



Master STPE – Paleontology, Paleoclimatology, Paleoenvironments (PALEO)

Academic year 2024-2025

M1 Memoir

Study of benthic foraminiferal communities over the past centuries in the Bay of Brest:
natural vs. anthropogenic drivers?

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Date of defense:
12th June 2025

Remerciements

Je tiens tout d'abord à remercier Amélie Penaud pour m'avoir offert l'opportunité de réaliser ce stage au sein du projet PACTE, ainsi que pour son accompagnement bienveillant tout au long du travail, en particulier dans les dernières étapes de rédaction du rapport.

Un immense merci à Clara Valero pour ses précieux conseils, ses cours improvisés sur Inkscape et ses relectures nocturnes toujours pertinentes. Ton aide m'a été précieuse à chaque étape.

Merci à vous, Charlotte et Margot pour votre bonne humeur.

Je souhaite également exprimer ma gratitude envers Frédérique Eynaud, Catherine Crônier et Éric Armynot du Châtelet qui m'ont fait découvrir les foraminifères au fil de mes années d'études, et ont largement contribué à éveiller mon intérêt pour ce groupe fascinant, jusqu'à me donner l'envie d'y consacrer mon stage de M1.

Merci à Vincent pour nos nombreuses conversations enrichissantes et sa disponibilité à répondre à toutes mes questions, même les plus récurrentes.

Merci à Pierre-Antoine pour son aide et nos débats passionnés pour trancher si c'était *Elphidium decipiens*... ou pas.

Je remercie aussi chaleureusement Évelyne Goubert pour son expertise précieuse dans l'identification des espèces et pour son aide précieuse dans l'élaboration de mon rapport.

Un grand merci à Léa pour avoir pris le temps de relire mon rapport malgré ses propres échéances, et pour son soutien constant depuis le début.

Enfin, je remercie mes parents pour leur soutien indéfectible dans mes choix d'études... et pour tout le reste.

Résumé

L'étude des foraminifères benthiques issus d'une carotte sédimentaire de la rade de Brest révèle une structuration verticale marquée des assemblages spécifiques, en lien avec les variations granulométriques et géochimiques du sédiment. Les niveaux supérieurs sont dominés par des espèces tolérantes et opportunistes telles qu'*Elphidium crispum* et *Ammonia sp.*, traduisant probablement des conditions environnementales instables ou perturbées (eutrophisation, hypoxie, apports organiques récents). À l'inverse, les niveaux intermédiaires montrent une diversité plus élevée, avec des assemblages plus équilibrés et une présence accrue d'espèces plus sensibles, indiquant des conditions plus stables.

L'analyse granulométrique montre une alternance de fractions fines et plus sableuses, influençant la composition des communautés. La diversité tend à diminuer dans les niveaux argileux profonds, souvent associés à des conditions plus réductrices. Les données géochimiques (teneurs en carbone organique, azote, rapport C/N) appuient ces observations : les pics de TOC et les variations de C/N sont corrélés à des changements dans les assemblages foraminifériques.

La comparaison avec une carotte prélevée dans un autre secteur de la rade (Daoulas, 2023) met en évidence des similarités dans les tendances générales de diversité, mais aussi des différences locales notables en termes d'abondance et de dominance. Cette approche intégrée montre l'intérêt des foraminifères benthiques comme bioindicateurs sensibles des dynamiques sédimentaires et environnementales passées, dans le cadre d'un suivi écologique à haute résolution.

Mots-clés :

Foraminifères benthiques, Diversité spécifique, Bioindicateurs, Estuaire de l'Aulne, Analyse sédimentaire, Géochimie organique

Abstract

The study of benthic foraminifera from a sediment core collected in the Bay of Brest reveals a clear vertical structuring of species assemblages, linked to granulometric and geochemical variations in the sediment. The upper layers are dominated by tolerant and opportunistic species such as *Elphidium crispum* and *Ammonia sp.*, likely reflecting unstable or disturbed environmental conditions (eutrophication, hypoxia, recent organic inputs). In contrast, intermediate levels show higher diversity, with more balanced assemblages and an increased presence of sensitive species, suggesting more stable conditions.

Grain-size analysis reveals an alternation of fine and sandier fractions, influencing community composition. Diversity tends to decrease in deeper clay-rich layers, often associated with more reducing conditions. Geochemical data (total organic carbon, nitrogen, and C/N ratio) support these observations: TOC peaks and C/N variations are correlated with changes in foraminiferal assemblages.

Comparison with another core from a different sector of the bay (Daoulas, 2023) highlights similarities in general diversity trends, but also notable local differences in abundance and dominance. This integrated approach underscores the value of benthic foraminifera as sensitive bioindicators of past sedimentary and environmental dynamics, within the framework of high-resolution ecological monitoring.

Keywords:

Benthic foraminifera, Species diversity, Bioindicators, Aulne estuary, Sediment analysis, Organic geochemistry

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Introduction

Estuarine ecosystems are among the most dynamic and vulnerable environments on the planet (Barbier et al., 2011). Due to their position at the interface between land and sea, these systems are characterized by intense material and energy exchanges and are often home to high biodiversity (Barbier et al., 2011). Historically, estuaries have also been favored areas for human settlement, and over time, societies have significantly reshaped them. Since the end of World War II, increasing anthropogenic pressures — such as intensive agriculture, growing coastal urbanization, industrial pollution, and river regulation — have profoundly impacted these environments (Lotze et al., 2006). These human-induced disturbances, coupled with natural climate variability and recent warming trends, have disrupted the historical trajectories of estuarine systems.

The Bay of Brest (western Brittany, France; Figure 1) is a compelling example of such environmental dynamics. This semi-enclosed bay, influenced by strong tidal forces, is connected to the Atlantic Ocean through a narrow strait known as "Le Goulet," and is also fed by several rivers, including the Aulne, Éloron, and Mignonne. The Bay has been the focus of pioneering research addressing eutrophication, diffuse pollution, phytoplankton dynamics, and the evolution of benthic communities (Quéguiner & Tréguer, 1984; Le Pape & Ménesguen, 1997).

In the context of ongoing climate and anthropogenic change, the ISblue flagship project PACTE ("Past to Current Land-Sea Continuum: Socio-Ecosystem Trajectories Derived from a Regional Pilot Site," PI: Aurélie Penaud) aims to reconstruct, at very high temporal resolution (i.e., multi-annual to decadal scale), the evolution of the Bay of Brest over the past two centuries. This is achieved using a multidisciplinary framework, combining tools from geochemistry, sedimentology, palynology, micropaleontology, historical archives, and environmental modeling.

This study was conducted in parallel with the PhD work of Clara Valero (palynology and sedimentology, 2022–2025), and extends other investigations including those by Théo Guérin (micropaleontology, BSc internship, 2022), Margot Girardeau (geochemistry, MSc internship, 2025), and Charlotte Gasne-Destaville (diatoms, ongoing). It focuses on a sediment core collected from the Aulne estuary: core PACTE-AL-IS02. The aim of this internship is to document the main environmental disruptions recorded in this system over the past 150 years through the study of benthic foraminifera.

The goal is to identify phases of disturbance or relative stability within the Aulne estuary in order to provide a clearer understanding of this ecosystem's recent trajectory.

I. Study Context

1. Estuaries and Environmental Indicators

Estuaries are transitional environments between land and sea, subject to strong physico-chemical (e.g., salinity, turbidity, oxygenation, suspended matter inputs) and biological (e.g., phytoplankton cycles, fish migrations, benthic community fluctuations) variations (Elliot & McLusky, 2002). Their functioning is highly dynamic, driven by interactions between natural processes (tides, sediment inputs, river flows) and anthropogenic pressures (urbanization, agriculture, industry), making them extremely sensitive to changes along the land–sea continuum.

The main pressures affecting estuarine ecosystems include excessive nutrient inputs (e.g., nitrogen and phosphorus), which can lead to local algal blooms and water column eutrophication, contamination by heavy metals and organic pollutants, alterations in the hydro-sedimentary regime (e.g., dredging, embankments, dams), and the influence of climate change (increasing water temperatures, shifts in rainfall regimes). Such disturbances can sometimes trigger difficult-to-reverse ecological regime shifts (Duarte et al., 2009).

To investigate the ecological trajectories of estuaries in the past, various environmental indicators — or *proxies* — can be derived from sediment core analysis. In this study, several key proxies are applied :

- Benthic foraminifera, calcareous micro-organisms, are highly sensitive to variations in salinity, dissolved oxygen, organic and heavy metal pollution. Their assemblages reflect prevailing environmental conditions, and their abundance, diversity, and the presence of indicator species make them effective markers for diagnosing past environmental changes (Armynot du Châtelet et al., 2004; Alve, 1995).
- Geochemical data (e.g., Ti/Ca ratio, total carbon content, %TOM, enrichment factors) provide insight into terrigenous inputs, primary productivity, organic matter content, and metal contamination. For instance, the Ti/Ca ratio is a robust proxy for identifying increased continental runoff phases (Lambert et al., 2018).
- Stable isotopes $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, measured on foraminiferal shells, respectively inform on the origin of organic carbon (e.g., productivity, vegetation) and past water temperature and salinity (Grossman, 1987; Siani et al., 2013).

Combining these different analytical approaches within a so-called multi-proxy framework enables a more detailed and reliable reconstruction of ecosystem responses to historical environmental pressures.

2. The Aulne Estuary and the Contributions of the PACTE Project

This study focuses on the Bay of Brest in Brittany, and more specifically on the Aulne Estuary, located in the eastern part of the bay (Figure 1). Covering an area of 181 km², the Bay of Brest is a semi-enclosed coastal basin characterized by a macrotidal regime and an average depth of 8 m. It opens into the Atlantic Ocean through the narrow "Goulet de Brest," a natural bottleneck where current speeds can reach up to 4 m/s (Grégoire, 2016).

Tide gauge data recorded in Brest since 1846 (SONEL, <https://www.sonel.org/>) indicate a steady rise in sea level. Compared to 1900, the mean sea level has increased by approximately 20 cm over the following 120 years, reflecting a trend consistent with global observations of sea-level rise. This evolution, related to climate change, can affect estuarine dynamics by altering salinity, sedimentation patterns, and benthic communities.

The estuarine system of the Bay of Brest can be subdivided into three main zones:
-the outer domain, open to the ocean (Iroise Sea),
-the intermediate domain, including the Goulet and the paleo-channels of the Aulne and Élorne rivers,
-the inner domain, comprising coves, semi-enclosed bays, and river mouths (Grégoire, 2016).

Within this inner domain, the Aulne Estuary is a preferential site for sediment deposition, where silty deposits dominate due to low hydrodynamic energy and significant fluvial inputs. The Aulne River, the main watercourse in the watershed (~1,900 km²), plays a crucial role in supplying sediments and nutrients to the bay. These inputs are intensified during flood events or periods of heavy runoff, often amplified by upstream agricultural practices (land consolidation, drainage, fertilization). Grégoire (2016) demonstrated that this part of the bay accumulates fine, organic-rich sediments, making it an ideal location for preserving high-resolution paleoenvironmental archives.

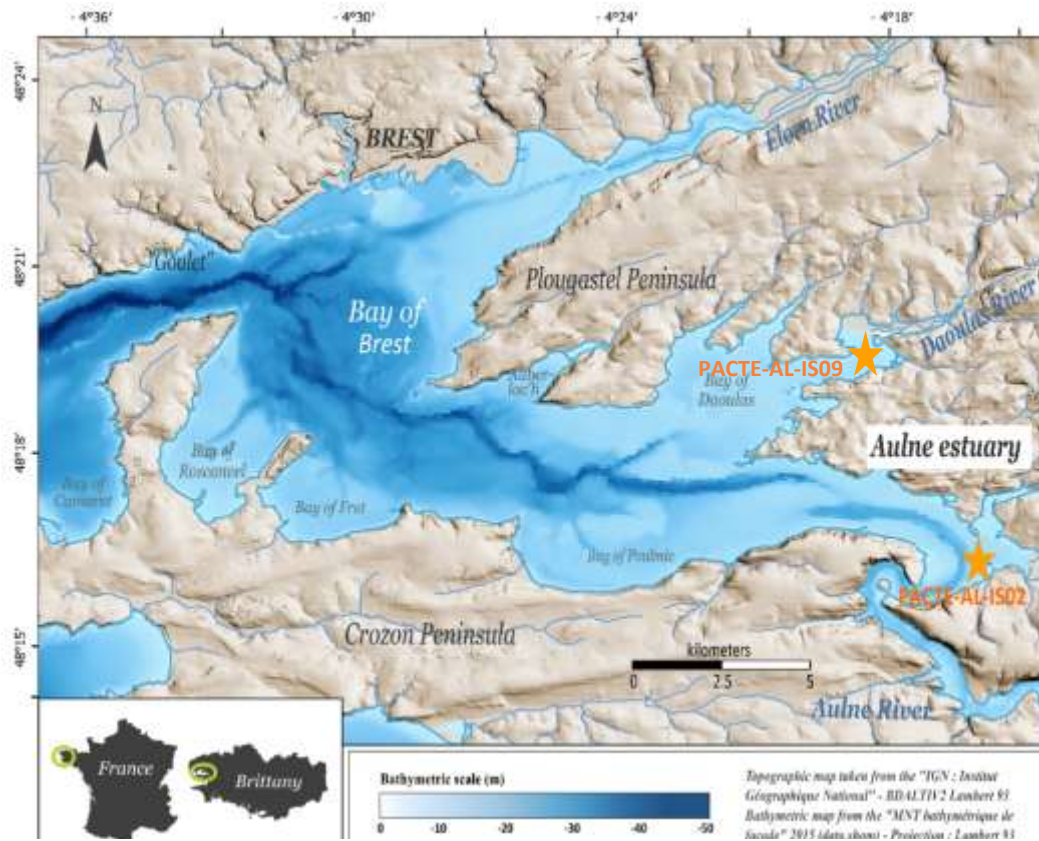


Fig. 1. Location of coring sites IS-02 and IS-04, respectively in the Aulne Estuary and the Bay of Daoulas, within the Bay of Brest.

Topographic data from the BD ALTI V2 database (IGN) and bathymetry from the 2015 coastal bathymetric DEM (data.shom.fr). Projection : Lambert 93.

The Aulne Estuary is heavily influenced by agricultural activities within its watershed. Starting in the 1960s–1970s, land consolidation — marked by the systematic removal of hedgerows and embankments — intensified surface runoff, resulting in an increase in the average grain size of sediments and a rise in nutrient inputs, particularly nitrates. These transformations altered local hydrological dynamics and the nature of terrigenous inputs to the estuary, with lasting consequences on benthic habitats and the composition of biological assemblages.

In addition, historical pollution from former lead-zinc mines in Poullaouen and Huelgoat, located upstream of the Aulne, has left a persistent geochemical imprint in the sediments (Ifremer, 2018). Traces of heavy metals (Pb, Zn, Cd) have been detected along the entire lower course of the Aulne, down to its mouth, highlighting the value of a multi-proxy approach to identify key environmental events in the recent past.

3. The AL-IS02 Core from the PACTE Project

This internship focuses on the PACTE-AL-IS02 core (hereafter referred to as IS02), collected from the Aulne Estuary (Figure 1). This 34 cm-long sediment core was retrieved aboard the R/V *Thalia* during the PACTE campaign in August 2023 (UMR 6538 Geo-Ocean, Ifremer).

The age model of the core (Figure 2) was established using depth profiles of excess ^{210}Pb , a naturally occurring radionuclide ($T_{1/2} = 22.3$ years), and ^{137}Cs , an artificial radionuclide ($T_{1/2} = 30$ years) resulting from atmospheric nuclear tests in the early 1960s and, to a lesser extent, the Chernobyl accident in 1986 (cf. Avsar et al., 2015). The estimated sedimentation rate is 0.2 cm/year, allowing the core to cover the period from 1853 to 2022, with a study resolution of approximately 10 years.

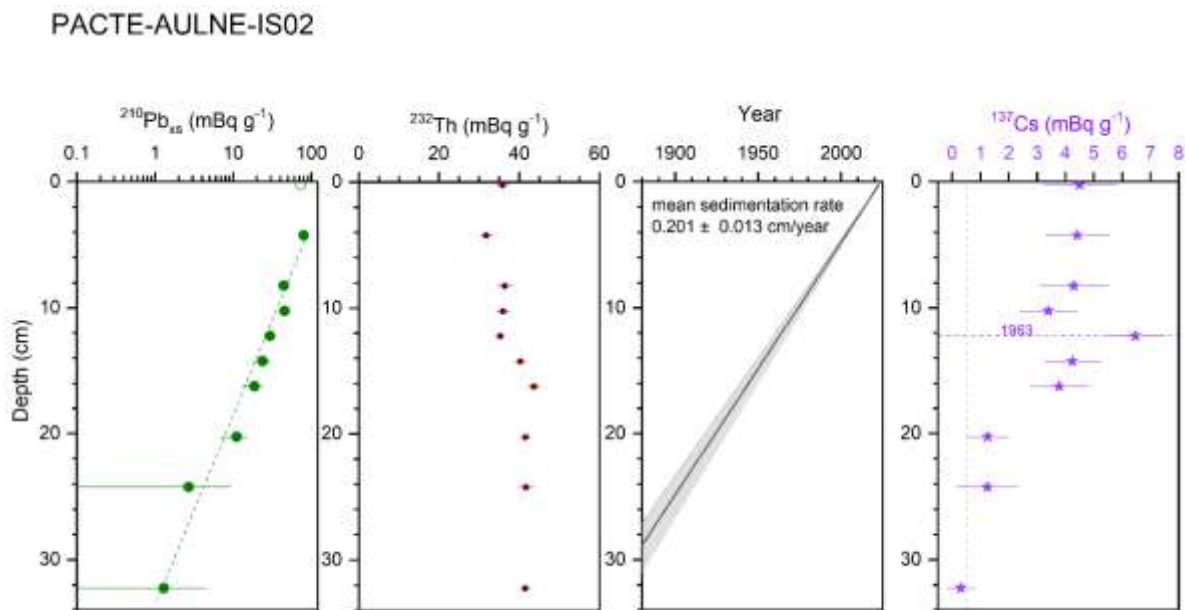


Fig. 2. Age model of the PACTE-AL-IS02 core based on radioisotopic dating

This sediment core spans the period from 1853 to 2022. It is predominantly silty and organic (Figure 3), with a coarse shell debris layer at its base (between 26 and 30 cm) and a layer enriched in slipper limpets (*Crepidula*) near the top (approximately 0 to 8 cm).

The analysis of this core is part of a multi-proxy study (Figure 3), which includes: palynological and sedimentological data (grain size, carbonate and organic matter content via loss-on-ignition) (Valero et al., in prep), geochemical data (major and trace elements, lead isotopes) (M2 internship by Margot Girardot, 2025), as well as benthic foraminiferal data (assemblages, stable isotopes) (this internship).

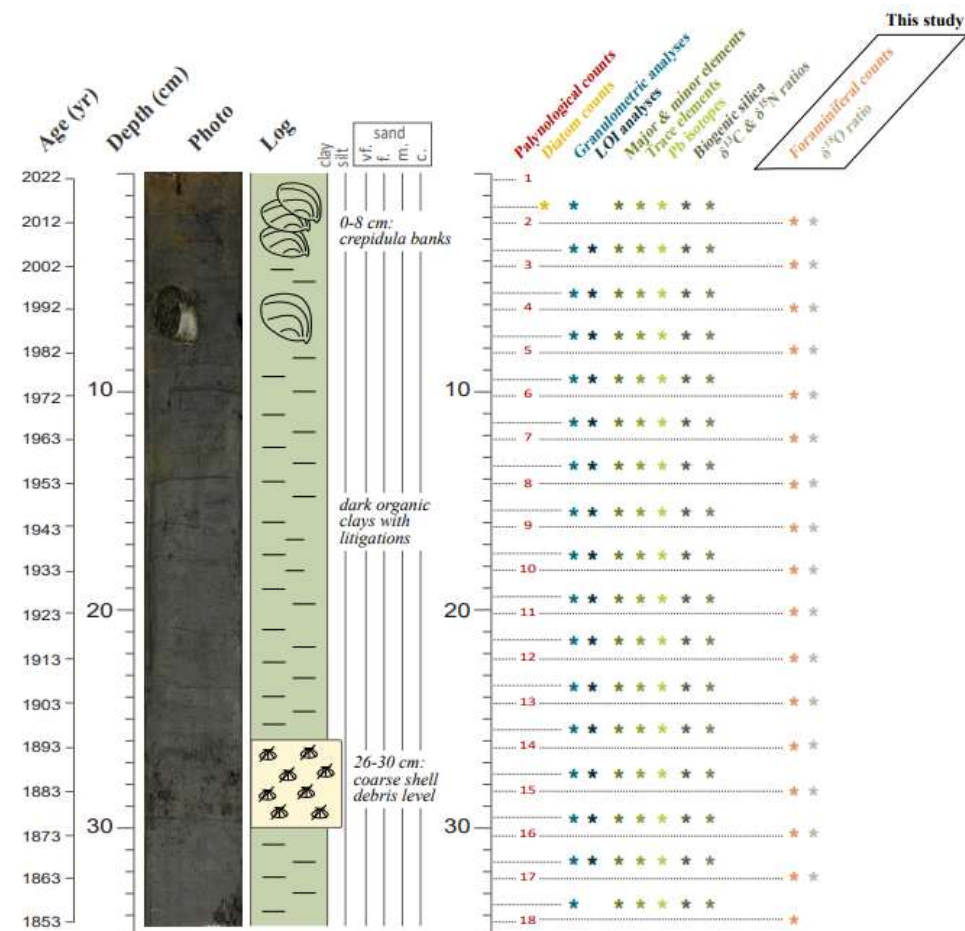


Fig. 3. Lithological and stratigraphic description and distribution of multi-proxy analyses conducted on core IS-02 (Aulne Estuary).

Photograph, simplified sedimentary log, radioisotopic dating, and synthesis of analyses carried out as part of the PACTE project, including this study.

II. Materials and Methods

Preliminary treatments (core slicing, sieving, drying) were completed prior to the start of the internship. Several analyses were carried out by other members of the PACTE project or during previous internships:

- Grain size analysis: measurements were performed using a laser granulometer.
- Organic matter content: estimated by loss on ignition (LOI), expressed as % TOM.
- Geochemistry: concentrations of major and trace elements (Ti, Ca, Pb, Zn, etc.) were measured using XRF (IR-MS) and ICP-MS. The Ti/Ca ratio was calculated as a proxy for terrigenous input.

My main contribution focused on counting benthic foraminifera. Aliquots were taken every 2 cm. The sediments were pre-washed with freshwater on a 125 μm sieve, then dried at low temperature. Only the >125 μm fraction was kept for analysis. Samples were examined under a binocular microscope, and all foraminifera were counted at each level without applying a minimum threshold, in order to obtain exhaustive sampling without splitting the sample.

Identification was carried out at the species level using a binocular microscope and several key taxonomic and ecological references, including Armynot du Châtelet (2003), Goubert (2005), Debenay (2012), Jorissen et al. (2023), and the WORMS database. The latter helped refine morphotype recognition within a group known for its high morphological plasticity. Specimens from the *Ammonia* genus were not identified to species level due to high intraspecific variability and the absence of SEM imaging; they were therefore grouped under *Ammonia sp.* for the entire dataset.

Ecological interpretations and morpho-ecological groups were established using various references including Goubert et al. (2001), Murray (2006), Armynot (2017), and Bouchet (2022).

Data were used to calculate standard indices:

- Shannon Diversity Index (H'): $H' = -\sum p_i * \ln(p_i)$, where p_i is the proportion of species i .
- Pielou's Evenness Index (J'): $J' = \frac{H'}{\ln(S)}$, where S is the total number of species.

Data processing and analysis were performed in Excel for index calculation, table formatting, and figure creation. Figures included in the report were made using Inkscape. The software Psimpoll was occasionally used to generate CONISS dendrograms for stratigraphic clustering of assemblages. In addition, PAST software was used for unconstrained hierarchical clustering, allowing independent analysis of vertical profiles.

Grain size data were processed using GradiStat, which provided statistical parameters of particle size distributions. This helped identify dominant and secondary granulometric modes for each level, later used in multi-proxy comparisons.

For each sample, 10 individuals of each of the two most dominant species were selected, cleaned, and analysed by mass spectrometry to obtain $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values. Results are expressed in ‰ relative to the V-PDB standard.

All available datasets (foraminifera, isotopes, geochemistry, grain size) were interpreted in a multi-proxy framework to identify major environmental changes recorded in core IS-02.

III. Results

1. Benthic foraminiferal assemblages

Counts performed throughout the IS-02 core yielded comprehensive data on the distribution of benthic foraminifera. The total number of individuals per sample ranges from 34 to 742 (see Appendix 1). In total, 31 different taxa were identified across the 17 studied levels. Appendix 2 shows the percentage occurrence of each species across all studied levels.

Appendix 3 summarizes the main ecological traits of the identified species: test type, known environmental preferences, tolerance to eutrophication or organic pollution, and their frequency of occurrence in core IS-02.

Analysis of assemblage composition highlights a strong dominance of five main species: *Ammonia gr. tepida*, *Elphidium acculeatum*, *Haynesina germanica*, *Lobatula lobatula*, and *Elphidium crispum*, which together account for the vast majority of individuals (Figure 4). The vertical distribution shows a peak in abundance between 28 and 30 cm, followed by a marked decline and a secondary increase between 18 and 8 cm.

Among dominant species, *Ammonia* is consistently present in all samples, with relative abundances ranging from 18% (at 34 cm) to 36% (at 20 cm). It is the most abundant species across the entire core. Other species such as *Elphidium acculeatum* and *Haynesina germanica* are also well represented, particularly at intermediate levels (e.g., *E. acculeatum* reaches 28% at 2 cm, *H. germanica* up to 31% at 6 cm). *Elphidium crispum* and *Lobatula lobatula* are generally less dominant (often <10%), although *L. lobatula* reaches a local peak of 20.5% at 34 cm.

Diversity indices display a structured pattern: species richness varies from 10 to 24 species depending on the level. The Shannon diversity index ranges between 1.84 and 2.26, with a clear decline in the central section of the core (approximately 1933–1893), where diversity drops and *Ammonia* becomes highly dominant. Pielou's evenness reflects this trend, with minimum values between 0.68 and 0.73 during the same period.

In the upper levels (post-1992), the indices show a gradual increase in diversity, reflecting an enrichment of the species pool and a more balanced distribution among taxa.

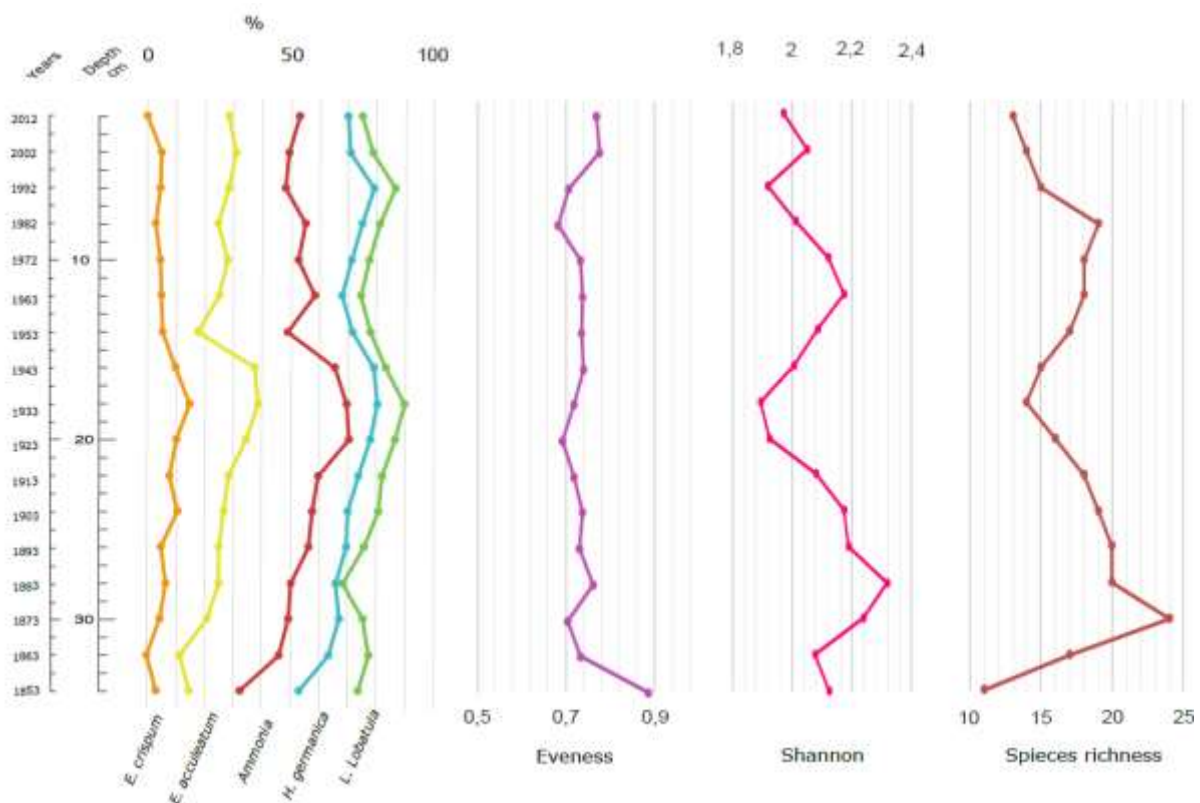


Fig. 4. Temporal Variation of Dominant Foraminiferal Taxa and Diversity Indices in Core ISO2 (1853–2012)

An unconstrained hierarchical clustering was applied to the relative abundances of dominant taxa using the PAST software (Figure 5). This clustering, independent of stratigraphic position, allowed the identification of groups of samples sharing similar species composition.

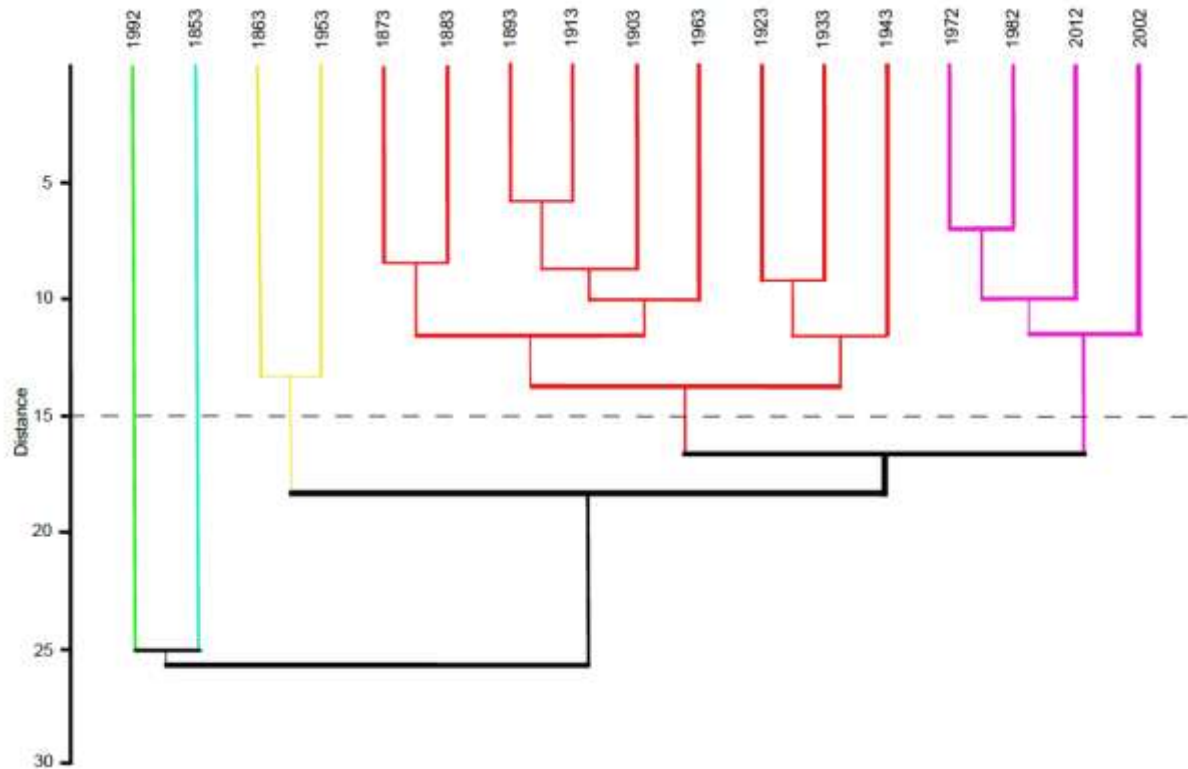


Fig. 5. Unconstrained hierarchical clustering dendrogram based on the relative abundances of benthic species from core IS-02 (Aulne Estuary).

The results of this classification were then projected onto the stratigraphic diagram generated with Psimpoll (Figure 6) using colored markers. To characterize the evolution of benthic foraminiferal assemblages within core IS-02, a stratigraphically constrained hierarchical classification (CONISS method, via Psimpoll software) was conducted. This approach allowed the identification of five main zones (I-1 to I-5), corresponding to distinct ecological phases (Figures 6 and 7).

In an estuarine context such as the Bay of Brest, the trio *Ammonia gr. tepida* / *Haynesina germanica* / *Elphidium excavatum* represents a set of indicator species typical of intertidal to subtidal environments, influenced by mixed tidal and continental processes that vary across different temporal scales (tide, season, year). The distribution of this trio has been previously described in the Gulf of Morbihan (Perez-Belmonte, 2008).

Each species presents specific ecological preferences: a dominance of *Ammonia tepida* generally reflects hydrodynamic confinement and low water mass renewal; *Haynesina germanica* tends to indicate continental trophic inputs; *Elphidium excavatum* is often associated with turbid, organic-rich waters, though this does not necessarily imply increased sedimentation rates (Goubert, 1997).

Regarding the other *Elphidium* species:

- *E. aculeatum* is an epibenthic species typical of coarser substrates than those inhabited by *E. crispum*.
- *E. crispum* is mainly epiphytic and epifaunal, preferring silty substrates, intolerant of high turbulence or turbidity, and poorly adapted to large salinity fluctuations.

- *E. margaritaceum*, also epifaunal, tends to favor slightly agitated silty environments and shows better tolerance to disturbance.
- *E. excavatum* has an epifaunal to deeper endofaunal lifestyle, suited to turbid, organic-rich environments.
- *E. williamsoni* is generally found in muddy depressions within salt marshes.

E. gerthi, *E. decipiens*, and *E. oceanense* were grouped together based on similar ecological behavior (shallow epi-/endofauna) and tolerance to low oxygen and high organic content. Likewise, the two epiphytic taxa *Neoconorbina spp.* and *Lobatula lobatula* were combined into a single category.

All porcelaneous taxa (*Quinqueloculina seminulum*, *Q. carinatastriata*, *Miliolinella subrotunda*, *Pyrgo sp.*) were grouped together as typical marine forms. Spherical forms transportable by flood tides were also clustered as a single entity.

A final group included underrepresented non-spherical marine benthic forms, such as rare or indeterminate individuals (one at 28 cm and another at 12 cm), along with a few *Globigerina* specimens (one at 4 cm, one at 26 cm).

Lastly, a single agglutinated specimen was identified as *Miliammina fusca*. Given the known presence of this species at the schorre-slikke transition in the Bay of Brest (Valéro, ongoing PhD), this individual was grouped with *E. williamsoni*, both of which are typical of muddy depressions within salt marshes.

% Foraminiferal taxa and

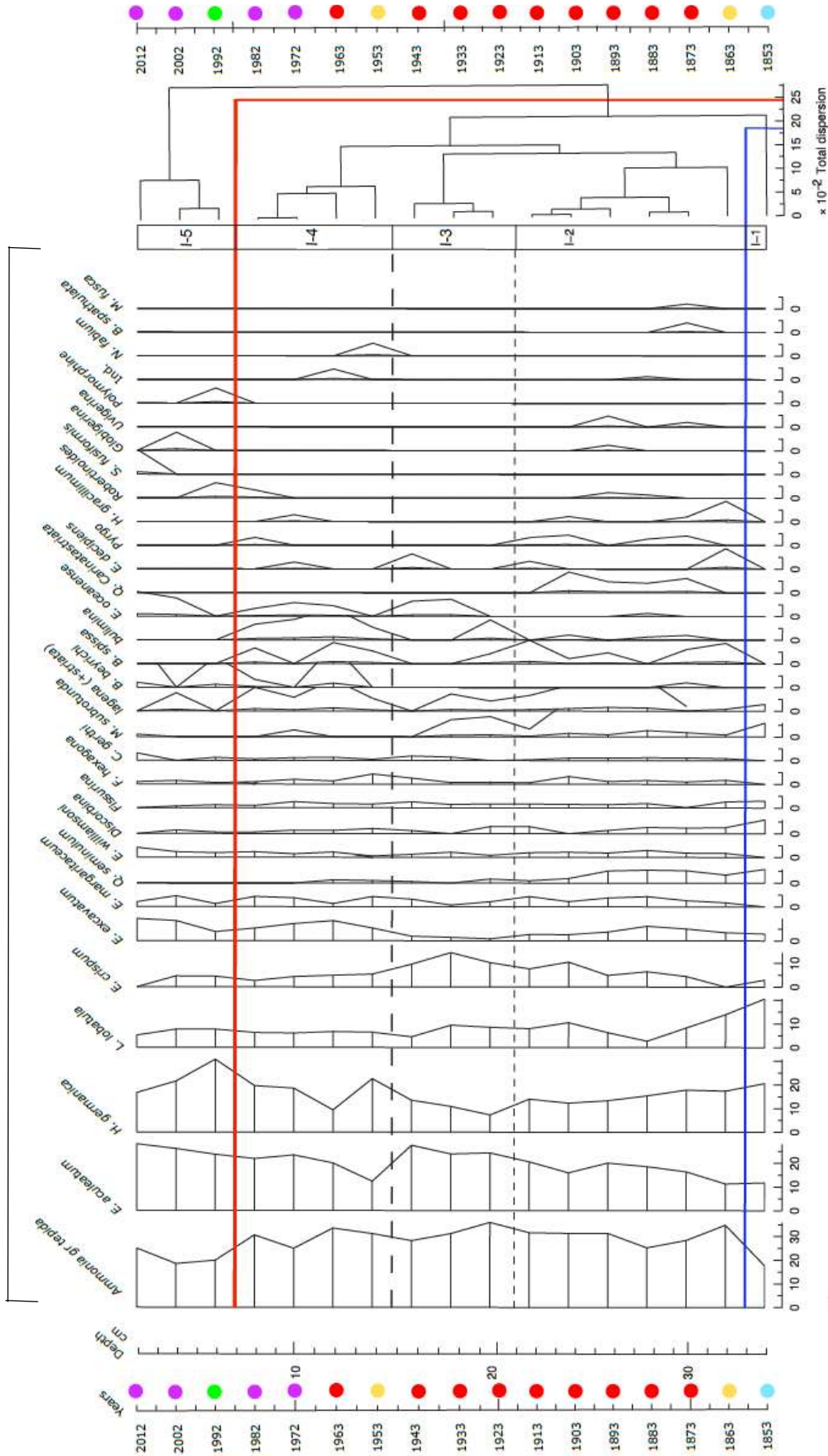


Fig. 6. Stratigraphic diagram of benthic foraminifera from core IS-02 generated with Psimpoll (relative abundances by species). Colored markers indicate groups defined by an unconstrained clustering (UPGMA) performed using Psimpoll software.

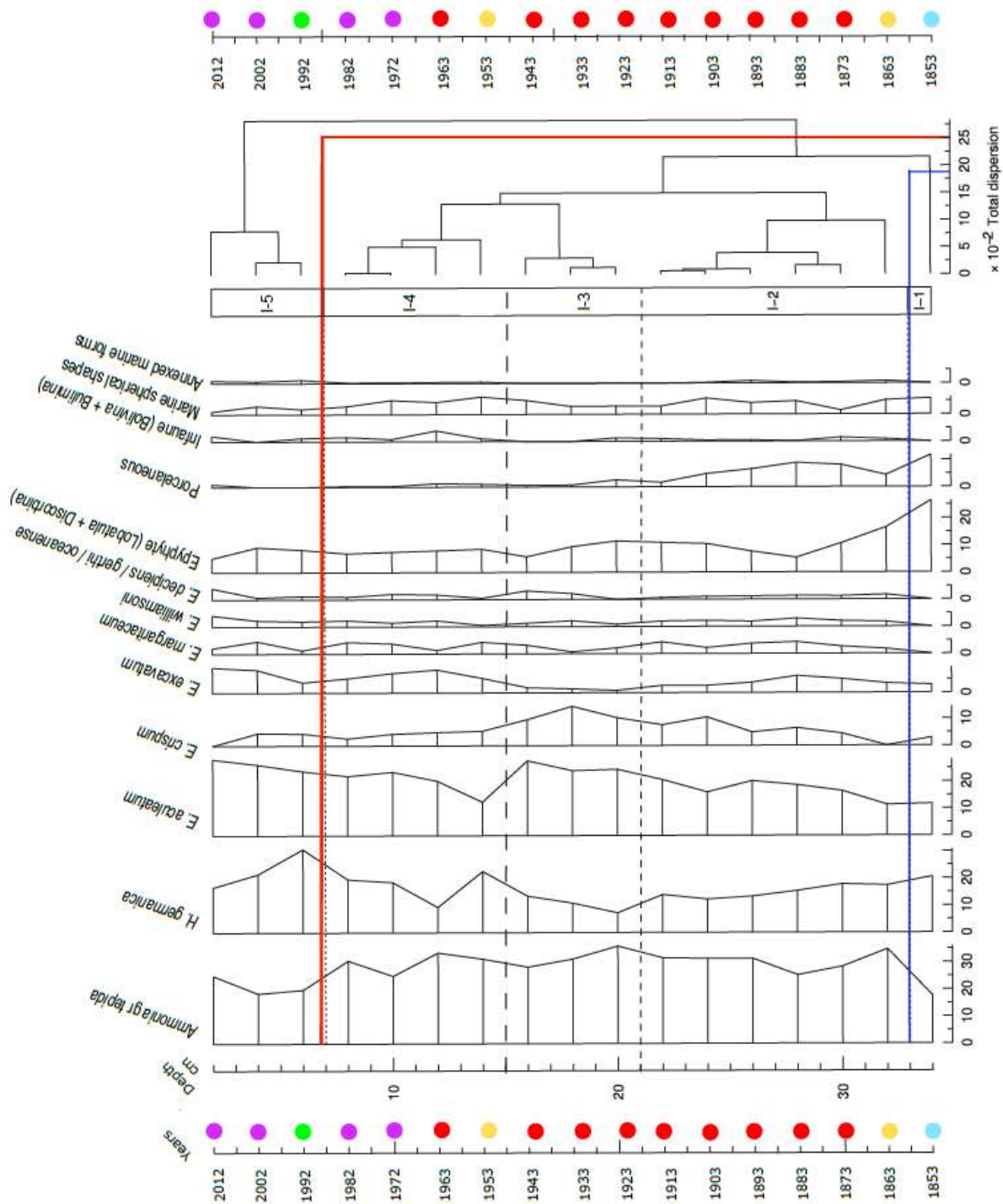


Fig. 7. Stratigraphic diagram of benthic foraminifera from core IS-02 generated using P-simpoll (relative abundances by species). Colored dots indicate groups defined by an unconstrained cluster analysis (UPGMA) performed in P-simpoll, with taxons ordered by morphoecological affinities.

The vertical structuring of benthic foraminiferal assemblages reflects both gradual and abrupt reorganizations, consistent with several environmental shifts recorded in other proxies. A visualization factor ($\times 10$) was applied to rare species to improve graphical readability without impacting statistical outcomes. Figure 6 illustrates the temporal distribution of taxa by decreasing abundance, while Figure 7 groups foraminifera according to their morphoecological affinities. A notable transition occurs around the 1950s–1960s, marked by a restructuring of species assemblages. This major shift is accompanied by the gradual disappearance of taxa typical of less-disturbed environments, replaced by species tolerant to eutrophication and anthropogenic stress.

The analysis of benthic assemblages within core IS-02 reveals overall compositional stability over time, though several significant transitions are identifiable. Two major shifts are observed at the I-1/I-2 and I-4/I-5 boundaries, along with two more subtle changes at I-2/I-3 and I-3/I-4. Overall, a trend toward increased abundance of *Haynesina germanica* in the upper layers suggests evolving environmental conditions, likely driven by intensified continental inputs.

Quinqueloculina seminulum, present at the base of the core, shows a sharp decline from around 1893. This reduction may reflect changes in benthic vegetation, as *Q. seminulum* is typically associated with vegetated substrates (epiphyte) (Sadri et al., 2011). Simultaneously, an increase in *Elphidium crispum*—also linked to vegetated environments—could indicate a shift in plant cover, such as the replacement of seagrasses by algae.

The co-occurring rise of *Elphidium excavatum* and *H. germanica*, alongside a decline in *Ammonia*, supports the hypothesis of increasing terrigenous influence. *Ammonia* is generally associated with confined, poorly flushed environments (Alve, 1995), whereas *E. excavatum* and *H. germanica* tolerate more dynamic, terrestrially influenced settings (Armynot du Châtelet et al., 2004).

Epibenthic species like *Elphidium aculeatum* and *E. margaritaceum* are considered opportunistic, similar to *E. excavatum*, which is known for its tolerance to stressed environments and rapid recolonization capabilities (Nikulina et al., 2008).

This dual approach highlights a major ecological shift around the 1950s–1960s. In particular, the red cluster—strongly correlated with *Elphidium crispum*—gradually disappears, giving way to an assemblage dominated by *Elphidium excavatum*. This substitution suggests an environmental transition from a clear, vegetated, and stable habitat favorable to *E. crispum*, to a more turbid, low-light, and disturbed environment characteristic of habitats tolerated by *E. excavatum*. This reflects a progressive degradation of benthic conditions, likely linked to increased continental inputs and eutrophication. Finally, the limited presence of strictly marine species suggests a weak marine influence in this part of the Aulne estuary.

Grain-size analysis enabled the characterization of particle size distributions within core IS-02, particularly distinguishing dominant and secondary modes, calculated using the GradiStat software. The results are summarized in Appendix 4, showing standardized sediment fractions (fine to coarse silt, and fine to coarse sand). This analysis focused on the overall grain-size distribution; mineralogical fractions and major elements were not detailed in this study.

Although the agricultural land consolidation (“remembrement”) in the Aulne watershed, initiated in the 1960s–1970s, is historically associated with increased runoff and enhanced inputs of nutrients and coarser material, no clear granulometric shift is observed in core IS-02 during this period. Sediments deposited between 1960 and 1970 remain unimodal and predominantly silty, around 30–40 μm . This might suggest that the effects of land consolidation were gradual or locally dampened by estuary-specific hydrodynamic or topographic factors.

A comparison of granulometric and foraminiferal data for core IS-02 (Figure 8) was performed at regular 2 cm intervals. Cluster I-5, located at the top of the core, is characterized by a unimodal grain-size mode centered on coarse silt to very fine sand. Older clusters I-4 and I-3 show more pronounced bimodality, possibly reflecting a more complex depositional regime. Still, an intermediate level between 1950 and 1960 retains a silty unimodal mode.

Between 1970 and 1980, the dominant grain-size mode reaches 85 μm (fine sand), while a secondary mode around 15 μm indicates a persistent fine fraction. This transition aligns with a change in sediment dynamics.

The foraminiferal assemblages in clusters I-3 and I-4 also diverge, confirming a co-evolution of biological communities and sediment input. At the base of the core (I-1 and I-2), the signal is less distinct, both granulometrically and in foraminiferal composition, with more scattered data and less differentiated assemblages—possibly reflecting more diffuse or disturbed depositional conditions.

A synthesis of the main sedimentological, geochemical, and foraminiferal proxies for core IS-02 is presented in Figure 9. The 26–30 cm interval, identified lithologically as a shell-rich layer, shows elevated $\delta^{18}\text{O}$ values in *Ammonia* and *Elphidium excavatum*, and an increase in $\delta^{13}\text{C}$ in *E. excavatum*. This coincides with a marked drop in diversity (Shannon), evenness (Pielou), and species richness, suggesting a localized ecological disturbance.

Simultaneously, a rise in D50 indicates coarser inputs, potentially linked to runoff events or increased hydrodynamic energy. The slight decrease in TOC supports this interpretation. The enriched $\delta^{18}\text{O}$ values could reflect either increased marine influence or brief cooling.

A calcimetry peak at 15 cm (~50%) does not correlate with foraminiferal abundance and likely reflects larger bioclastic remains (e.g., bivalves, gastropods). This highlights that foraminifera, while abundant, do not significantly contribute to bulk CaCO_3 content. The carbonate peak at 6 cm may indicate increased productivity, possibly linked to a *Crepidula* shell bed. Upper levels, however, are harder to interpret and may reflect reworking or secondary inputs.

Finally, a temporary anti-correlation at 16 cm between $\delta^{18}\text{O}$ values in *Ammonia* and *E. excavatum* contrasts with their generally parallel trends. This decoupling remains unclear at this stage.

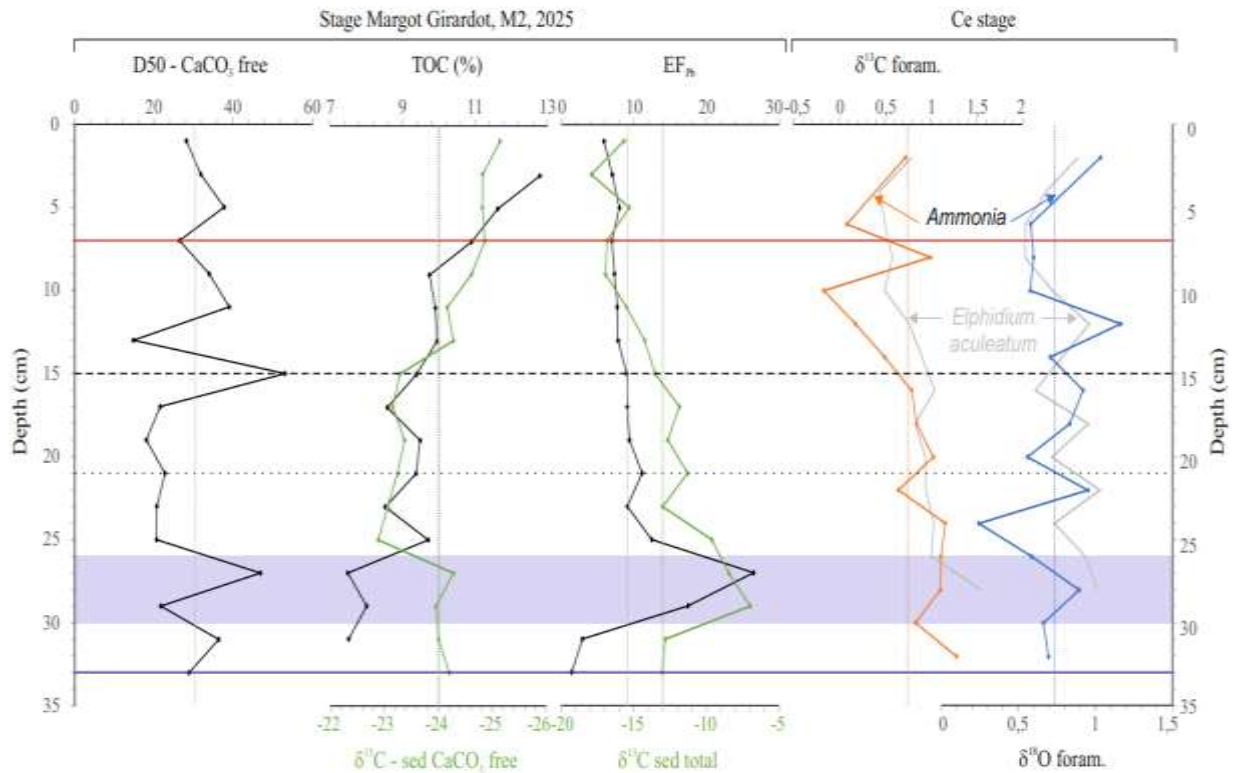


Fig. 9. Cross-plots of sedimentological (D50, %TOC), geochemical (EF_{Pb} , sedimentary $\delta^{13}C$), and foraminiferal proxies ($\delta^{13}C$ and $\delta^{18}O$ measured on *Ammonia* and *Elphidium excavatum*, foraminiferal concentration, and relative abundances of selected dominant species) along core IS-02. The shell-rich interval (26–30 cm) is highlighted in purple. Data derived from this study and the PACTE project.

The median particle diameter (D50), an indicator of fine sediment grain size, ranges from 15 to 53 μm in core IS-02 (Figure 9). The highest values (above 35 μm) are recorded in the most recent levels (post-World War II), potentially reflecting renewed input of coarser material linked to anthropogenic or hydrodynamic disturbances.

Total organic matter (TOM), estimated via loss on ignition, ranges from 7.5% to 12.8%, with higher contents in the layers deposited after 1945. This trend is consistent with the documented eutrophication processes in the Bay of Brest from the mid-20th century onward. This observation is supported by the work of Alain Ménesguen (Ifremer), who highlighted a significant increase in nitrogen inputs to the Bay of Brest since the 1950s, mainly due to intensified agricultural practices and urban discharges. These inputs triggered eutrophication phenomena, such as green algal blooms and changes in phytoplankton communities. Total organic carbon (%C_TOC) shows a similar pattern, with a minimum of 0.55% around 1956, suggesting possible dilution by mineral inputs.

IV. Discussion

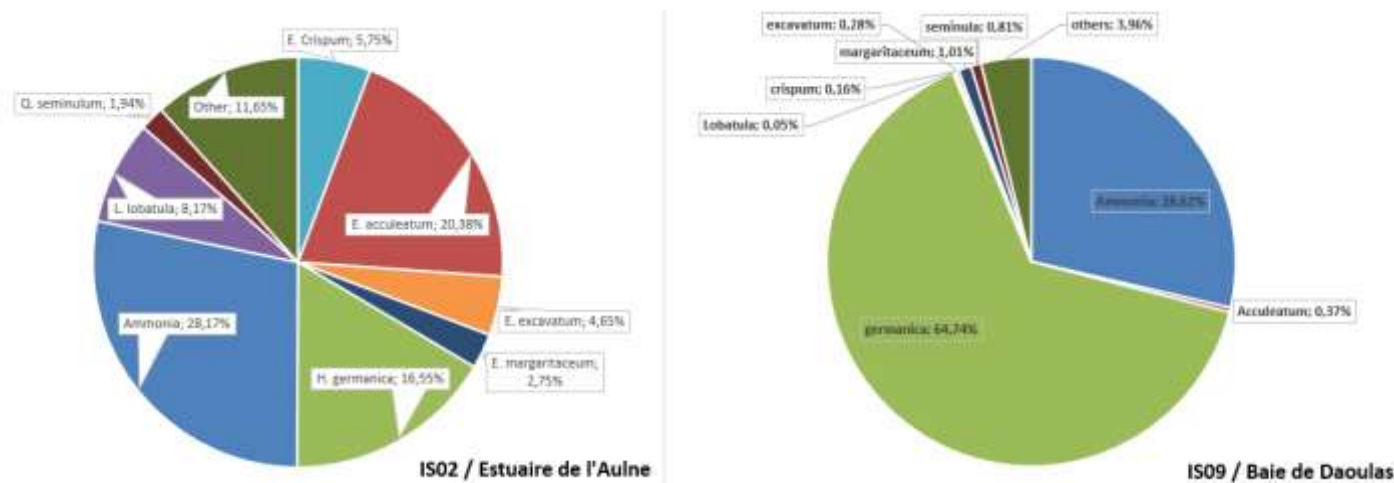


Fig. 10. Relative distribution of dominant benthic foraminiferal taxa in two estuarine sediment cores: IS02 (Aulne Estuary) on the left and IS09 (Daoulas Bay) on the right.

The benthic foraminiferal assemblages from cores IS02 (retrieved from the Aulne Estuary) and IS09 (located in Daoulas Bay) (Figure 10) were compared using the eight most abundant species identified in core IS02. This comparison highlights marked differences in community structure between these two estuarine environments, despite their geographical proximity.

In the Aulne Estuary, the assemblages are dominated by *Ammonia* (28.2%) and *Elphidium acculeatum* (20.4%), followed by *Haynesina germanica* (16.6%), *Lobatula lobatula* (8.2%) and *Elphidium crispum* (5.8%). This relatively high diversity reflects a more dynamic and variable environment, where species tolerant to fluctuating conditions (e.g., *Ammonia*) coexist with indicators of more stable, oxygenated environments (e.g., *Lobatula lobatula*), under relatively reduced hydrodynamic stress, though subject to tidal mixing due to proximity to paleo-channels.

In contrast, core IS09 from Daoulas Bay—a more restricted and sheltered setting—shows a strong dominance of *Haynesina germanica* (64.7%), alongside *Ammonia* (28.6%), with all other taxa nearly absent (<1%). The overwhelming presence of *H. germanica* suggests a more stressed or organically enriched environment, consistent with the confined nature of Daoulas Bay, which receives diffuse continental inputs (e.g., agricultural runoff, urban effluents) and is influenced by tidal forcing and marine incursions.

The higher diversity observed in IS02 may result from increased exposure to hydrodynamic mixing, fostering more heterogeneous microhabitats.

This comparison aligns with observations made in the Gulf of Morbihan, as described by Pérez-Belmonte (2008), where *H. germanica* tends to dominate inner, more confined settings subjected to strong continental influence and fine sediment inputs. Conversely, more open and better-oxygenated environments, such as the outer Morbihan or the Aulne Estuary, show higher species richness with greater representation of *Ammonia* and *Elphidium*. These regional parallels support the palaeoecological interpretations derived from the foraminiferal assemblages.

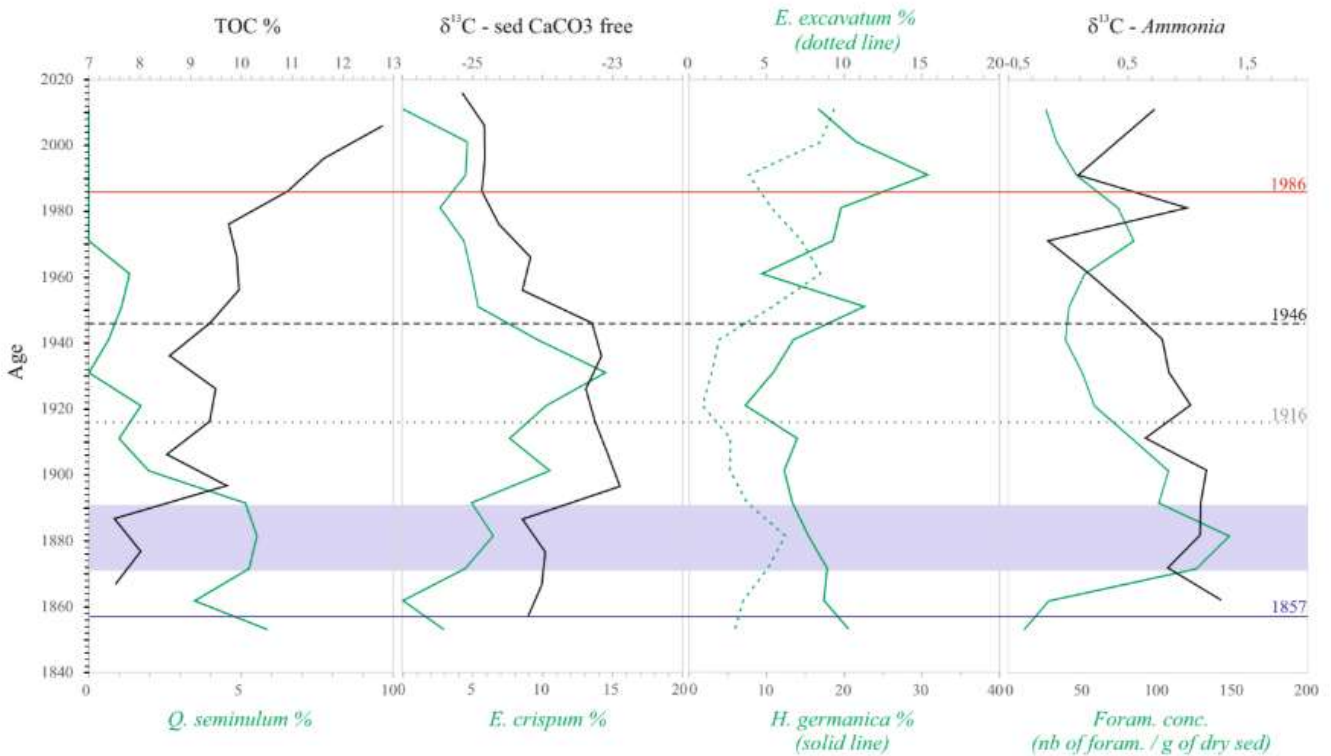


Fig. 11. Temporal evolution of multiple geochemical and biological variables in core IS-02 (Aulne Estuary), from 1857 to 2020. From left to right: total organic carbon content (TOC, in %), stable carbon isotope composition of organic matter ($\delta^{13}\text{C}$, decarbonated sediment), relative abundances of *Quinqueloculina seminulum*, *Elphidium crispum*, and *Haynesina germanica* (solid lines), *Elphidium excavatum* (dashed line), and $\delta^{13}\text{C}$ measured on *Ammonia* tests. The final panel shows total foraminiferal concentration (number of individuals per gram of dry sediment).

Figure 11 illustrates the temporal variation of selected benthic foraminiferal species alongside total organic carbon content (TOC), $\delta^{13}\text{C}$ values of carbonate-free sediment, $\delta^{13}\text{C}$ measured on *Ammonia* tests, and absolute foraminiferal concentrations.

Between 1857 and the early 20th century, a phase of high foraminiferal concentration (up to ~150 forams/g dry sediment) coincides with a gradual increase in *Elphidium crispum* and *Quinqueloculina seminulum*. This interval also corresponds to a slight rise in sedimentary $\delta^{13}\text{C}$, possibly reflecting better oxygenation or enhanced marine organic matter input.

From 1916 to 1946, a sharp decline in foraminiferal concentration is observed, accompanied by a relative peak in *E. excavatum* (dashed line) and *H. germanica* (solid line).

This transition is mirrored by a drop in $\delta^{13}\text{C}$ values in *Ammonia* tests, potentially indicating shifts in redox conditions or increased organic matter remineralization.

After 1986, foraminiferal concentrations remain low, possibly reflecting persistent environmental stress or eutrophication effects that may obscure signals of increased productivity.

It is important to note that *Elphidium excavatum* is capable of burrowing deeply into sediments, down to approximately 15 cm (reference to be added if necessary). This vertical bioturbation raises questions about the effective temporal resolution of the sampled intervals, particularly when each sample represents only 0.5 cm of sediment. In such cases, a single sample may contain both living individuals and older, reworked tests, potentially mixed by biological activity.

Moreover, since the sediment grain size distribution is often bimodal, using the D_{50} (median grain diameter) as a synthetic indicator may be misleading, as it does not capture the

full complexity of the particle size distribution. A combined interpretation of both dominant and minor modes is therefore preferable to more accurately characterize sedimentary dynamics.

Conclusion

The study conducted on core IS-02, retrieved from the Aulne estuary, is part of an interdisciplinary effort to reconstruct the socio-ecosystem dynamics of the Bay of Brest over the past two centuries. By integrating granulometric, geochemical, and benthic foraminiferal analyses, this work identified major environmental shifts linked to regional anthropogenic disturbances and natural estuarine evolution.

Results highlight a pronounced transition during the 1960s–1970s, coinciding with agricultural land consolidation (remembrement), marked by increased mean grain size, enhanced terrigenous input, and notable changes in benthic assemblage composition. The detection of heavy metal (Pb, Zn) peaks and shifts in $\delta^{13}\text{C}$ values further reflects the cumulative impacts of past mining activities and eutrophication processes.

This multiproxy approach confirms the relevance of benthic foraminifera as sensitive bioindicators of environmental stress, while also emphasizing limitations related to stratigraphic resolution, particularly due to bioturbation. The initial results from core IS-02 provide a valuable framework for comparison with other estuarine records, contributing to a more integrated and spatially contextualized understanding of recent environmental changes in the Bay of Brest.

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Appendices

Liste des espèces présentes dans la carotte IS-02	% max	Nb occurrences (/17 échantillons)	
<i>Ammonia gr. tepida</i> (Cushman, 1926)	35,9	17	Espèces dominantes
<i>Haynesina germanica</i> (Ehrenberg, 1840)	30,8	17	
<i>Elphidium aculeatum</i> (d'Orbigny, 1846)	28,1	17	
<i>Lobatula lobatula</i> (Walker & Jacob, 1798)	20,6	17	
<i>Elphidium crispum</i> (Linnaeus, 1758)	14,5	15	
<i>Elphidium excavatum</i> (Terquem, 1875)	9,4	17	Espèces communes
<i>Neoconorbina</i> spp.	5,9	14	
<i>Miliolinella subrotunda</i> (Montagu, 1803)	5,9	11	
<i>Quinqueloculina seminulum</i> (Linnaeus, 1758)	5,9	11	
<i>Elphidium margaritaceum</i> Cushman, 1930	4,6	16	
<i>Favulina hexagona</i> (Williamson, 1848)	4,3	16	
<i>Elphidium williamsoni</i> Haynes, 1973	4,2	16	
<i>Elphidium gerthi</i> van Voorthuysen, 1957	3,1	14	
<i>Fissurina</i> sp.	2,9	16	
<i>Lagena striata</i> (d'Orbigny, 1839)	2,9	14	
<i>Bolivina variabilis</i> (Williamson, 1858)	2,1	5	Espèces accessoires
<i>Bulimina marginata</i> d'Orbigny, 1826	1,3	8	
<i>Elphidium oceanense</i> (d'Orbigny in Fornasini, 1904)	1,0	8	
<i>Stainforthia fusiformis</i> (Williamson, 1858)	1,0	1	
<i>Bolivina spissa</i> Cushman, 1926	1,0	9	
<i>Quinqueloculina carinatastriata</i> (Wiesner, 1923)	0,9	4	
<i>Elphidium decipiens</i> (O.G.Costa, 1856)	0,9	4	
<i>Hyalinonettrion gracillimum</i> (Seguenza, 1862)	0,9	4	
<i>Globigerina</i> spp.	0,8	2	
<i>Robertinoides</i> sp.	0,6	4	
<i>Polymorphina</i> sp.	0,6	1	
<i>Nonion fabum</i> (Fichtel & Moll, 1798)	0,5	1	
<i>Uvigerina</i> sp.	0,5	2	
Indéterminés	0,4	2	
<i>Pyrgo</i> sp.	0,4	5	
<i>Bolivina spathulata</i> (Williamson, 1858)	0,4	1	
<i>Miliamina fusca</i> (Brady, 1870)	0,2	1	

Appendix 1 : List of Foraminiferal Species from Core IS-02

Sample	Prof (cm)	Pourcentages																							Nb espèces	Nb d'individus comptés												
		A. gr. tepida	H. germanica	E. aculeatum	E. crispum	E. excavatum	E. margaritaceum	E. marginatum	E. orbiculus	H. hexa	E. gemm	E. decipiens	E. oceanense	Neoconorbina spp.	L. lobatula	Q. seminulum	Q. subrotunda	K. subrotunda	Pyrgo sp.	B. spissa	B. spathulata	B. variabilis	Bulimina marginata	F. hexagona			Favulina sp.	L. striata	Uvigerina sp.	Hyalinonettrion gracillimum	Robertinoides sp.	Stainforthia fusiformis	Polymorphina sp.	Nonion fabum	Indéterminés	Globigerina spp.		
IS-02 (2-2.5)	2,25	25,0	10,7	20,1	-	9,4	2,1	4,2	-	3,1	-	1,0	-	5,2	-	-	1,0	-	-	-	-	2,1	-	1,0	-	-	-	-	-	-	-	-	-	-	-	14	96	
IS-02 (4-4.5)	4,25	18,5	21,5	28,2	4,6	8,5	4,6	2,3	-	-	-	0,8	1,5	7,7	-	-	-	-	-	-	-	-	-	-	1,5	0,8	0,8	-	-	-	-	-	-	-	0,8	15	130	
IS-02 (6-6.5)	6,25	19,9	30,8	23,7	4,5	3,8	1,3	1,9	-	1,3	-	-	0,6	7,7	-	-	-	-	-	-	-	1,3	-	0,6	1,3	-	-	-	-	-	-	-	-	-	0,6	16	150	
IS-02 (8-8.5)	8,25	30,8	19,8	21,8	2,7	5,3	4,3	2,3	-	0,7	-	0,3	0,7	8,3	-	-	-	0,3	0,7	-	0,3	0,7	1,0	1,0	1,0	1,0	-	-	-	-	-	-	-	-	0,3	20	301	
IS-02 (10-10.5)	10,25	24,9	18,6	23,5	4,8	7,2	3,8	1,4	-	1,2	0,3	0,6	1,4	6,1	-	-	0,3	-	-	-	-	-	-	0,9	2,0	2,6	0,6	-	-	-	-	-	-	-	0,3	19	345	
IS-02 (12-12.5)	12,25	33,5	9,4	20,1	4,8	8,5	1,3	2,2	-	1,3	-	0,4	1,3	6,7	1,3	-	-	-	0,8	-	1,8	1,3	1,3	1,8	1,3	1,3	-	-	-	-	-	-	0,4	-	20	224		
IS-02 (14-14.5)	14,25	31,2	22,0	12,4	5,4	6,4	4,3	0,5	-	0,5	-	-	2,2	8,5	1,1	-	-	-	0,5	-	-	-	0,5	4,3	1,6	0,5	-	-	-	-	-	0,5	-	-	0,5	18	180	
IS-02 (16-16.5)	16,25	28,2	13,5	27,6	9,6	1,9	3,2	1,3	-	1,9	0,6	0,6	1,3	4,5	0,6	-	-	-	-	-	-	-	-	2,6	2,6	-	-	-	-	-	-	-	-	-	0,6	16	156	
IS-02 (18-18.5)	18,25	31,2	10,9	23,9	14,5	1,4	0,7	2,2	-	1,4	-	0,7	-	9,4	-	-	0,7	-	-	-	-	-	-	0,7	1,4	0,7	-	-	-	-	-	-	-	-	-	0,7	15	138
IS-02 (20-20.5)	20,25	35,9	7,5	24,4	10,3	0,9	2,1	0,9	-	-	-	-	3,0	8,5	1,7	-	0,9	-	0,4	-	-	-	0,9	0,9	1,7	0,4	-	-	-	-	-	-	-	-	-	0,4	17	234
IS-02 (22-22.5)	22,25	31,8	14,0	20,6	7,6	2,7	4,3	2,0	-	0,3	0,3	-	3,0	8,0	1,0	-	0,3	0,3	1,0	-	-	-	0,7	1,7	0,7	-	-	-	-	-	-	-	-	-	-	0,3	19	301
IS-02 (24-24.5)	24,25	31,3	12,3	16,0	10,5	2,8	2,2	2,2	-	1,1	-	-	10,5	2,0	9,9	1,5	0,4	0,2	-	-	-	-	0,2	3,3	1,5	1,5	-	-	-	-	-	-	-	-	-	0,2	20	457
IS-02 (26-26.5)	26,25	31,3	13,3	20,1	4,9	3,7	3,7	1,9	-	1,2	-	-	1,4	6,3	6,1	0,6	0,9	-	0,5	-	-	-	-	1,2	1,4	1,6	0,6	-	-	-	-	-	-	-	0,2	21	428	
IS-02 (28-28.5)	28,25	25,2	15,4	18,6	6,5	6,2	4,3	3,0	-	1,2	-	0,1	2,7	2,7	5,5	0,4	2,7	0,3	-	-	-	-	0,1	1,6	1,9	1,3	-	-	-	-	-	-	0,1	-	22	742		
IS-02 (30-30.5)	30,25	28,3	17,8	16,4	4,5	5,1	2,8	1,8	0,2	1,2	-	-	2,4	8,3	5,3	0,6	1,8	0,4	0,6	0,4	0,2	0,2	1,0	0,2	0,2	0,2	0,2	-	-	-	-	-	-	-	-	0,2	25	494
IS-02 (32-32.5)	32,25	34,8	17,4	11,3	-	3,5	1,7	1,7	-	0,9	0,9	-	2,6	13,9	3,5	-	0,9	-	0,8	-	-	-	-	1,7	2,8	0,9	-	0,9	-	-	-	-	-	-	-	0,9	18	115
IS-02 (34-34.5)	34,25	17,8	20,9	11,8	2,9	2,9	-	-	-	-	-	-	5,9	20,8	6,9	-	5,9	-	-	-	-	-	-	-	2,9	2,9	-	-	-	-	-	-	-	-	-	1,2	34	

Appendix 2: Percentage Occurrence of Each Species

Species	Test	Ecological preferences	Sensitivity/pollution	Presence in the core
<i>Ammonia</i>	Hyaline	Euryhaline, tolerates wide variations in substrate (TOC, salinity), common on the continental shelf (Polodova 2008; Alve 1999)	Opportunistic species dominant in eutrophic areas with fluctuating salinity (Asghar 2016; Roozpeykar 2016)	Very frequent, dominant throughout the core
<i>Elphidium acculeatum</i>	Hyaline	Shallow coastal environments, muddy or sandy-mud substrate, moderate conditions (Murray 2006; Alve 1995)	Moderately tolerant species, common in unstable estuarine environments (Alve 1995)	Frequent to dominant in the middle section of the core (10–30 cm)
<i>Haynesina germanica</i>	Hyaline	Euryhaline species typical of shallow, muddy environments, estuaries rich in organic matter (Murray 2006; Alve 1995)	Highly tolerant, common in polluted or eutrophic zones, environmental stress bio-indicator (Alve 1995; Arminot 2004)	Very frequent, dominant between 10 and 30 cm with a peak at 28.5 cm; lower at both ends
<i>Lobatula lobatula</i>	Hyaline	Coarse substrate, well-oxygenated seabed, high hydrodynamic energy zones (Murray 2006; Jorissen et al. 2007)	Oxiphilic species, sensitive to eutrophication, disappears in strongly organic environments (Alve 1995)	Present at all levels, peaking at 24
<i>Elphidium crispum</i>	Hyaline	Coastal marine environment, fine to moderately coarse substrate, sometimes associated with macroalgae (Murray 2006)	Sensitive to eutrophication, oxiphilic species indicative of balanced marine conditions (Alve 1995)	Frequent between 10 and 30 cm, peaking at 24 and 28 cm
<i>Elphidium excavatum</i>	Hyaline	Shallow, muddy environments, tolerates variable salinity conditions (Murray 2006)	Relatively tolerant species, may colonize slightly disturbed environments (Alve 1995)	Present in almost all levels, peak at 28 cm
<i>Elphidium margaritaceum</i>	Hyaline	Shallow coastal environment, muddy to sandy-mud substrate, variable salinity (Murray 2006)	Moderately tolerant, present in disturbed estuarine environments (Alve 1995)	Present at all levels except 34 cm; peak at 28
<i>Quinqueloculina seminulum</i>	Porcelaneous	Shallow marine environment, high salinity, sandy to algal substrate (Murray 2006)	Sensitive to low salinity and eutrophication, indicator of marine influence (Alve 1995)	Abundant between 24 and 30 cm, maximum at 28 cm (41 individuals); absent in surface levels
<i>Elphidium willamsoni</i>	Hyaline	Estuarine environment, muddy substrate, variable salinity, typical of tolerant environments (Murray 2006)	Tolerant to eutrophic conditions and salinity variation (Alve 1995)	Present in most levels; peak at 28 cm, lower at base and top
<i>Discorbina</i>	Hyaline	Well-oxygenated environment, sandy-mud substrate, often associated with good water quality (Murray 2006)	Sensitive to eutrophication; indicator of stable marine environment (Alve 1995)	Rare to infrequent; isolated peak at 28 cm, absent in several levels
<i>Fissurina</i>	Agglutinated	Little specific information; observed in calm, organic-rich environments (Murray 2006)	Limited data, often associated with oxygen-poor environments	Poorly represented; isolated peak at 28 cm, present in almost all levels
<i>Favulina hexagona</i>	Agglutinated	Shallow to moderately deep marine environment, sandy-mud substrate, tolerates variable conditions (Murray 2006)	Moderately tolerant, sometimes associated with unstable or mesotrophic conditions (Alve 1995)	Present in most levels; maximum at 24 cm, moderate abundance elsewhere
<i>Criboelphidium gherli</i>	Hyaline	Muddy to sandy-mud moderately deep environment, often in estuarine context (Murray 2006)	Tolerant to moderately tolerant, common in low-oxygen estuarine environments (Alve 1995)	Poorly represented; present in most levels, maximum at 30 cm
<i>Miloinella subrotunda</i>	Porcelaneous	Shallow marine environment with relatively stable salinity, sandy-mud substrate (Murray 2006)	Sensitive to strong disturbances, indicator of stable conditions (Alve 1995)	Irregularly present; peak at 28.5 cm, absent in several levels
<i>Logena</i>	Hyaline	Shallow to moderately deep marine environments, sandy-mud or organic-rich substrate (Murray 2006)	Relatively sensitive species, prefers stable oxygenated conditions (Jorissen et al. 2007)	Poorly represented but regular; present in almost all levels, peak at 28.5 cm
<i>Bohivina beyrichi</i>	Hyaline	Muddy environment, often associated with fine sedimentation and low oxygenation (Jorissen et al. 2007)	Tolerates oxygen-poor conditions; indicator of high organic matter (Alve 1995)	Rare; present in a few levels only, up to 4

<i>Bolivina spissa</i>	Hyaline	Muddy environment, moderate to high organic deposition, tolerates poorly oxygenated environments (Jorissen et al. 2007)	Indicator of organic load; tolerant to suboxic conditions (Alve 1995)	Present in many levels but always in low abundance (max. 3 individuals)
<i>Bulimina</i>	Hyaline	Muddy substrate, tolerates low oxygen and high organic load (Jorissen et al. 2007)	Indicator of oxic stress; tolerant species often linked to eutrophication (Alve 1995)	Irregularly present; up to 3 individuals, concentrated near the base
<i>Elphidium oceanense</i>	Hyaline	Muddy coastal environment, prefers relatively stable marine salinity (Murray 2006)	Low tolerance to eutrophication; indicator of stable marine conditions (Alve 1995)	Very rare; found in few levels, max 2
<i>Quinqueloculina carinatastriata</i>	Porcelaneous	Shallow environment with stable salinity, sandy or sandy-mud substrate (Murray 2006)	Strictly marine species, low tolerance to estuarine disturbances (Alve 1995)	Rare; found only in upper levels (≤ 24 cm), max 4 individuals
<i>Elphidium Decipiens</i>	Hyaline	Coastal marine species, prefers shallow sandy-mud bottoms (Murray 2006)	Rather sensitive, rarely reported in strongly disturbed environments (Alve 1995)	Very rare; occasionally observed in 4 levels (1 individual max)
<i>Pyrgo</i>	Porcelané	Well-oxygenated marine environment, soft or mixed substrate, stable marine salinity (Murray 2006)	Sensitive species, indicator of good ecological quality (Alve 1995)	Rare; observed in 6 levels, with a maximum of 2 individuals
<i>Hyalinonetricia gracillimum</i>	Hyaline	Poorly documented benthic marine species, reported in muddy and well-oxygenated environments (Murray 2006)	Estimated moderate sensitivity; rarely reported in stressed contexts (Murray 2006)	Very rare; observed in 4 levels; always 1
<i>Robertinoides</i>	Hyaline	Calm muddy environments, sometimes associated with high organic content (limited literature, cf. Murray 2006)	Low to moderate tolerance; rarely observed in polluted contexts	Very rare; found in 4 levels, always 1
<i>Stainforcia fusiformis</i>	Hyaline	Suboxic to anoxic environment, often muddy; known for tolerance to stressed conditions (Alve 1995)	Very tolerant, indicator of deoxygenation or organic enrichment (Murray 2006)	Extremely rare; observed only once (1 individual)
<i>Globigerina</i>	Hyaline	Planktonic species living in open water, indicator of oceanic influence (Murray 2006)	Not concerned by benthic conditions; transported or secondarily deposited (Murray 2006)	Very rare; observed in only two levels (1 individual each)
<i>Uvigerina</i>	Hyaline	Muddy marine environment, often suboxic, sometimes indicative of eutrophication (Murray 2006)	Tolerant to organic load, but absent from most stressed zones (Jorissen et al. 2007)	Very rare; found in 3 levels with 1 to 2
<i>Polymorphina</i>	Porcelaneous	Coarse sandy to sandy-mud substrate, often associated with well-oxygenated waters (Murray 2006)	Sensitive marine species, indicator of good ecological status (Jorissen et al. 2007)	Extremely rare; observed only once in the entire core (1 individual)
<i>Nanion fabum</i>	Hyaline	Muddy, well-oxygenated environment, stable marine salinity (Murray 2006)	Sensitive to low oxygen levels, indicator of good ecological status (Alve 1995)	Very rare; observed in only 2 levels with 1 individual each
<i>Bolivina spathulata</i>	Hyaline	Muddy, suboxic to anoxic environment, often associated with high organic content (Jorissen et al. 2007)	Tolerant, indicator of oxic stress or high organic load (Alve 1995)	Very rare; observed in only 1 level with 2 individuals
<i>Millammina fusca</i>	Porcelané	Estuaries and salt marshes, muddy environments with very low salinity, high tolerance (Murray 2006)	Highly tolerant; classic bioindicator of heavily stressed environments (Alve 1995)	Extremely rare; observed only once (1 individual)
<i>Ind.</i>	—	—	—	3 individuals

Appendix 3: Ecological Characteristics of the Main Benthic Foraminifera Identified in Core IS-02

	Prof (cm)	Age cal (model)	MODE dominant (μm)	MODE Mineur (μm)	d 10 % (μm)	d 50 % (μm)	d 90 % (μm)	Clay to Fine silt % < 8 μm	Coarse and medium silt % 8-32 μm	Very coarse silt % 32-63 μm	Fine and very fine sand % 63 μm - 250 μm	Medium sand to coarse sand % 250 μm - 2 mm
IS-02 1-2	1,5	2016	37,7		5,7	28,2	97,2	15,6	38,4	25,0	20,16	0,90
IS-02 3-4	3,5	2006	53,3		5,4	31,8	123,0	16,7	32,7	22,6	25,04	2,82
IS-02 5-6	5,5	1996	67,1		5,8	37,8	133,6	14,7	30,0	21,7	32,04	1,56
IS-02 7-8	7,5	1986	47,5		4,9	26,5	98,7	19,2	35,8	22,5	22,07	0,37
IS-02 9-10	9,5	1976	84,5	13,4	5,2	34,0	141,0	17,7	30,5	16,9	33,63	1,23
IS-02 11-12	11,5	1966	84,5	13,4	5,5	39,0	150,2	16,2	28,9	17,8	35,08	2,09
IS-02 13-14	13,5	1966	9,5		4,0	14,9	76,3	28,7	41,7	15,7	13,86	0,10
IS-02 15-16	15,5	1946	94,8	15,0	6,2	53,1	165,9	13,3	24,0	17,9	41,61	3,14
IS-02 17-18	17,5	1936	11,9	75,3	4,7	21,6	127,2	21,6	37,2	15,2	24,13	1,89
IS-02 19-20	19,5	1926	10,6	67,1	4,3	18,1	107,4	24,7	38,7	15,0	20,98	0,55
IS-02 21-22	21,5	1916	13,4	94,8	4,8	22,8	135,3	20,8	36,6	14,8	26,26	1,48
IS-02 23-24	23,5	1906	11,9	106,4	4,6	20,8	137,1	22,6	37,1	13,5	25,33	1,48
IS-02 25-26	25,5	1896	13,4		4,7	20,6	130,5	21,7	39,1	15,0	21,68	2,43
IS-02 27-28	27,5	1886	106,4	11,9	5,6	46,9	181,3	16,0	26,6	14,1	38,46	4,84
IS-02 29-30	29,5	1876	11,9		4,8	21,8	138,0	21,4	37,6	15,4	22,21	3,34
IS-02 31-32	31,5	1867	69,8		6,0	36,4	140,5	14,1	31,4	21,7	30,67	2,14
IS-02 33-34	35,5	1857	42,3		5,3	28,9	119,7	17,1	35,3	21,5	24,80	1,30

Appendix 4 : Grain Size Results – Dominant Modes and Textural Classes