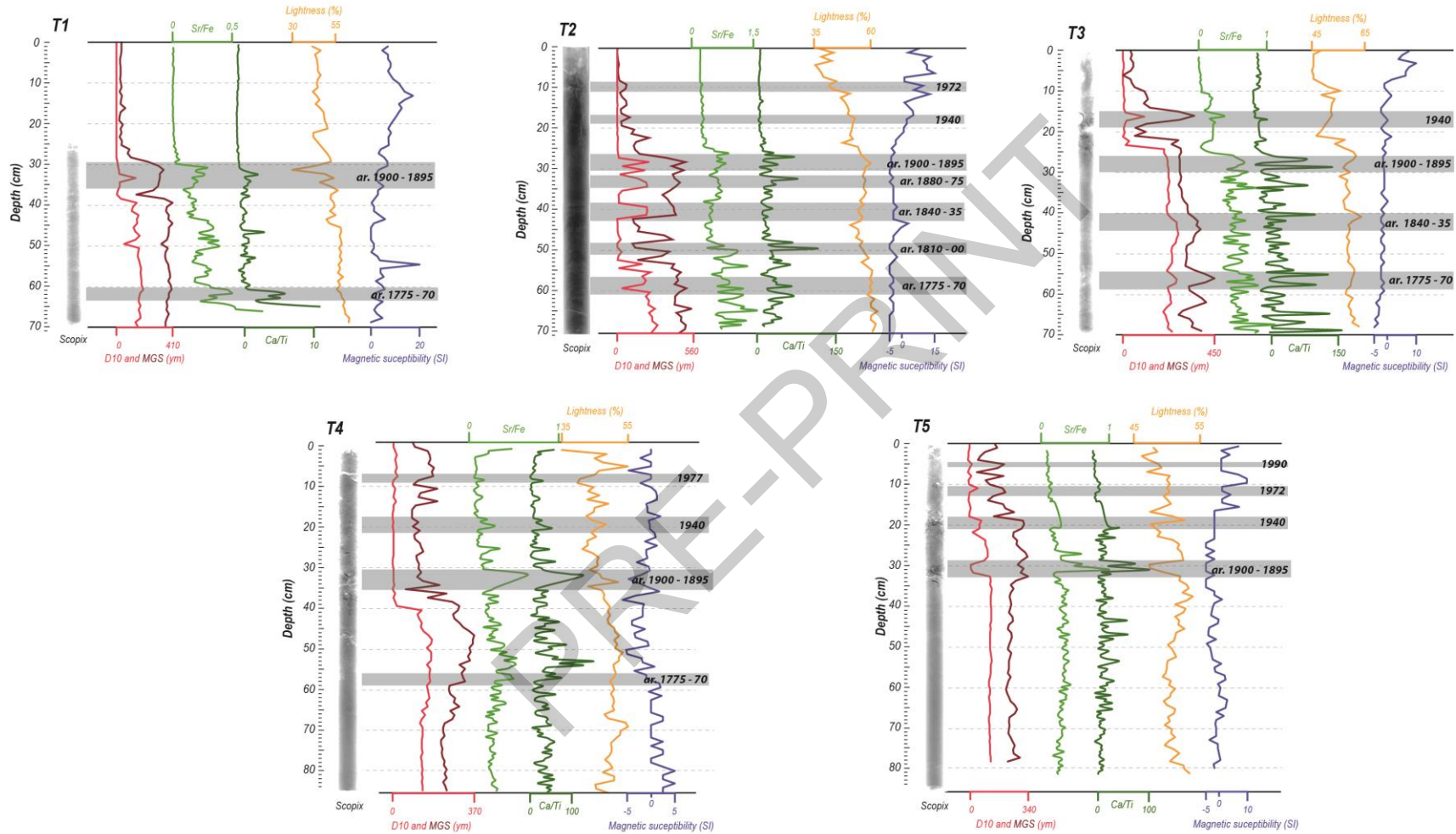






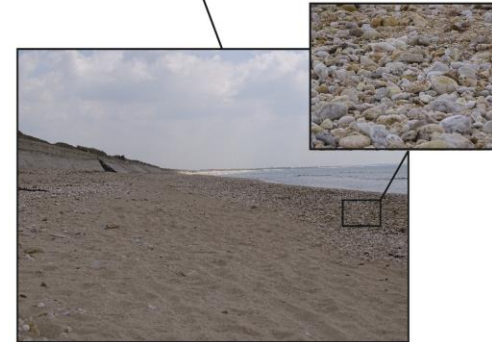
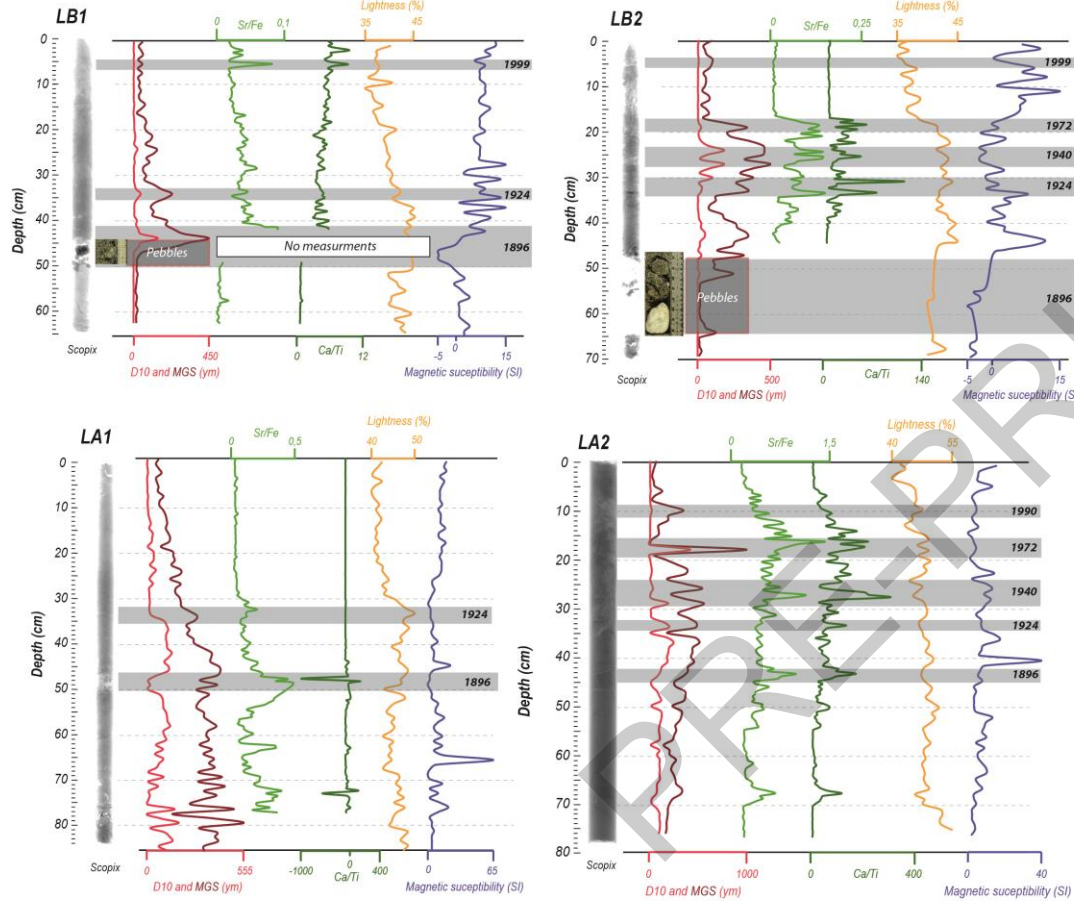


Pays-de-la-Loire region 1751 to 1999 marine flooding dates recorded in historical archives :  
 1751 - 1760 - 1775 - 1811 - 1838 - 1876 - 1880 - 1884 - 1890 - 1896 - 1905 - 1924 - 1928 - 1934 - 1940 - 1972 - 1977 - 1987 - 1990 - 1999



1940 : Dates AD found with dating in sedimentological and historical archives for probable extreme wave event  
 ar. 1775 - 70 : period estimated with the sedimentation rate for a probable extreme wave event (ar. : around)

Brittany region 1751 to 1999 marine flooding dates recorded in historical archives :  
 1751 - 1760 - 1811 - 1876 - 1890 - 1896 - 1905 - 1924 - 1934 - 1940 - 1972 - 1987 - 1990 - 1999



1940 : Dates AD found with dating in sedimentological and historical archives for probable extreme wave event