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

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Abstract

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

Keywords: French Atlantic coast, storm events, geochemical ratios, historical archives, 1896 event.

Highlights

Good sedimentological and historical correlation for the last three centuries

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

Eleven extreme events recorded in French Atlantic coast sediments

1. Introduction

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

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

2. Material and methods

2.1. Study area

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

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

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

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

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

2.2. Sampling and sediment analysis

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

2.3. Dating

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

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

2.4. Historical archives

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

The historical research is mainly based on ancient documents: i) ancient maps, ii) narrative sources (chronicles, diaries, memories etc.) and iii) documents (books of accounts, records of repairs, surveys conducted after a disaster, barometric observations, newspapers etc.) preserved in libraries and in municipal, departmental, and national archives. These documents contain observational and descriptive data on past extreme weather hazards (descriptions of the storm and the damage caused), as well as impacts on societies and their reactions and adaptation. For the period studied in this paper, we also considered instrumental data such as barometric information and data from Meteo France. In order to cover and reconstruct the history of storms and sea flooding that occurred on the central western French coast over the last 300 years, we consulted more than 398 documents, of which only 264 contained data on past storms and coastal floods.

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

2.5. Statistical analysis

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

3. Results and discussion

3.1. Dating and age-depth modeling

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

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

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

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

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

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

3.2. Cored sediments characteristics

3.2.1. Development of extreme event indicators

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

3.2.2. Traicts du Croisic

All five cores show two different systems with a base of coarser grain sized, and generally more marine geochemical elements (Fig. 6). The 20-30 cm upper part of the cores shows lower morphogenic activity, with mostly silt or clayey sediment and lower Sr/Fe, Ca/Ti and lightness with higher MS values, testifying to more continental inputs. This large difference between these two systems is due to the evolution of the sandy spit, which became thicker with time (Fig. 1, Fig. 6), thus isolating this north-western part of the coastal marsh from the sea. This is why more storminess is identified in the coarser base of the core than in the upper clayey layer: as the spit became thicker during the last decade, the upstream marsh became more protected from the sea. Storms cannot disturb this environment now as much as when the dune was thinner.

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

3.2.3. Petite Mer de Gâvres

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

Two different sites were drilled, “LA” and “LB”, because our preliminary core tests showed that an important storminess variation is recorded behind a thick (LB) and a thin (LA) dune barrier (Fig. 1, Fig. 7). First, an important storminess is recorded near cm. 50 in the LB area, with coarse pebbles detected between two clayey layers. A 6-cm diameter pebble was extracted from the core. These pebbles come from the mixed sandy/pebbly beach on the other side of the dune barrier (photograph I, Fig. 7), confirming the washover origin of this layer. Furthermore, the nearshore sediment surface is also composed by pebbles, thus demonstrating their marine origin (Fig. 2A). In our core analyses, no pebble is observed in the LA environment although we think that it was impacted as much as LB, as shown by the sedimentology comparisons and dating carried out in these two sites. In the LA area, we can assume that this significant event breached the dune barrier where the vegetation is less dense, and that the wave backflow evacuated these coarser deposits. Geochemical ratios show that storminess is also recorded in the LA area, without these pebbles. In the LB environment, it is the opposite: the thicker sandy barrier caught the pebbles in the marsh, explaining why they were found during drilling. According to sediment observations and analysis results, this storminess corresponds to the marine input at 45-50 cm depth of the LA area. The fall in the Ca/Ti ratio is due to measurement disturbances made by a hole where a marine shell was removed before analysis, and with its correlation with the low MS values and increase of lightness and Sr/Fe ratio, proves the marine input for this section.

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

3.3. Historic records of extreme events

3.3.1. Coupling with historical data

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

3.3.2. Extreme event reconstruction

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

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

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

The great majority of storms are not violent enough to affect societies and ecosystems dramatically. Since only the most extreme events are recorded in sediments, once these data are coupled with historical observations, meteorological characteristics and descriptions of the damage caused, we can refine the knowledge of some important hazards. This makes the combination of different methods introduced in this paper relevant, because as the coastal population is expected to increase during the next decades (Lutz and Samir, 2010), the damages enhanced by coastal flooding will undoubtedly follow these dynamics (Chaumillon et al., 2017). With a better knowledge on past stormy dynamics, coastal societies directly exposed to this hazard will be prepared to face it, and consequently be less vulnerable to their induced damages. Past storm historical chronologies are essential to assess extreme events recurrence intervals and to subsequently prepare society more reliably to face the future storm and coastal flooding hazards (Goslin and Clemmensen, 2017). Therefore, for their wide source of historical information, plaeodata have to be included in risk assessment to better prepare coastal societies and enable them to develop a more resilient way of life (Naylor et al., 2017).

i) Traicts du Croisic cores

T1, located just behind the sandy barrier, only records a pre-XXth century storm. Its location too near the sandy barrier probably prevented later overwash deposits (Fig. 1, Fig. 6). Just two overwashes are recorded there, when the coastal split was thinner. From T2 to T5, numerous marine flooding markers are recorded, with a growing signature gradient from the barrier to the center of the lagoon: the core located nearest the coastline records the most storminess, while the three others have only four potential markers. With the five cores retained, four main certain and accurate dates for the XXth century can be determined from our historical research: 26th February 1990 (cm. 5 for T4 core), 11th January 1978 (cm. 7 for T5 core), 13th February 1972 (cm. 10 for T2 and T5 cores) and 17th November 1940 (cm. 15-20 for T2, T3, T4 and T5 cores). From historical records, three different storms crossed the study area in 1990, including its strongest that crossed a 104 high tide coefficient (SHOM) on February 26-28, 1990. The three storms caused 100 fatalities over the whole country, with winds reaching 176 km/h maximum in western France and many reports of flooded houses and broken dikes (http://tempetes.meteofrance.fr/Daria-le-25-janvier-1990.html, http://tempetes.meteofrance.fr/ Herta-le-03-fevrier-1990.html,http://tempetes.meteofrance.fr/ Viviane-du-26-au-28-fevrier-1990.html; Municipal Archives of Nantes, 23 Z 355; 24 PRES 152, 05/02/1990 and 24 PRES 152, 27 and 28/02/1990, Departmental Archives of Vendée, 1856 W 38). The second date from found in sedimentology is 1977. From historical archives, the two different events of December 2, 1976 or January 11, 1978 can be related. As in the first case the tide coefficient was very low, ca. only 50, and it reached 109 in the second (SHOM), the second date is therefore more likely. With ten deaths and fatalities reported, the 1978 storm crossed a large part of the country with damage notified from Dunkerque to the Gironde estuary (numerous shipwrecks and marine flooding reported in Le Marin 1595, MetMar 101 and (Steers et al., 1979) for other English damages). Historical records show that these two last earlier storms of 1972 and 1940 created a wind speed of 200 km/h that uprooted trees, damaged bell towers, toppled cranes, destroyed dikes, boats and roofs with many coastal floods. While the second one mostly hit western France (http://tempetes.meteofrance.fr/Tempete-du-13-fevrier-1972.html; Municipal Archives of Nantes, 1038 W 327; Departmental Archives of Vendée, 78/31 1953-1975 – tempête du 13 février 1972), the first affected the whole country for three days, destroying whole forests and leading to nearly 30 deaths (http://tempetes.meteofrance.fr/Tempete-du-16-au-17-novembre-1940.html; Departmental Archives of Loire-Atlantique, 75 W 274 –31/12/1940, 75 W 274 – 18/02/1941, 75 W 274 – 12/05/1941; Departmental Archives of Vendée, BIB B 1036/1-2).

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

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

ii) Petite Mer de Gâvres cores

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

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

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

4. Conclusion

Coupling historical and sedimentological archives helps to date recent marine deposits and obtain information about extreme wave events. We detected three main impacting storm dates found in the two different sites: 1990 AD, 1972 AD and 1940 AD. Three other stormy events also disturbed one of the two lagoons: 1924 AD, 1977 AD and 1999 AD, with four other 19th and XVIIIth century extreme wave event hypotheses reported in the central western French coast: 1775 AD, 1811 AD, 1838 AD and 1876 AD. Moreover, we propose that an important storm event completely disturbed a part of the French Atlantic coast in 1896 AD.

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

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1038 W 327

55PRES21, 03/03/1811

23 Z 355

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24 PRES 152, 05/02/1990, Presse Océan

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7 S 181

7 R 1/1509

109 S 167, 05/11/1927

575 S 1

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3 Z 195

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1 M 558

1856 W 38

78/31 1953-1975 – tempête du 13 février 1972

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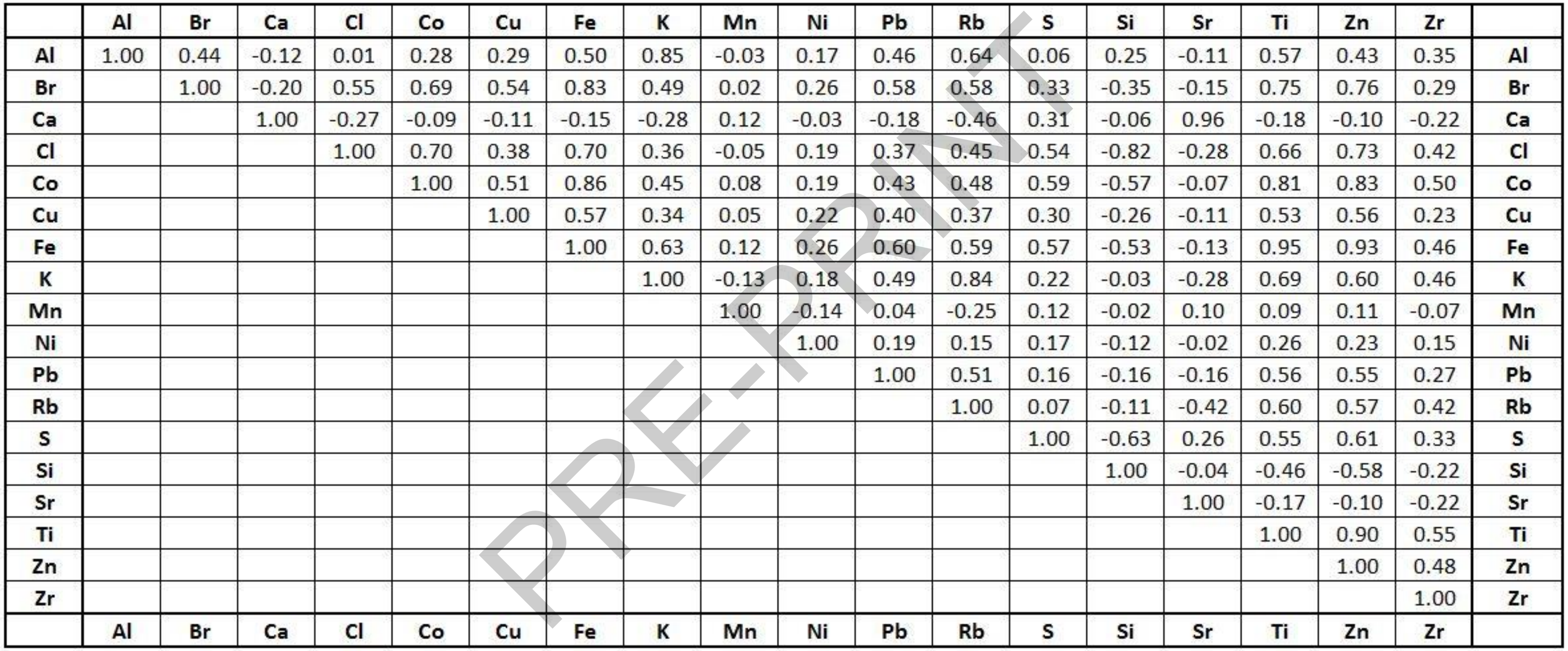
Table 1. Geochemical correlation matrix



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

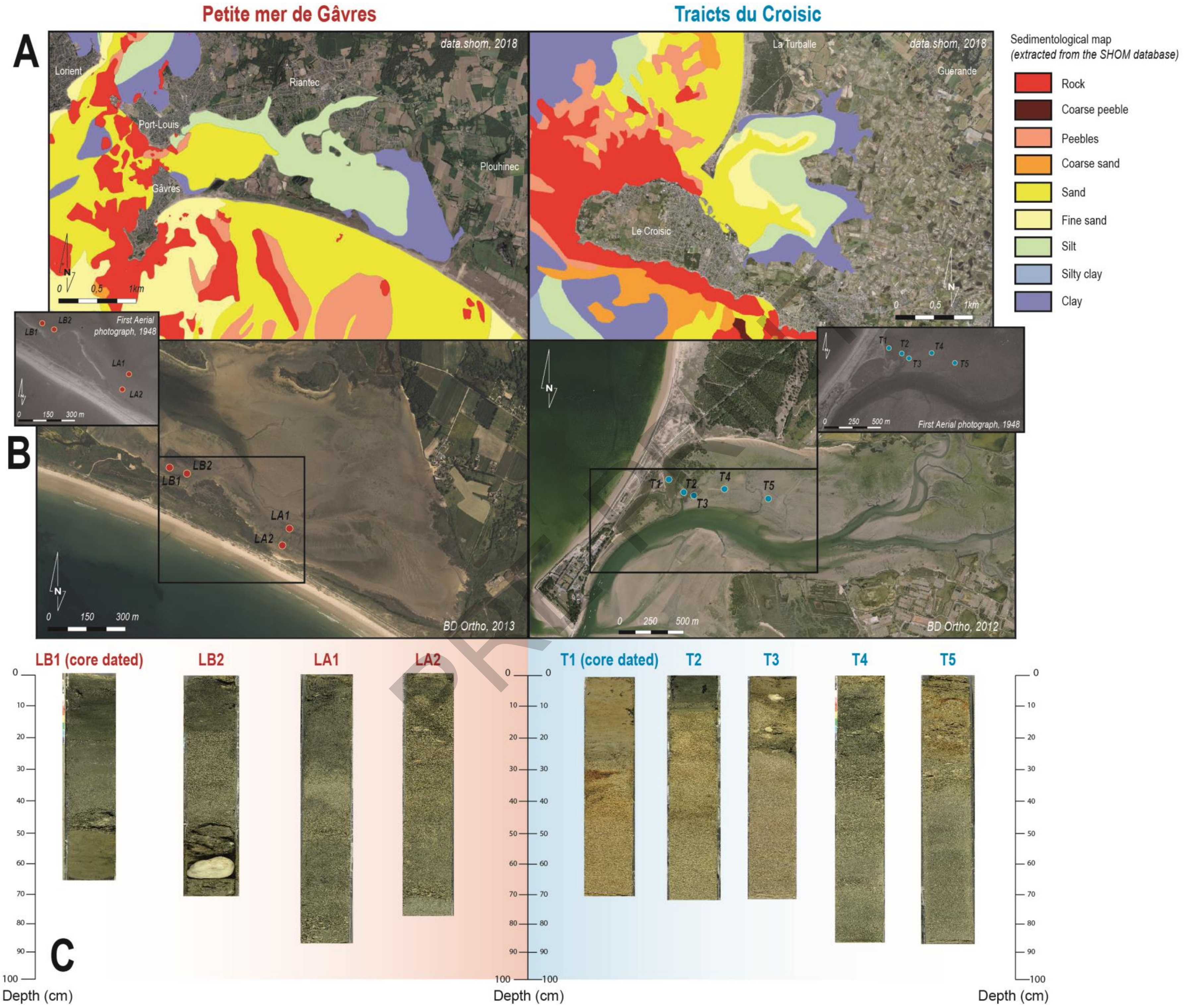
Figure 4. Geochemical elements dendrogram

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

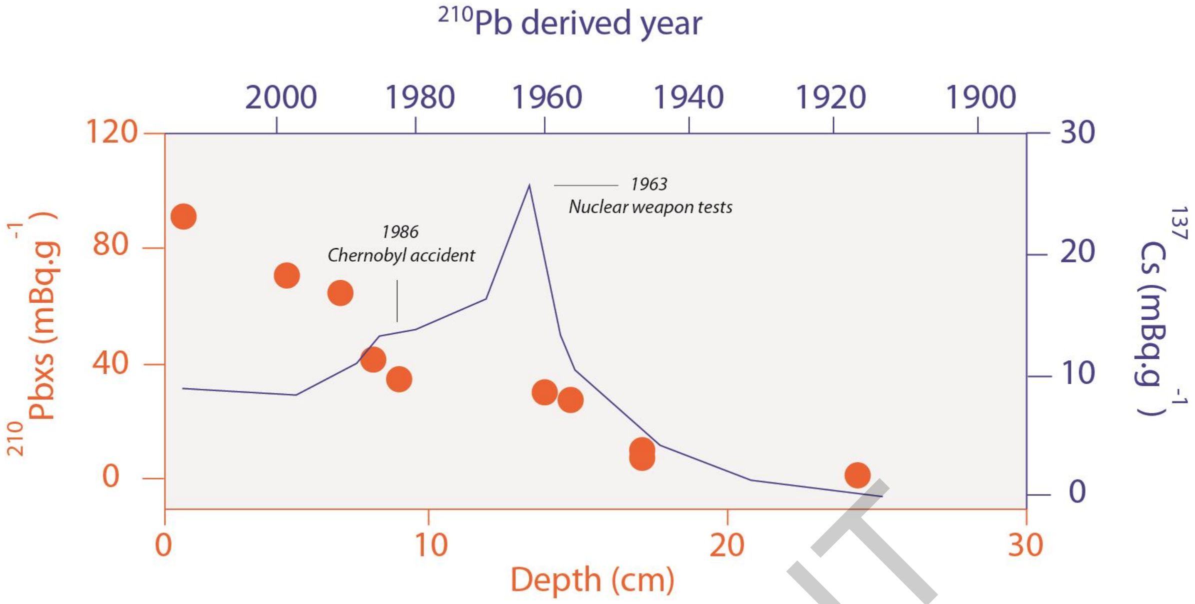
Figure 6. Detection of Traicts du Croisic paleoevents

Figure 7. Detection of Petite Mer de Gâvres paleoevents

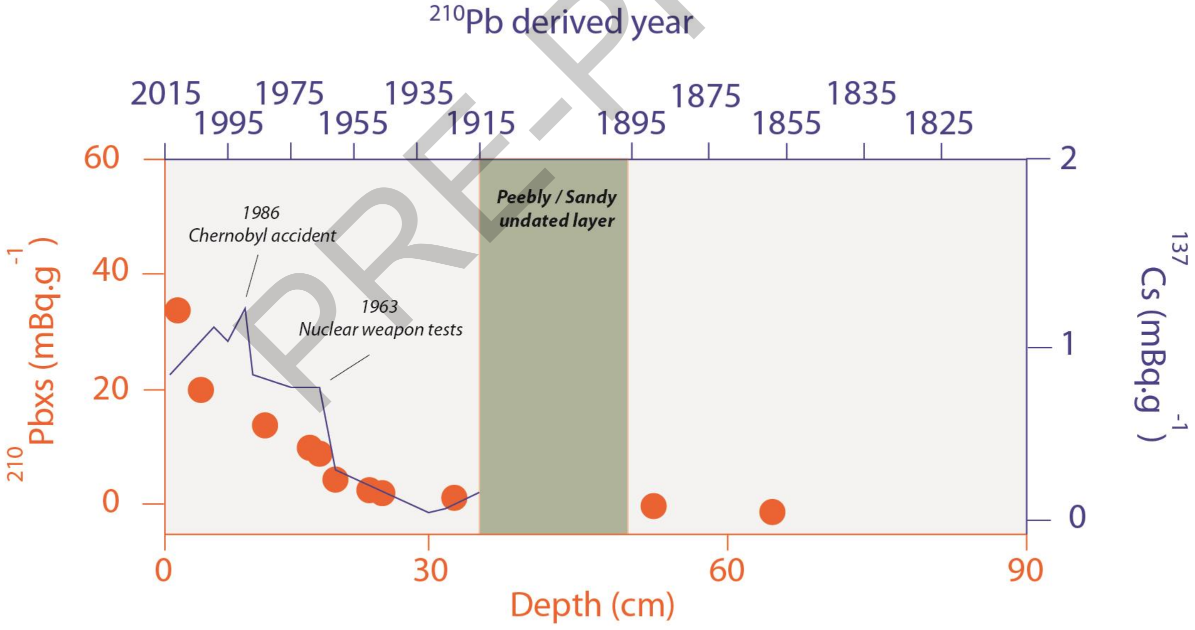

Lorient
Port-Louis
Riantec
Plouhinec
Gâvres
Core locations
N
0 0,5 1 km
BD Ortho, 2013
La Turballe
Guérande
Core location
Le Croisic
BD Ortho, 2012
Etat - Major map, 1848
Cassini map, 1789
Petite mer de Gâvres
Traicts du Croisic
Quimper
Pontivy
RENNES
Blavet
Lorient
Vilaine
Vannes
Redon
Île de Groix
Baie de Quiberon
Belle-Île
Saint-Nazaire
NANTES
Île de Noirmoutier
Baie de Bourgneuf
ATLANTIC OCEAN
Vie
0 20 40 km
Etat - Major map, 1847
Cassini map, 1787

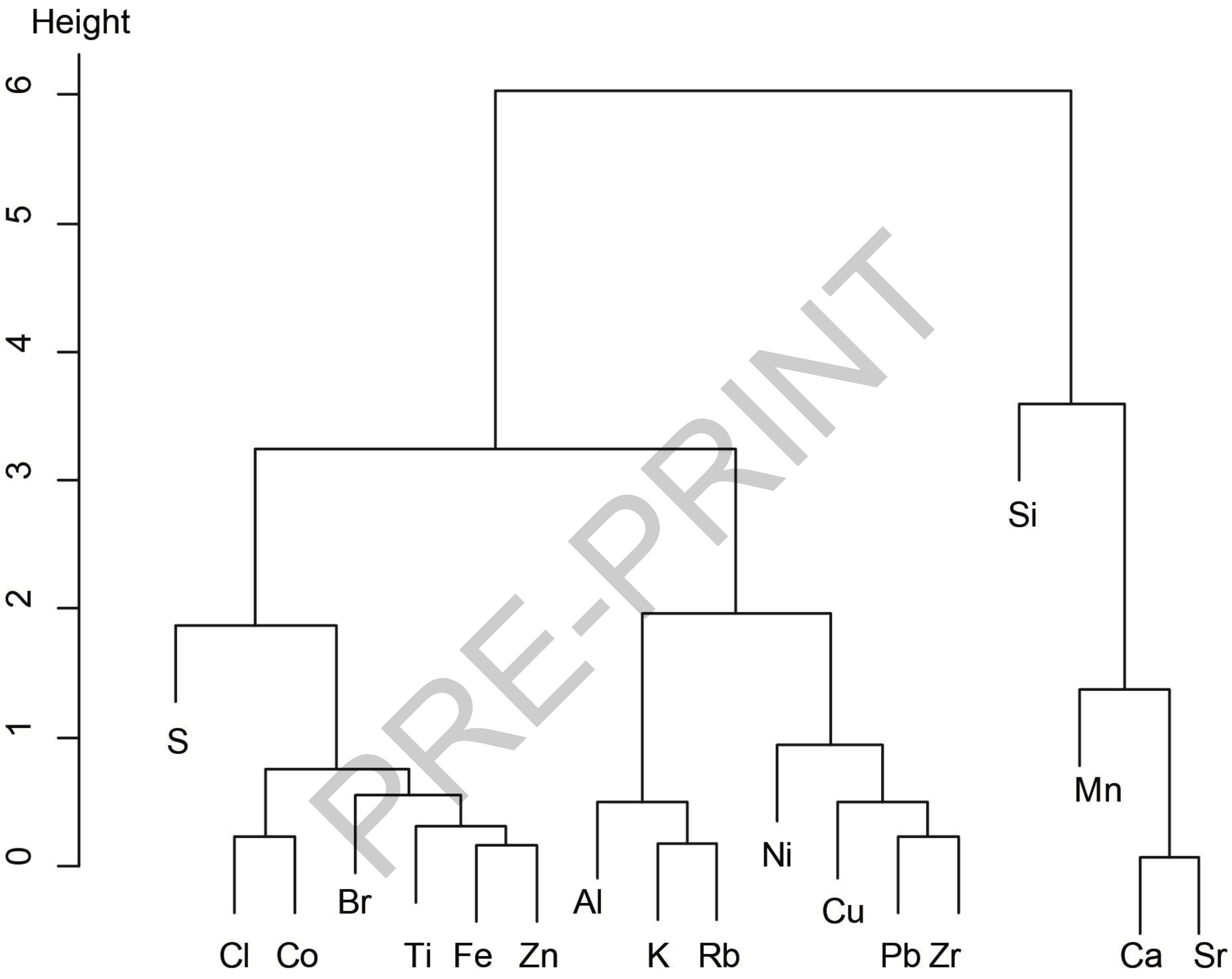

Petite mer de Gâvres
Traicts du Croisic
A
data.shom, 2018
Lorient
Riantec
Port-Louis
Plouhinec
Gâvres
N
0 0,5 1km
La Turballe
Guérande
Le Croisic
Sedimentological map
(extracted from the SHOM database)
Rock
Coarse peeble
Peebles
Coarse sand
Sand
Fine sand
Silt
Silty clay
Clay
B
First Aerial photograph, 1948
LB1
LB2
LA1
LA2
0 150 300 m
BD Ortho, 2013
T1
T2
T3
T4
T5
0 250 500 m
BD Ortho, 2012
C
LB1 (core dated)
LB2
LA1
LA2
T1 (core dated)
T2
T3
T4
T5
0
10
20
30
40
50
60
70
80
90
100
Depth (cm)

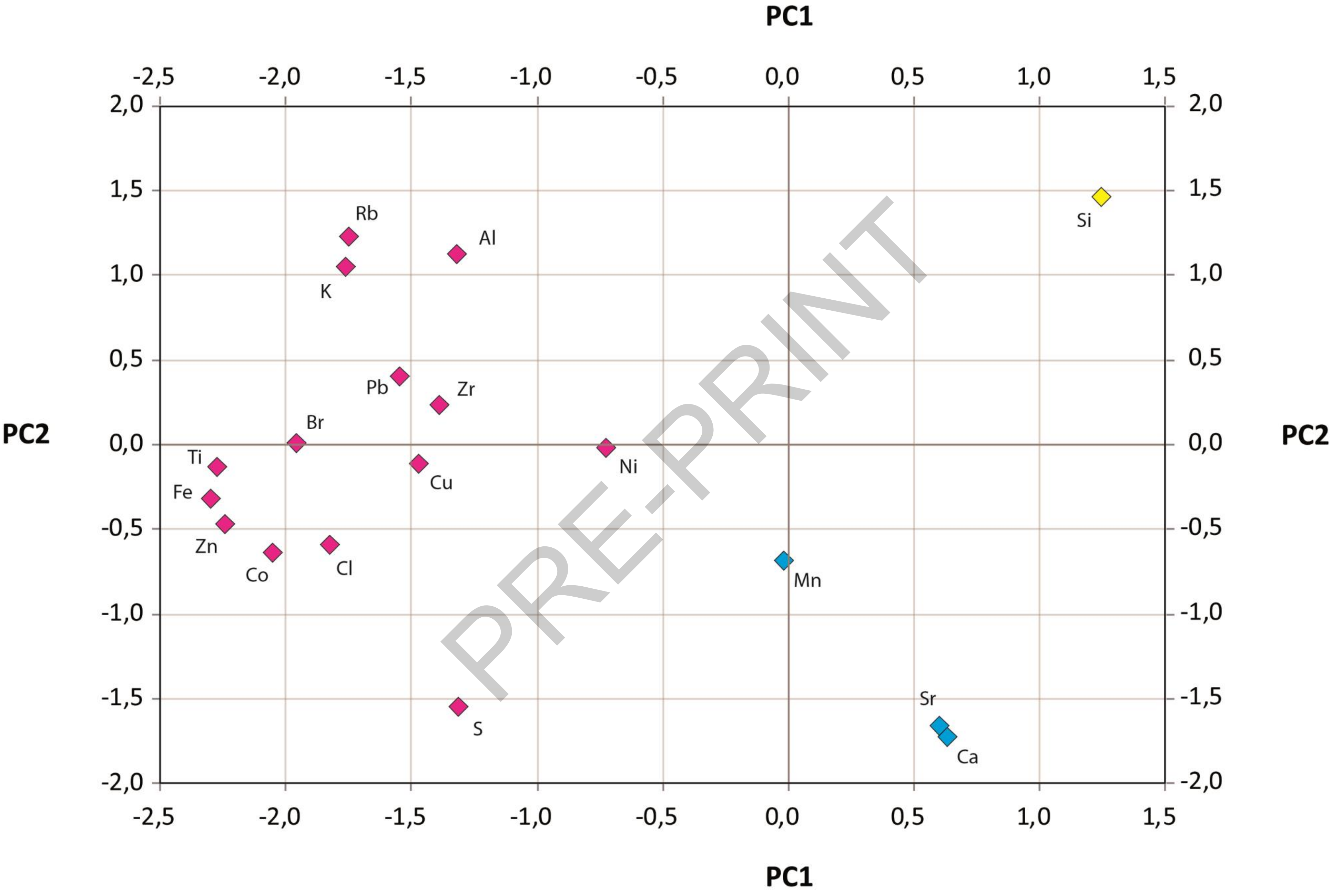
A. Traicts du Croisic (T1)



B. Petite mer de Gâvres (LB1)

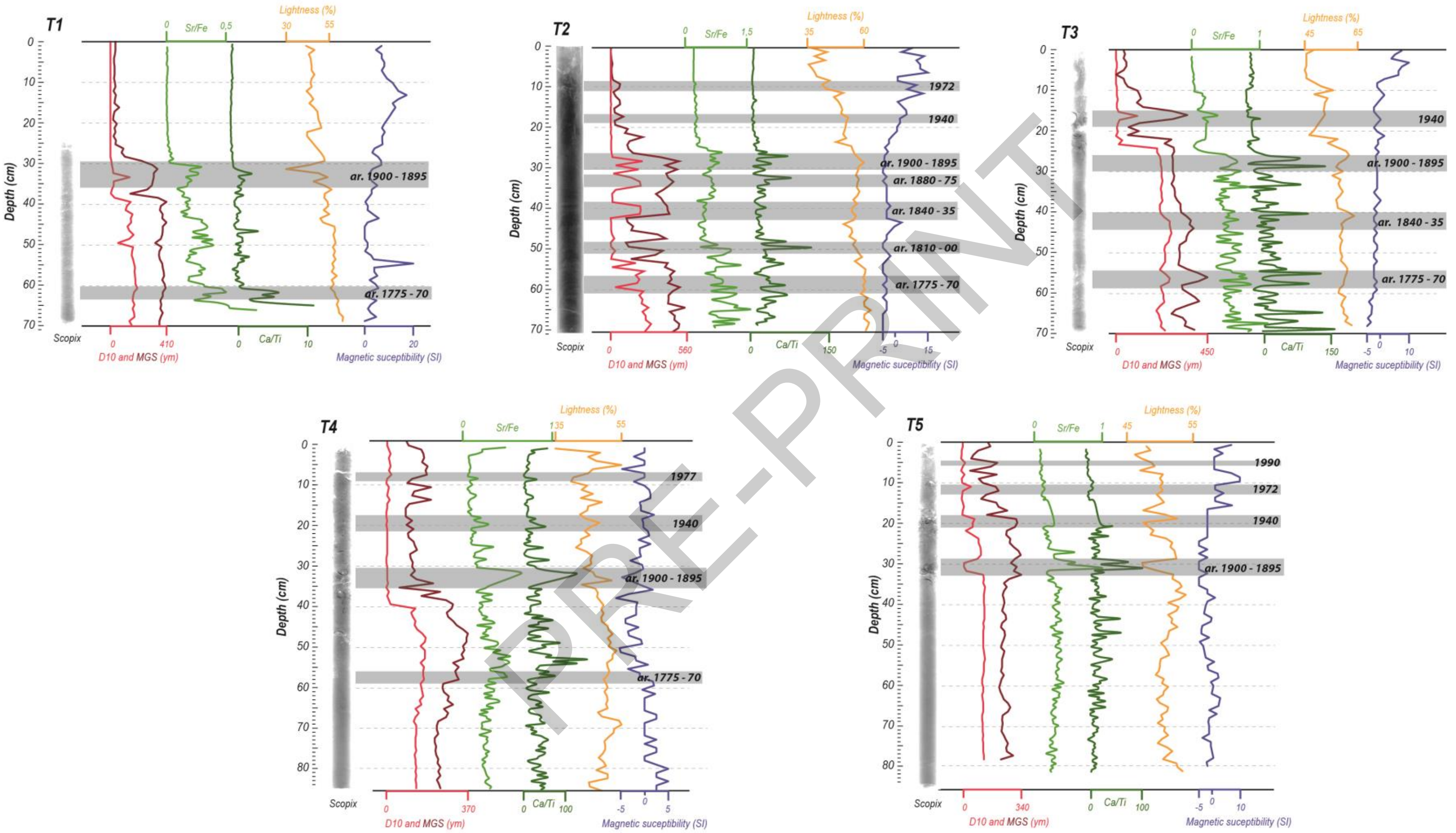



Height
0
1
2
3
4
5
6
S
Cl
Co
Br
Ti
Fe
Zn
Al
K
Rb
Ni
Cu
Pb
Zr
Si
Mn
Ca
Sr


PC1
-2,5
-2,0
-1,5
-1,0
-0,5
0,0
0,5
1,0
1,5
PC2
2,0
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
Rb
K
Al
Pb
Zr
Br
Ti
Fe
Zn
Co
Cl
Cu
Ni
S
Mn
Sr
Ca
Si

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