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# Infilling of the Canche Estuary (eastern English Channel, France): Insight from benthic foraminifera and historical pictures

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ABSTRACT

A multiproxy approach based on benthic foraminifera, sediment grain-size, total organic carbon content, major and trace element concentrations, and radionuclide activities was used to investigate the recent landscape evolution of the Canche Estuary (eastern English Channel, France). In the present study the radiometric dating based on $^{210}Pb$ and $^{137}Cs$ activities could only establish that the sediments were deposited recently. As an alternative method, aerial historical pictures were used for the first time to date core sediments as well as to enhance the palaeoenvironmental interpretations. In approximately one hundred years, an initial naked tidal flat has been gradually replaced by a vegetated salt marsh. In the bottom part of the core, foraminiferal assemblages are dominated by *Cribroelphium excavatum* and *Elphidium margaritaceum*. *Haynesina germanica* is the most abundant taxon in the middle part of the core while *Entzia macrescens* is dominant in the upper part. The sediment core represents a typical fining-upward succession in a low-impacted tide-dominated estuary filled by progradation. Our outcomes highlight how a multidisciplinary approach based on abiotic and biotic parameters is essential for understanding complex transitional areas like estuaries. When dating is not provided by classic radiometric methods, historical pictures (< 100 years) may constitute a valuable alternative method to reconstruct recent environments.

## 1. Introduction

Benthic foraminiferal assemblages show clear responses to changing environmental conditions in terms of species composition (Bouchet et al., 2007; Frontalini et al., 2014; Armynot du Châtelet et al., 2018). Their high abundance and biodiversity in marine sediments allow them to have a high potential for preservation along the sedimentary record (Alve, 1991; Murray, 2007). Many studies have interpreted recent palaeoenvironmental changes on the basis of benthic foraminifera (Alve, 1991; Gehrels, 1999; Hayward et al., 2010; Calvo-Marcilese et al., 2013). Palaeoenvironmental reconstructions were done predominantly in coastal marginal areas, which are appealing to researchers due to their high variability in terms of physical, chemical, and biological parameters, rapid landscape transformations, sea level changes, human interactions, accessibility and low cost of research. Foraminifera can serve as proxies providing a first-order picture of past conditions in a variety of coastal settings (Scott et al., 2001; Leorri et al., 2008). Among them estuaries are one of the most enigmatic systems for investigations of the ecological interactions between the biota and the environment. Estuaries are seaward portions of drowned valleys and are the result of a complex mixing of river, marine and tidal processes (Dalrymple et al., 1992). The recent geomorphological and ecological transformations of these land-sea transitional areas have been often related to natural infilling due to sediment accumulation and/or the increasing of human activities (such as deforestation, agricultural land use, wetland drainage) (Billeaud et al., 2005; Horrocks et al., 2007).

In a macrotidal regime, intertidal areas such as salt marshes or mangrove forests can be often covered by dense vegetation. In these environments, foraminifera occur within narrow vertical zones, constrained by the tidal frame (Scott and Medioli, 1978; Scott and Medioli, 1980; Horton and Murray, 2007; Francescangeli et al., 2017). Hence palaeoenvironmental reconstructions based on foraminifera appear particularly robust (Cearreta et al., 2002; Allen et al., 2006; Cearreta et al., 2013). However, taphonomical processes can alter foraminiferal assemblages during burial. It can modify as much as 60–90% of the living assemblages (Hayward et al., 2015). For example, in intertidal

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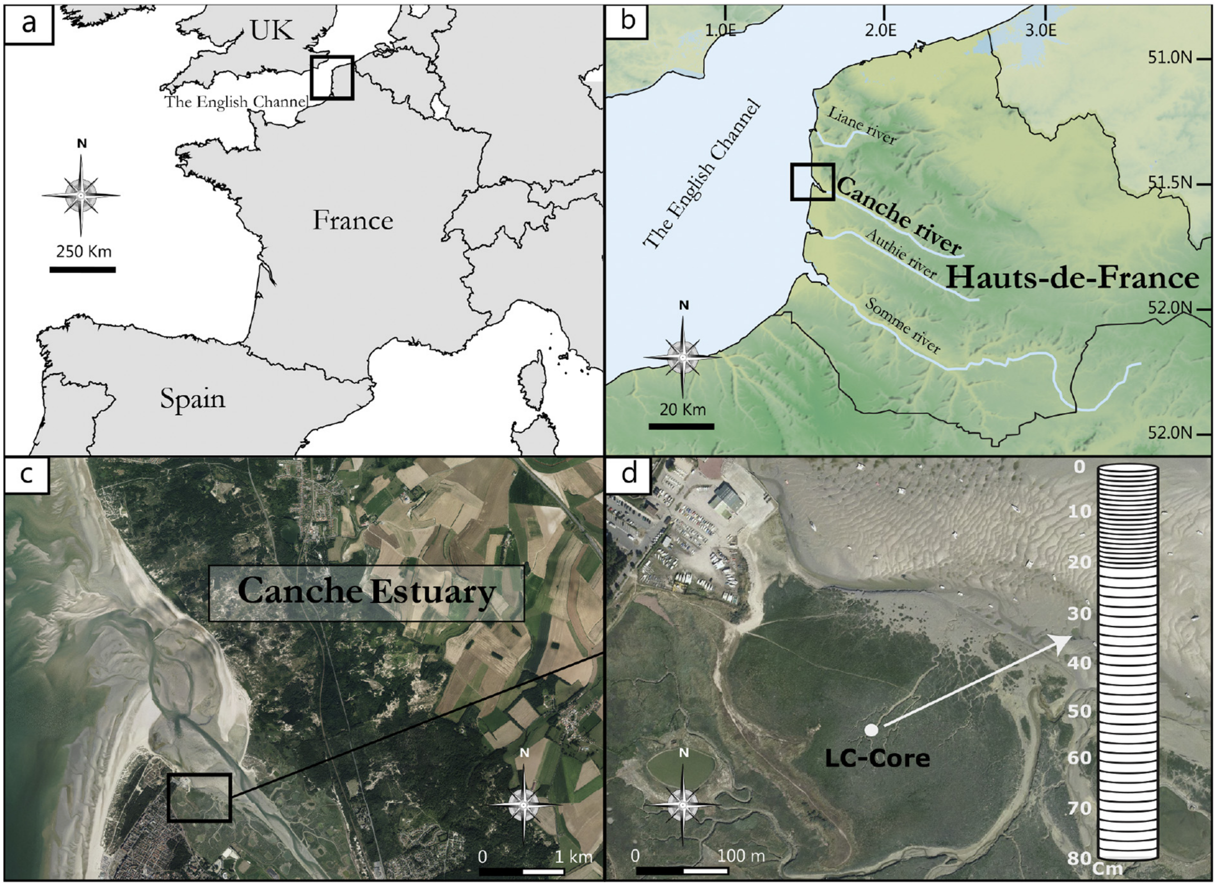


**Fig. 1.** Location of the study area: a) map of France; b) relief map of Hauts-de-France with the main rivers (mod. IGN, 2017); c) large aerial view of the Canche Estuary at low tide; d) position of LC-Core in the salt marsh (Aerodata-France, 2009) with a scheme of the sample frequency.

areas with high variability of dissolved-water pH, dissolution of calcareous tests may alter the fossil assemblages (Goldstein and Watkins, 1999). At the salt marsh/tidal flat transition, dead and living faunas are inevitably different, the dead one resulting from a mix of autochthonous and allochthonous taxa mainly triggered by hydrodynamical features (Martins et al., 2016a). As a consequence, palaeoenvironmental reconstructions based uniquely on foraminiferal investigations may lead to biased interpretations (see review in Berkeley et al., 2007). To enhance the palaeo-characterisation of modern environments, the use of multidisciplinary approaches is often needed (Grauel et al., 2013). For example, Delaine et al. (2014) underscored how sediment size, clay mineralogy, testate amoebae and foraminifera allowed for the reconstruction of the Loire Valley in Nantes (France). In another study, benthic foraminifera were coupled with trace metal concentrations and aerial photography to characterise the process of human disturbance on the intensely impacted eastern Cantabrian coast (García-Artola et al., 2016). Broad range of proxies, physical, biological, and chemical analyses in the sediments, and historical sources may improve the efficiency of palaeoenvironmental interpretations (Alve, 1991; Hayward et al., 2004; Alve et al., 2009; Francescangeli et al., 2016).

Estimation of sedimentation rate and the age of sediments appear essential in palaeoenvironmental reconstructions. Over the past 40 years, $^{210}$Pb dating (associated with $^{137}$Cs and other gamma ray emitters) has been one of the most commonly used means to date recent sediments (those approximately 100–150 years old) (Appleby and Oldfield, 1978; Appleby, 2001). In estuarine environments, such as tidal flats or salt marshes, the $^{210}$Pb method may be successfully applied and gives reliable chronologies (among these Allen et al., 1993; Irabien et al., 2008; Andersen et al., 2011; Cearreta et al., 2013). However, applying radiometric methods in tidal flats and sometimes in salt marshes may be difficult due to natural features of these environments. These natural features may include sediment mixing (due to bioturbation and/or physical disturbance), sediment grain-size dependency (deposits should be fine-grained), post-depositional mobility and choice of dating model (Andersen, 2017). As an alternative method, the use of historical maps and pictures can provide important information on the timing of environmental variations (Lukas, 2014), in coastal evolution reconstructions (Crowell et al., 1991; Baumann et al., 2017) or salt marsh losses and changes (Bromberg and Bertness, 2005; García-Artola et al., 2016). However, this method should be used with caution, taking into account issues related to both the moment when the survey was conducted (high tide vs low tide or season) and image quality (Stäuble et al., 2008).

The coastal environments of the Hauts-de-France region (eastern English Channel, France) are characterised by a differential degree of disturbance. In these areas benthic foraminifera form specific assemblages in response to natural and anthropogenic conditions (Francescangeli, 2017). In the human-stressed area of the Boulogne-sur-Mer harbours (northern part of the region), foraminiferal assemblages consisted of a few taxa tolerant to high metal concentrations and to high organic carbon contents. In two retrospective studies, Francescangeli et al. (2016) and Armynot du Châtelet et al. (2017), investigated the recent palaeoecological evolution of the same harbour. Benthic foraminifera allowed a pre-industrial period, characterised by excellent and good ecological conditions, to be distinguished from an industrial period with principally poor conditions. In the mildly impacted areas of the Canche Estuary (20 km south of Boulogne-sur-Mer harbour), intertidal living foraminifera are principally driven by the natural features of this area, i.e., tidal subaerial exposure (Francescangeli et al., 2017) and sediment grain size and clay contents

(Armynot du Châtelet et al., 2009a). Although the ecology of living benthic foraminifera is quite well detailed in the coastal area of the Canche Estuary, a thorough assessment of the fossil background is missing.

The present study provides a detailed environmental history of a salt marsh area, located along the Canche Estuary, using a multiproxy approach based on benthic foraminifera and sediment characteristics (grain size, total organic carbon, and major and trace element concentrations). In the present study we propose the use of historical aerial pictures as an alternative to classic chronological methods based on radionuclides. The biotic- and abiotic-based multiproxy approach is crossed with the analysis of historical pictures to enhance the palaeolandscape interpretation.

## 2. Materials and methods

### 2.1. Study area and core sampling

An 80-cm long core (50.53° N, 1.59° E; 4.3 m above MSL) was collected in July 2013 from the tidal marsh of the Canche Estuary (Hauts-de-France, Northern France) along the eastern part of the English Channel (Fig. 1). The Canche Estuary mainly displays muddy sediments (silt dominated), which become very fine (clayish mud) in the innermost parts of the estuary (Anthony and Héquette, 2007). Because of a hyper-tidal (McLusky and Elliott, 2004) range exceeding 9 m during the highest astronomical tides, the morpho-sedimentary dynamics of the Canche Estuary are strongly influenced by tides. The transition between tidal flats and salt marshes is marked by the occurrence of mostly halophytic grasses (*Halimione portulacoides*, *Aster tripolium*, *Salicornia europaea* and *herbacea*, *Spartina maritima* and *Suaeda maritima)*. The salt marsh area is a planar vegetated platform regularly flooded by tides. The highest salt marsh is reached by water only **a** few days per year during the highest astronomical tides. This estuary can be considered as slightly impacted, only moderately impacted by urban development (Amara et al., 2007) (more details can be found in Francescangeli, 2017). However, the watershed of the Canche is dominated by agricultural practices, which tends to increase the turbidity, nutrient and pesticide concentrations in the river.

The sediment core (LC-Core) was sectioned every 1 cm down to 20 cm, then every 2 cm until the bottom of the core. This resulted in the collection of 46 samples (Fig. 1d). A first aliquot composed of the 46 samples was used to measure environmental variables: sediment grain size, carbonate content, total organic carbon, sulphur and the activity of $^{210}$Pb and $^{137}$Cs. A second aliquot, composed of 25 samples (one sample out of 2 over the entire length, adding samples 56–58 and 68–70) was used to measure the concentrations of major and trace elements and to perform foraminiferal analyses.

### 2.2. Grain-size and total organic carbon

Grain-size analyses were performed using the principle of diffraction and diffusion of a monochromatic laser beam on suspended particles (Malvern Mastersizer 2000, red He–Ne laser). The method is based on near-forward scattering of a laser beam by particles in suspension (Trentesaux et al., 2001). Measurements can range from 0.02 to 2000 μm with an obscuration ranging between 10 and 20%. Several grain size fractions were considered: clays (< 4 μm), fine silts (4–10 μm), cohesive sortable silt (10–63 μm), fine sands (63–125 μm), medium sand (125–250 μm), and coarse sand (> 250 μm). Silt fraction and motility are discussed in McCave et al. (1995). The sorting as a descriptive parameter of the grain size was calculated following Folk and Ward (1957); the better the sorting, the lower the values.

A Flash EA 1112 Elemental Analyzer (Thermo) equipped with an auto-sampler was used to determine the total contents of C and S. The analysis was performed on 1.5 to 2 mg of sample added to approximately 5 mg of vanadium pentoxide, used as a combustion catalyst. 2.5-Bis (5-tert-butyl-benzoxazol-2-yl) thiophene (BBOT) was used as a standard. The Total Organic Carbon (TOC) was determined by subtracting carbonate carbon from total carbon concentrations. This calcium carbonate content was determined using a Bernard calcimeter. Triplicated measurements were carried out for each sample using 0.5 g of finely crushed dried sediment.

### 2.3. Major and trace element concentrations (total mineralisation)

The total concentration of Al (g/kg), Cd (mg/kg), Cu (mg/kg), Fe (g/kg), Pb (mg/kg), and Zn (mg/kg) were analysed for each selected level. Samples were sieved at 63 μm, then dried at room temperature and gently crushed. Then, 200 mg of the fine fraction were added to a mixture of 5 mL of suprapur nitric acid and 10 mL of a concentrated HF solution at ebullition over 48 h. After evaporation of these acids, 10 mL of a freshly prepared HNOR3R/HCl mixture (1/2 v:v) were added in order to eliminate the remaining solid grains. After partial evaporation of the acids, the recovered solutions were subsequently diluted in a known volume of ultrapure water and analysed using ICP-AES (inductively coupled plasma – atomic emission spectroscopy; Varian Vista-PRO, axial view) and ICP-MS (inductively coupled plasma – mass spectroscopy; Thermo Elemental X series). This attack procedure and the accuracy of the analytical procedure were validated using the following sediment standard reference materials (Canadian International Standards): HISS-1, MESS-3 and PACS-2. It was found that the values of the certified standard materials and our experimental results were in good agreement.

In order to assess sediment contamination and evaluate possible anthropogenic influences, the enrichment factor (EF) relative to the content of Al (Woitke et al., 2003; Duan et al., 2014) was calculated for each element. The enrichment factor was normalised against aluminium to take into account the evolution of the grain size, especially for the fine particles (silts and clays), which partly overcomes the bias linked to the nature of the sediment. For the calculation of EFs, reference values were taken from the very bottom of the core, and these values were in the same order of magnitude as those previously found in the same regional area (Henry et al., 2004; Amara et al., 2007; Francescangeli et al., 2016). The following criteria were used to evaluate the degrees of pollution according to the values of EF: EF $<$ 2: no relevant enrichment; 2 $<$ EF $<$ 10: moderate contamination; EF $>$ 10 strong contamination (Birth, 2003; Kerambrun et al., 2012).

### 2.4. Radionuclide chronology

The samples have been analysed for the activity of $^{210}$Pb, $^{226}$Ra and $^{137}$Cs via gamma spectrometry at the Gamma Dating Centre, Department of Geosciences and Natural Resource Management (University of Copenhagen). The measurements were carried out on a Canberra ultra-low background Ge-detector. $^{210}$Pb was measured via its gamma-peak at 46.5 keV, $^{226}$Ra via the granddaughter $^{214}$Pb (peaks at 295 and 352 keV) and $^{137}$Cs via its peak at 661 keV. The concentration of unsupported $^{210}$Pb was found by subtracting the supported $^{210}$Pb (measured as $^{214}$Pb) from the total $^{210}$Pb concentration.

### 2.5. Aerial pictures, interpretation and dating

Twelve historical aerial pictures were used to observe the environmental variations through time, from 1935 to the present. The pictures were selected from a database containing 34 aerial surveys https://remonterletemps.ign.fr/ (IGN, 2017). Each picture, initially not georeferenced, was integrated in QGIS (version 2.14.5) using at least four ground control points. The reference coordinate system used was Lambert 93 (RGF93). Stable territorial features (such as buildings or crossroads) were used as ground control points. In each picture the exact location of the LC-Core has been plotted. In order to allow temporal image comparisons, the same areal extent was adopted and each

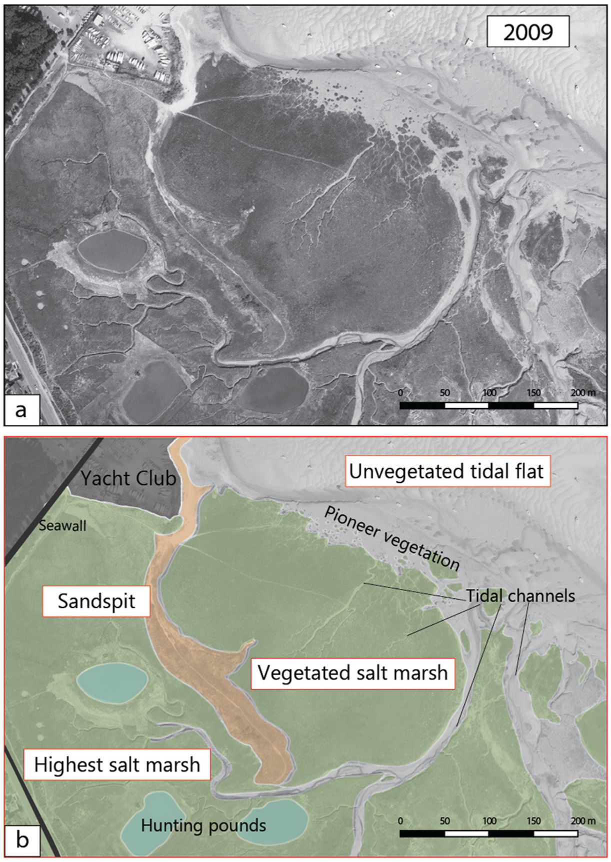


**Fig. 2.** a) Aerial picture of study area in 2009 from Aerodata-France (2009); b) Interpretation of the main sedimentary facies. The vegetated marsh area (in green) is darker than the un-vegetated tidal flat. Sand bodies (such as a sandspit) (in orange) generally have a lighter colour than mudflat sediments. In the highest marshes, hunting ponds (in light blue) can be identified. Tidal channels drain the salt marsh area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

picture has been converted to greyscale.

The reference map PPIGE 2009 displays the way the pictures have been interpreted (Fig. 2). Based on many field campaigns, we were able to associate each colour (or shade of grey) with a different type of substrate and coverage. The studied, natural, intertidal surface is separated from the supratidal zone by two rectilinear seawalls. In front of them, the vegetated salt marshes are darker than the un-vegetated tidal flats. In this area, an elongated sand body, corresponding to a sandspit extending from the Yacht Clubcar park, is shown in a lighter colour than the muddier tidal flat sediments. A sandspit usually develops parallel to the coast according to the longshore drift direction. This is the case here, where, due to a man-made coast (embankments), the spit has a bowed shape. At the origin, the sandspit separated two domains: one in front with quite exposed conditions corresponding to a sandy surface tidal flat or internal beach and, behind it, a protected area prone to mud sedimentation where salt marshes developed. This is no longer the case as salt marshes also developed in front of the 'abandoned' spit that transformed into a narrow aeolian dune field. The lowest part of the tidal flat is sandier and is covered by hydraulic sand dunes, especially in the deepest parts of the main Canche channel. Tidal channels drain the salt marsh area. In the highest salt marshes, hunting ponds can be identified.

After each historical picture was interpreted, it was assigned to the corresponding core level and used to date the LC-Core. To do this, we crossed the other biotic and abiotic proxies able to highlight the different environments in the estuarine study area.

### 2.6. Foraminiferal analysis

The foraminiferal samples were weighed, washed through a 63 μm mesh sieve, and then oven-dried at 40 °C. The investigations were carried out on the > 63 μm size fraction. Approximately 300 tests were chosen in each sample. This number is recommended in order to obtain a detailed quantitative aspect on species composition (Fatela and Taborda, 2002); this value is realistic for such a study. All the chosen specimens were mounted on faunal micro-slides, identified following Loeblich Jr and Tappan (1988) for genera, Debenay et al. (2001), Debenay (2012) and WORMS (WoRMS-Editorial-Board, 2018) for species classification. A binocular microscope, model Olympus SZX16, was used for the observations. The relative abundance of the taxa, the faunal density (tests/g) and the diversity (H = Shannon Weaver) were determined for each sample.

To evaluate palaeoenvironmental variations, foraminiferal species were assigned to 4 environmental groups according to the tidal vertical gradient (details in Supplementary materials). The four groups are: A) Middle/higher salt marsh, B) Lower salt marsh, C) Tidal flat/tidal channel, D) Seaward. Species which have been rarely found living within the salt marsh/upper tidal flat of Canche Estuary were included in the Seaward group (Armynot du Châtelet et al., 2009a; Francescangeli et al., 2017). These allochthonous specimens generally live in more subtidal conditions, probably having been transported upstream during more energetic sedimentation processes. As pointed out in Francescangeli et al. (2017), local environmental factors should be considered to characterise the distribution of species along a coastal gradient. Consequently, assignments of the main species were based principally on local studies (based on living fauna) from Francescangeli et al. (2017) and Armynot du Châtelet et al. (2009b) in the Canche Estuary. Species assignments were then compared to other studies from Debenay and Guillou (2002), Scott et al. (2001) and Murray (2006) and to other foraminiferal studies in macrotidal/hypertidal estuaries (such as Haslett et al., 2001; Horton and Murray, 2007). In order to avoid possible taphonomical effects, only the main species occurring in at least 10 samples and having an average relative abundance ≥2%, were considered.

### 2.7. Data analysis

The main species were grouped using a constrained hierarchical clustering analysis (HCA), after a logarithmic transformation of relative species abundances. A similarity tree was produced using the Euclidian distance. Coniss (Grimm, 1987) was used as the clustering method.

A detrended correspondence analysis (DCA), an ordination method that arranges samples and species along gradients, was carried out on the species' relative abundances. It arranges samples that are more similar in species composition closer together. DCA uses the variation in species composition between the samples to determine the underlying gradients influencing the data. The basic assumption of this method is that the most important environmental gradient causes the largest variation in the species composition. By means of a two-way weighted averaging algorithm, the direction of this variation was calculated and represented as the first DCA axis (Hill and Gauch, 1980; Versteegh and Zonneveld, 1994).

The R software (version 3.2.2) (R-Core-Team, 2014) was used for the calculations, using the following packages: Base (descriptive statistics), Entropy (Hausser and Strimmer, 2014) (diversity calculation), rioja (construction of diagrams with timescale), vegan (Oksanen et al., 2016), Hmisc (Harrell and Dupont, 2016), ade4 (Dray et al., 2007) (HCA and DCA), ggplot2 (histograms of foraminiferal relative abundances).

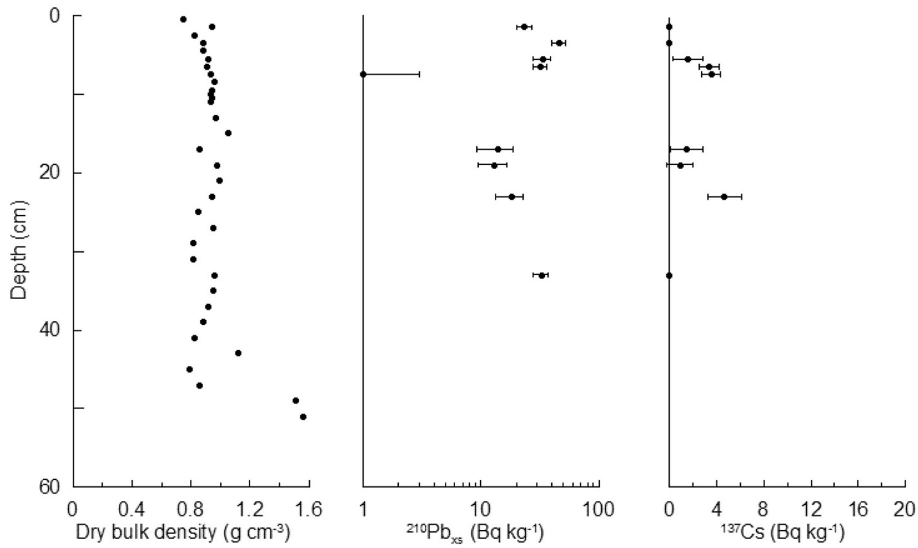


**Fig. 3.** Dry bulk density and radiometric data from the LC-Core.

## 3. Results

### 3.1. Chronology

Analysis of $^{210}Pb$ and $^{137}Cs$ does not allow calculation of a reliable chronology for the LC-Core (Fig. 3). Only 9 samples gave results above the detection limit. There is a peak of $^{137}Cs$ at 24 cm, which could correspond to the year 1984. It could be connected to the accumulation of nuclear reprocessing activities at COGEMA-La Hague in France in that period (Cearreta et al., 2002), already observed in Marion (2007). As a consequence, the few points above the detection limit could allow for only an approximate estimation of the sedimentation rate about 0.84 cm/yr for the first 24 cm. The activity of $^{210}Pb_{xs}$ is low and shows a distinct decrease with depth. This shows that the sediments were deposited recently and confirms the high sedimentation rate indicated by the $^{137}Cs$ data.

### 3.2. Environmental variables

The sediments at the base of the core are composed of about 60% silt and 40% sand (Fig. 4). At 72 cm, there is a sudden increase in sand content, reaching 93%. Upwards, sandy fractions between 125 and 500 µm gradually decrease from 58 to 48 cm to reach values close to 20%, replaced by silts and clay. The rest of the core is composed of quite homogenous sediment: sortable silts (60–70%), fine silt (about 20%), fine sand (63-125 µm) for about 18%, and clay, the less abundant grain size fraction (max 5%) showing the same trend as silts. Along the core, sediment is poorly sorted, except in the sandy interval (72–58 cm), where it is well sorted with a sorting index close to 1.

The TOC content (Fig. 4) ranges between 0% and 3.05%. It shows the lowest values in the bottom part (close to 0%) and increases from 55 cm upward. The $CaCO_3$ evolution (Fig. 4) is similar to the one of the TOC, with the highest values (48%) from 55 cm upward and lowest values in the sandy interval.

All the analysed elements (Al, Fe, Cd, Cu, Pb and Zn) have their lowest values in the bottom of the core (Supplementary material). From 55 cm up to the top their values rapidly increase, reaching stable values. The behaviour of Cd differs with a local but significant increase between 51 and 45 cm depth. Enrichment factors (EFs) of Cu, Pb and Zn show the same trends (Fig. 4): there is no relevant enrichment at the bottom of the core ($EF_{max} < 2$) and just moderate contamination starting from 55 cm ($EF_{Cu} = 3.6$). Cadmium presents globally the same trend as those recorded for the other trace metals. However, a moderately high contamination peak occurs at 47 cm ($EF_{Cd} = 7.7$).

### 3.3. Foraminiferal assemblages

A total of 78 species were identified along the core. Sixty-eight of these (87%) are hyaline, six are porcelaneous and four species belong to agglutinated test species (Table of counts in Supplementary materials). A barren zone occurs in the sandy 61–67 cm interval.

The faunal density (Fig. 5) varies between 6 and 166 (specimens/g). Lowest values are found at the base of the core and rapidly increase from 55 cm upward. The diversity (H) ranges from 1.26 to 3.11 (Fig. 5). It does not show a clear trend, but on average, the highest values are located in the bottom of the core, below 45 cm.

The assemblage is dominated by *Haynesina germanica* associated with *Elphidium margaritaceum*, *Quinqueloculina seminula*, *Entzia macrescens,* and *Cribroelphidium excavatum*. *Elphidium margaritaceum* (2–38%; 10% on average) and *C. excavatum* (0–41%, 8.8% on average) occur principally in the bottom part of the core (Fig. 5, the values of absolute abundance are shown in the supplementary materials). *Haynesina germanica* (4–71%; 29% on average) is largely dominant in the middle part of the core; the lowest values of its relative (and absolute) abundance are within the intervals 71-51 cm and 8.5–0.5 cm. *Quinqueloculina seminulum* (0–39%; 10% on average) and *E. macrescens* (0–47%, 9% on average) are the most common in the upper part of the core. Within the minor species (< 5% on average) bolivinids (*Bolivinita quadrilatera, Bolivina pseudoplicata, B. variabilis, Bulimina elegans)* and *C. williamsoni* occur irregularly along the core. *Trochammina inflata* is present in the upper part and *Cibicidoides lobatulus* only down core.

### 3.4. Environmental groups

Eighteen species were assigned (according to selected criteria) to 4 environmental groups (Fig. 6). The average loss of assemblage due to the grouping is 5.86%. In the very bottom part of the core, Low salt marsh is the dominant group (> 50%). In the 71–55 cm interval, the Tidal flat/Tidal channel group dominates the assemblages and decreases upward. The interval 61–67 was devoid of foraminifera. The Low salt marsh group largely dominates in the middle part of the core (47–19 cm) with proportions on average > 60%. In the upper part of the core, the Middle/high salt marsh group takes over, becoming the dominant one.

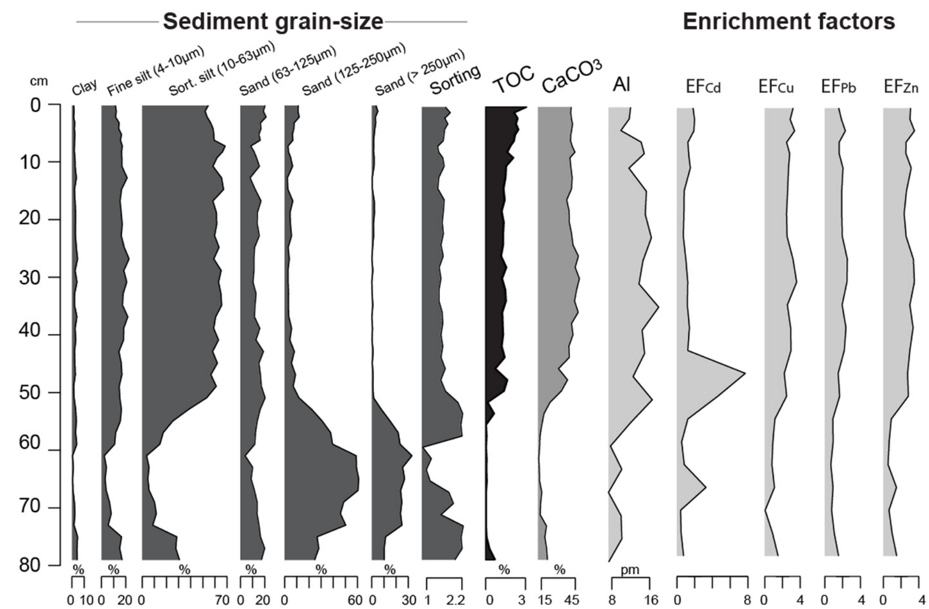


**Fig. 4.** a) Trends of environmental parameters along the LC-Core: sediment grain size fraction and distribution (Clay, Fine silt, Sortable silt, Sand, sorting), TOC, Sulphur (S), $CaCO_3$, Al and Enrichment factors (EFs) for trace metals (Cd, Cu, Pb and Zn) along the LC-Core.

### *3.5. Sample grouping and vertical structure of the core*

In the HCA analysis (based on relative specific abundance), two clusters (I and II) are identified along the LC-Core (Fig. 5b). Cluster I is divided into two sub-clusters: the first includes all samples from the bottom of the core up to 43 cm; the latter includes samples from 39 to 19 cm. Cluster II contains all samples from the upper part of the core.

In the DCA, the two first axes explain about 25% of the total variation (eigenvalues describing 20% and 5% of the total inertia, respectively) (Fig. 7). Samples are chronologically placed along the first axis. Samples belonging to Cluster I are placed at the positive position and samples belonging to Cluster III at the negative position of the first DCA axis, respectively. Foraminiferal species belonging to the Middle/High salt marsh group are located at the positive position of the first axis. Specimens of the Low salt marsh group are mainly placed at the positive position of the first axis. By contrast, species belonging to the Tidal flat/Tidal channel and Seaward are principally located at the negative position of the first axis.

### *3.6. Salt marsh landscape evolution*

In historical pictures from 1935 to 2009, many landscape changes of the study site can be observed (Fig. 8). In 1935, the LC-Core was located within the upper part of the tidal flat area, close to the limit between vegetated salt marshes and tidal flats. Further north, an elongated sandspit was developing, but did not reach the LC-core position. The

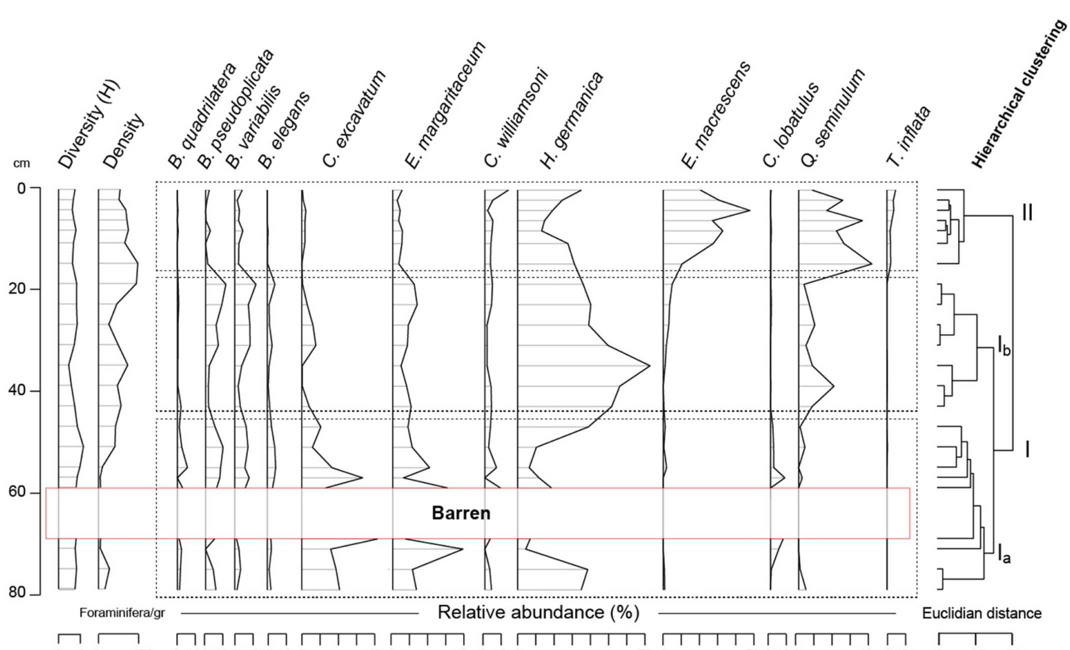


**Fig. 5.** Trends of faunal density (specimens/g), diversity (H) and the relative abundance of the principal species along the LC-Core. At right, a hierarchical cluster analysis (HCA) based on the relative abundance of the main species is proposed. Two clusters can be identified along the LC-Core, reflecting different environmental conditions.

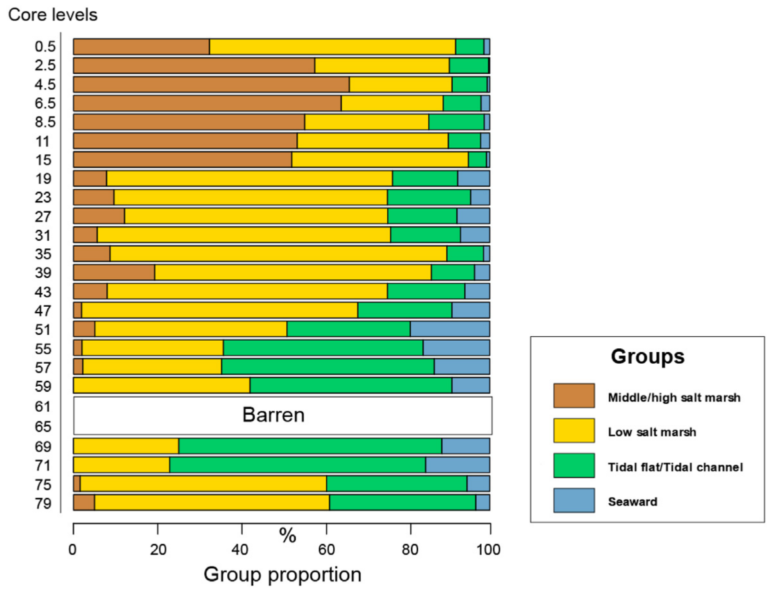


**Fig. 6.** Histograms of the temporal evolution of environmental groups. The grouping is based on the relative abundances of the assigned foraminiferal species. The depths are not to scale.

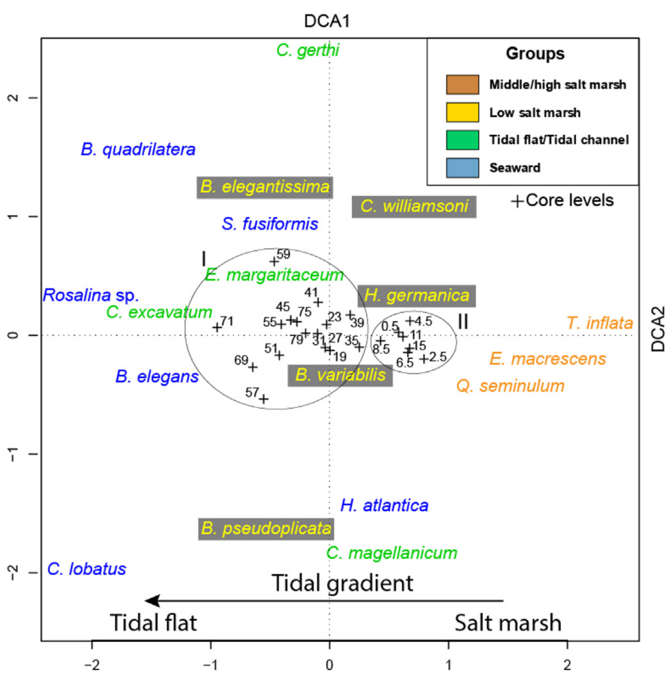


**Fig. 7.** Detrended correspondence analysis (DCA) based on species' relative abundance. After the ecological assignment of the species, the first axis represents a tidal/vertical gradient. Black crosses represent the samples. The Clusters I and II (aforementioned) are indicated as well, reflecting environmental conditions along the tidal gradient.

1947 picture displays a high number of just finished World War II bombing impacts and the development of the sandspit reaching the LC-Core. From 1947 to 1963, the sandpit was developing and had started to be eroded in the 1963 picture. At that time, LC-Core was facing a large intertidal area. Subsequently, in the 1971 picture, the sandspit is eroded, with a retreating shoreline as outlined by the limit between the salt marsh and tidal flat. From 1971 to 1977, the LC-Core stayed in the tidal flat area. In the 1983 picture, dark patchy objects are visible, corresponding to the occurrence of emerging pioneering plant patches. After this period, the vegetation developed rapidly. From 1989 on, the vegetation has continued its development and invaded most of the study area, except the Canche channel. In the pictures taken in 2005 and 2009 (reference map PPIGE 2009 interpreted previously Fig. 2) there are no relevant changes on the landscape configuration (Note that 1947, 1966, and 1995 pictures were taken at about mid-tide concealing the tidal flat/salt marsh limit).

## 4. Discussion

### 4.1. Historical pictures as an alternative to radiometric dating in estuarine areas

Dating sediment cores is fundamental in studies aiming to reconstruct the palaeo-environmental evolution of a study site. Radionuclide analyses in the present work did not allow for any reliable chronology of the LC-Core. In estuarine areas there is often difficulty in obtaining undisturbed sediment cores, mainly due to sediment mixing. Although sediment mixing induced by physical agents (waves or tidal currents) could be important in subtidal or intertidal environments (Andersen et al., 2000), the principal reason for mixing in estuarine sediments is bioturbation (Benninger et al., 1979). In some salt marsh deposits, there is intense bioturbation activity. This could produce an alteration of the vertical profiles of excess $^{210}$Pb ($^{210}Pb_{xs}$) and provide erroneous information of sediment accumulation rates (Baskaran et al., 2014). Another important factor to consider when using $^{210}$Pb dating is the grain size dependency. Only fine-grained deposits will be able to yield good chronologies, due to the unavoidable analytical uncertainties associated with assessment of $^{210}$Pb in low-activity samples (Andersen, 2017). Most likely the sediment grain size of LC-Core was too sandy to provide a reliable radiometric dating.

In estuarine areas, a few studies used historical sources (maps or aerial pictures) to support multiproxy approaches based on biotic and abiotic parameters (Cearreta et al., 2013; Francescangeli et al., 2016; García-Artola et al., 2016; Baumann et al., 2017). However, note that none of these used historical pictures to estimate the age of the environmental transformations. In the Canche Estuary, starting in 1935, a constant aerial survey was conducted every 5–10 years by the French National Geography Institute (IGN France), which provided a relevant historical database. The relatively good quality of the images and the temporal range encompassed by historical pictures have been the two fundamental elements for the applicability of this method. In the first 24 cm of the LC-Core, radiometric analysis allowed for only a rough

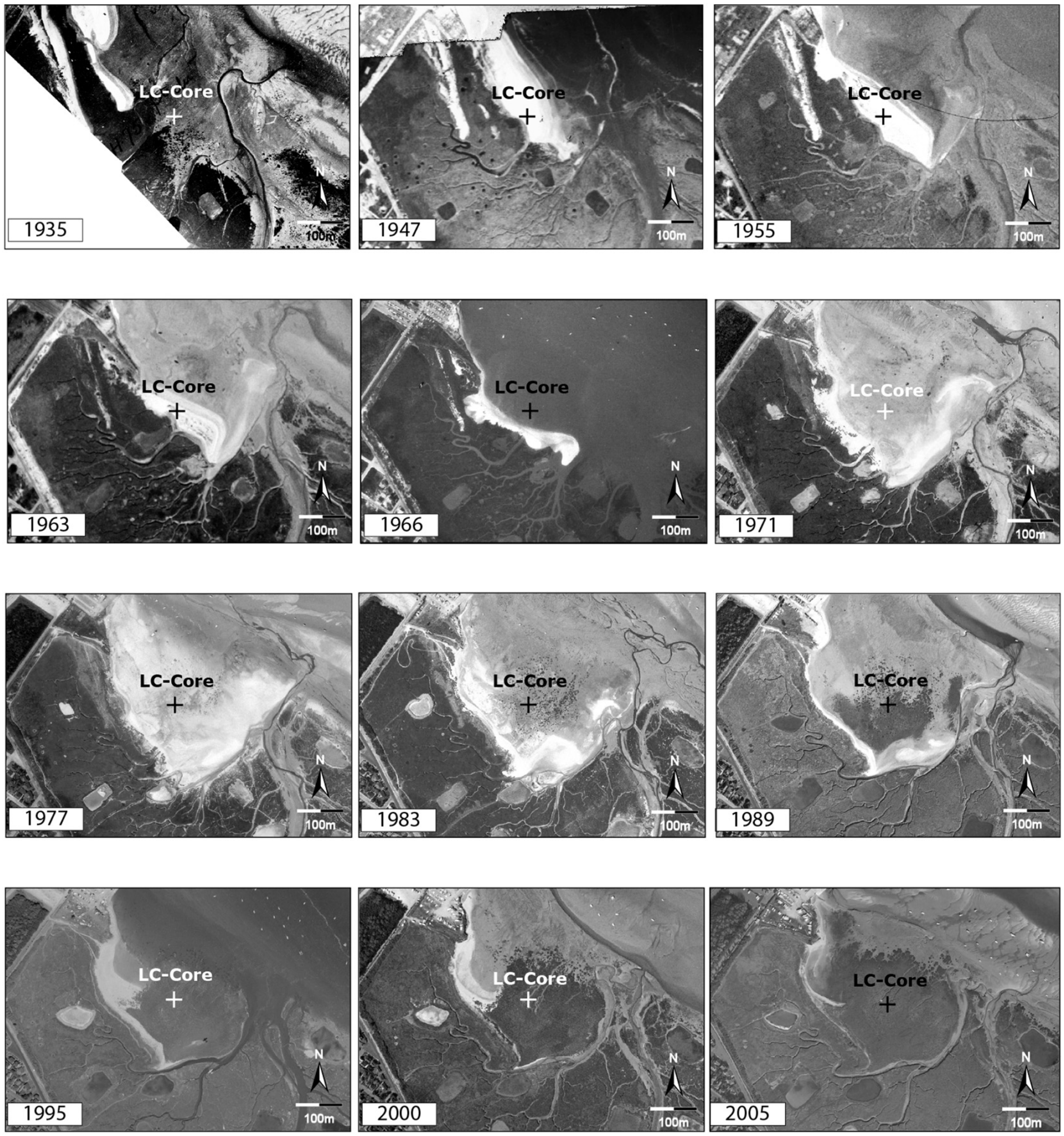


**Fig. 8.** Historical aerial pictures of the Canche Estuary, at the marsh area scale, from 1935 to 2005. Location of LC-Core is indicated on each picture.

estimation of the sedimentation rate of about 0.8 cm/yr. Assuming an approximate constant sedimentation rate all along the LC-Core, we could speculate that the sediments were accumulated during a period of decades within a global temporal scale of about 100 years. Note that for the studied sediment core, it is unlikely that there was in fact a constant sedimentation rate. This is due to the fact that during the period of silting up, submerging water column decreases led to a decrease in the potential for the deposit of sediment (in suspension) (Temmerman et al., 2004). In addition, aerial pictures display different sedimentary environments such as tidal flats, marshes or sandspits, each of them having a specific sedimentation rate. However, the range of our estimation appears reasonable when compared with the sedimentation rates obtained in other estuarine areas, such as in the Authie Estuary, a very similar estuary located 30 km south of the study site (Marion et al., 2009). Another element to be considered in defining the temporal scale is the strong enrichment of Cd in the middle of the LC-Core. In this lightly-impacted environment, it could be due to the use of cadmium-containing fertilizers in agricultural treatments. The use of these fertilizers has been often cited as the primary reason for the increase in the cadmium content of soils over the last 20 to 30 years in Europe (Jensen and Bro-Rasmussen, 1992). Therefore the use of historical pictures covering the last approximately 100 years appears to be a reasonable tool for estimating the age of the LC-Core in such a temporal range (Fig. 9).

### *4.2. Reconstruction the Canche Estuary infilling based on a multiproxy approach*

Industrial pollution in the Canche Estuary is low compared to the global average. In accordance with Amara et al. (2007), it can be considered as being slightly impacted by human activities. Thus the evolution of the area and the associated faunal changes are mostly due to its natural features, i.e. a sheltered bay with low energy. The LC-Core represents a typical fining-upward succession in a tide-dominated estuary filled by progradation (for details see Dalrymple et al., 1991; Dalrymple et al., 1992). The same situation was illustrated by Haslett et al. (2001) in the Severn Estuary (U.K.). The authors described an emergence sequence in which sea-level rise is less than accretion which introduces progressively higher foraminiferal zones at the site. In the small estuary of Havre de Surville (Normandy, France) Haslett et al. (2003) also showed a progressive up-core increase of agglutinated foraminifera, indicating a change from unvegetated sand flats to successively higher salt marsh environments. Accordingly, in the Canche core, we observed a shift from tidal flat to salt marsh foraminiferal

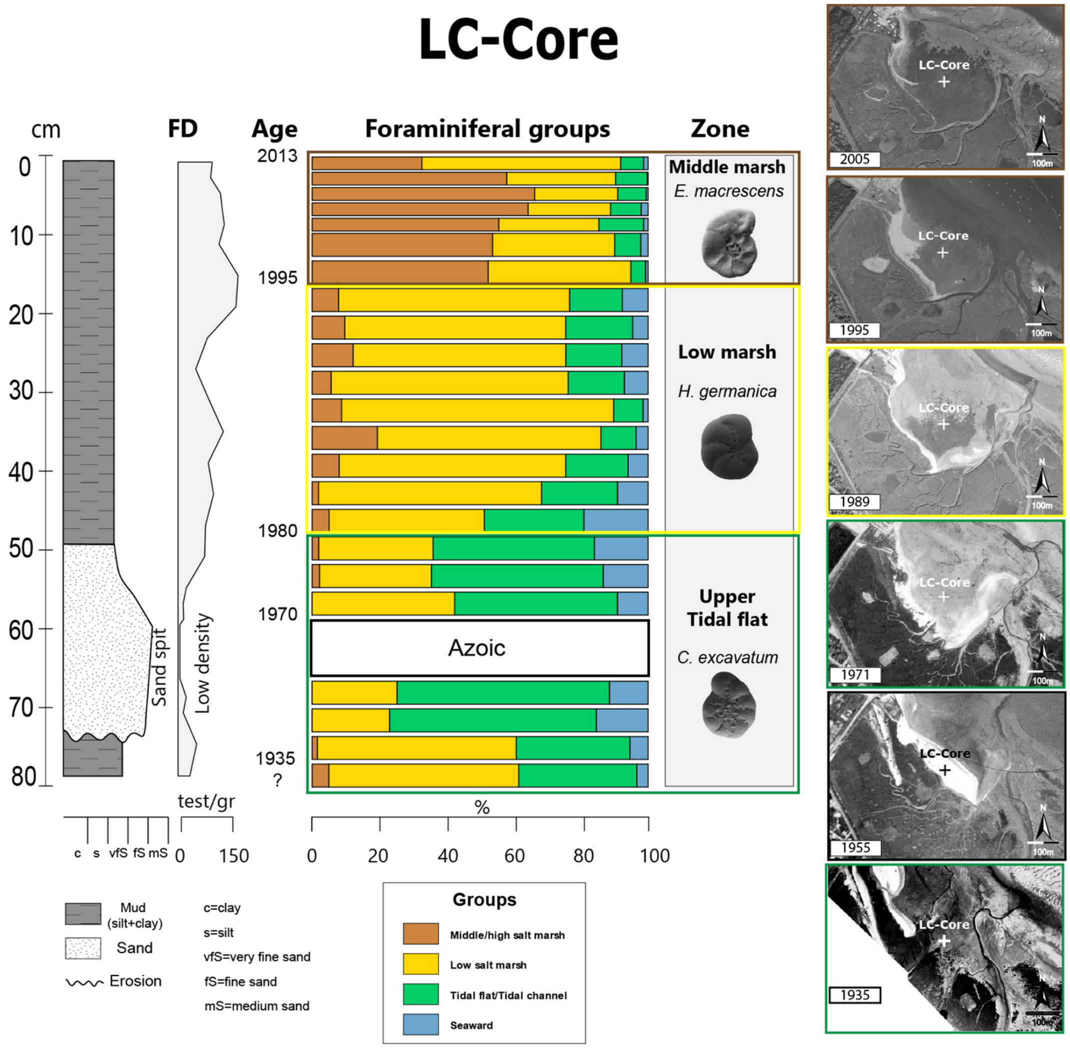


**Fig. 9.** Interpretation of environmental changes along the LC-Core. Chronologically, three environments can be identified: upper tidal flat, low salt marsh and middle marsh. The parameters used for the interpretation, from left to right: Grain-size (log), Faunal Density (FD), foraminiferal groups, historical pictures. An estimated chronology based on historical pictures is shown as well.

assemblages, highlighting an increase in the elevation at the study site. As observed in other estuaries (such as those mentioned in Haslett et al., 1997), the rate of sea level increase is slower than the sedimentation rate, which has led to a general silting up of the site and to a progressive continentalisation of this part of the estuary.

*4.2.1. From a sandy tidal flat to a muddy salt marsh (c. 1930–1995)*

Sediment grain size and benthic foraminifera constitute excellent tools to investigate environmental changes in estuarine areas (Alve and Murray, 1999; Allen et al., 2006; Mojtahid et al., 2009). In the Canche Estuary these proxies coupled with historical pictures allow a chronological vertical succession from an upper tidal flat to a salt marsh area to be identified (Fig. 9). Although it appears difficult to assign a precise age to the bottom of the core, we could estimate that the first centimetres of sediment settled around 1930. The bottom of the core up to 1980 is characterised by the highest contents of sand, similar sedimentary bodies like sand bars (sandspits) or sand/mixed flats (Saïdi et al., 2014). In this interval, the assemblage is dominated by species belonging to the tidal flat/tidal group. *Cribroelphium excatum, Elphidium margaritaceum* and *Haynesina germanica* are the most abundant taxa. They are common in marginal marine environments (Thomas and Schafer, 1982; Alve and Murray, 1994; Bouchet et al., 2007; Seuront and Bouchet, 2015). Whilst *H. germanica* is quite abundant along the entire core, *C. excavatum* and *E. margaritaceum* are specific to this lowest interval. *Cribroelphidium excavatum* prefers the lowest part of the intertidal gradient (Armynot du Châtelet et al., 2005). According to Murray (2006), this taxon would be able to span the continental shelf down to several hundred meters. Along the coasts of eastern North Sea, *C. excavatum* and *E. margaritaceum* have been found primarily outside the intertidal and subtidal marsh environments (Alve and Murray, 1999). In the Canche Estuary, *C. margaritaceum* was only found as living in the upper part of the tidal flat (Francescangeli et al., 2017). Thus the occurrence of these two taxa could suggest the presence of an unvegetated tidal flat, close to a main river channel. This hypothesis is also confirmed by the highest proportions of the Seaward group along the same temporal interval (for example *Cibicidoides lobatulus*, generally found in subtidal environments (Alve and Murray, 1999). Note that between 1940 and 1970 the sediment is better sorted than in the rest of the core, indicating a more energetic depositional environment. It could correspond to the setting of an elongated sandspit as illustrated in the aerial pictures taken between 1947 and 1963. This could also explain the azoic character of the sediment.

In the middle part of the core (1980–1995), the sand content decreases, being replaced by silt. The sediment grain size along this silt-dominated core interval is similar to the type of sediment described in Francescangeli et al. (2017) and Armynot du Châtelet et al. (2009a) within the salt marsh area of the Canche Estuary. In this interval the assemblage is dominated by species belonging to the low marsh foraminiferal group, with *H. germanica* being the most abundant taxon. Although it is able to span a wide tidal range (Debenay and Guillou, 2002; Debenay et al., 2006; Armynot du Châtelet et al., 2016), in the Canche salt marsh, it was only dominant in the lower vegetated marsh (Francescangeli et al., 2017). This tendency has been observed in other North Europe salt marshes (Haslett et al., 1997; Horton et al., 1999; Swallow, 2000). Foraminiferal species belonging to the Low salt marsh group dominate the assemblage. In approximately 20 years, there was a shift from an upper tidal flat to a lower marsh gradually colonised by vegetation.

#### 4.2.2. Complete establishment of salt marsh environments (1995 to the present)

The upper part of the core (1995 to the present) is characterised by benthic foraminifera belonging to the Middle/high marsh group: *Entzia macrescens* and *Quinqueloculina seminulum. Entzia macrescens* is one of the most abundant salt marsh foraminifera worldwide (Scott and Medioli, 1980; Scott et al., 2001). It is dominant in the middle/high part of vegetated marshes, often associated with *Trochammina inflata* (Sen Gupta, 1999). In the LC-Core, *T. inflata*, even in low abundance, only occurs in this interval. The presence of these two taxa is also characteristic of highly vegetated marshes in the region of northern Europe, from microtidal to macrotidal regimes (Murray, 1991). *Quinqueloculina seminulum* is widespread in marginal environments (Debenay and Guillou, 2002; Horton and Murray, 2007) and dominant in the lower tidal marsh/ tidal flat (Alve and Murray, 1999; Swallow, 2000). However, this taxon could be able to move up along the tidal gradient into the middle marsh (Franceschini et al., 2005; Horton and Murray, 2007; Shaw et al., 2016). Therefore the upper interval of the core shows how initial patchy vegetation developed rapidly, covering the whole tidal area and leading to the present landscape configuration.

### 4.3. Environmental parameter constraints

Moving upward along the LC-Core sediment from tidal flat to salt marsh, grain size decreases and TOC increases, echoing an increase in foraminiferal densities. Accordingly, in the same area, Francescangeli et al. (2017) observed very low densities of living species in sandier substrates towards the tidal flat. Conversely, Diz et al. (2004) found a relatively high abundance in sandy sediments and suggested that such substrates may provide a favourable settlement for benthic foraminifera. However, they explained that only epiphytic specimens dominated the assemblages. In such substrates, bacterial biofilms can develop on sandy particles as a trophic resource for epifaunal feeding (Bernhard and Bowser, 1993). In the LC-Core, the low TOC contents in the lower part could explain the relatively low density of benthic foraminifera, but it is not necessarily a bi-univocal relationship. For instance, on the Danish slope (North Sea), sand with low levels of TOC had high benthic fertility due to high food availability linked to particulate organic matter (and the associated bacteria) (Alve and Murray, 1997). Thus as pointed out in Murray (2006) the general assumption that there is "more organic matter in fine sediment than in sand" is not necessarily a reliable clue to food availability.

Furthermore, the sediment becomes devoid of foraminifera when sand contents are higher than 88% and TOC is close to 0%, as occurred during the development of the sandspit. When the sandspit was expanding, the vertical sedimentation rate was extremely high: one or two metres of sediment could be deposited in one stormy event. This prevented any faunal settlement. Then the sandspit was partly eroded, migrating shoreward, but this interval was devoid of foraminifera. In the Canche Estuary, the higher energy of the tidal flat area (whether part of the sandspit or not) inhibits particulate sedimentation (Armynot du Châtelet et al., 2009a). In the tidal flat, bacterial biofilms are seldom observed due to high-energy conditions that make it difficult for benthic foraminifera to feed, settle and develop. This means that sediment grain size (i.e., hydrodynamic conditions) is a limiting factor when it oversteps its critical threshold (Murray, 2001). In a recent study, Martins et al. (2016b) pointed out how in silicoclastic sandy sediments, the mechanical agitation of waves has a significant effect on the benthic fauna, namely, the destruction of small and more fragile specimens. They found that *Elphidium* spp. are more resistant to wave action when compared to other specimens, like the *Ammonia* group generally dominant in marginal environments. This could mean that the occurrence of *C. excavatum* and *E. margaritaceum* in the bottom part is not only a matter of different tidal levels, but is also linked to their potentially higher resistance to hydro-mechanical action. By contrast, in the small estuary of Havre de Surville (Normandy, France), *Ammonia beccarii* was found to have a positive correlation with the sandy sediment fraction, and therefore with higher hydrodynamic conditions (Haslett et al., 2003). Francescangeli et al. (2017) principally focused on the salt marsh area of the Canche Estuary, asserting that grain size and TOC were not the primary influence on benthic foraminiferal distributions. Here we can remark that when faunal investigations are extended to a wider tidal range, there is an increase in abiotic-biotic interactions, which makes ecological and palaeoecological interpretations more difficult.

Another aspect to note is that along the LC-Core the grain size is a constraint factor only when the sediment size is coarser than 125 μm. Indeed, the fine sandy fraction (63-125 μm) does not influence benthic foraminiferal distribution. In most studies, detailed information about grain-size distributions are not given. Sediment grain size is often expressed only in terms of Clay (< 4 μm), Silt (4-63 μm) and Sand (63-2000 μm). Therefore, in order to consider the influence of the grain size on foraminiferal assemblages, it could be more useful, as in the present study, to give extended information about grain size distribution.

## 5. Conclusion

To reconstruct past environments in the Canche Estuary, sediment grain size and benthic foraminifera, as well as data gleaned from the observation of historical pictures, have been used as a multiproxy approach. Over the last one hundred years, an upper tidal flat has been gradually replaced by a saltmarsh. In the bottom part of the core, the hydrodynamic condition, characterised by sandier sediment (grain-size > 125 μm), is a critical factor for the settlement and development of benthic foraminifera. The core stratigraphy represents a fining-upward succession of a tide-dominated estuary filled by the natural progradation of the sediments.

In estuarine areas, the difficulty in collecting undisturbed sediment cores often leads to nonperforming radiometric dating. The present study sheds light on how background knowledge provided by historical sources (such as pictures, maps, or chronicles) could be relevant to enhance modern palaeoenvironmental reconstructions. As an alternative method, historical aerial pictures could constitute a reliable option to estimate the age of recent sediments (< 100 years), when radionuclide measurements are inadequate.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marmicro.2018.05.003.

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