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EVOLUTION OF SEDIMENTARY DEPOSITION ENVIRONMENTS FROM THE IRON AGE TO THE PRESENT DAY IN CUL-DE-LOUP BAY (NORMANDY, FRANCE): AN ILLUSTRATION OF INTERTIDAL ENVIRONMENT VULNERABILITY UNDER SIGNIFICANT HUMAN IMPACT

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Abstract: Located in the northeast of the Cotentin Peninsula (Normandy, France), Cul-de-Loup Bay is currently undergoing significant hydro-sedimentary changes, marked by silting and coastal erosion. To better understand the future evolution of this back-bay environment, a study was conducted to analyze sedimentary deposits dating back to the Iron Age (2750 BP). A total of 11 surface cores were collected for grain-size, and geochemical analyses, and radiocarbon (¹⁴C) dating. Nine sedimentary facies grouped into five chronostratigraphic units have been distinguished. These sedimentary archives have recorded the impact of anthropogenic infrastructures on sediment dynamics, leading to a sudden retreat of depositional environments. Currently, sea level rise is exacerbating these transformations, enhancing the contrast between internal areas subject to rapid silting and more open coasts undergoing accelerated retreat, thereby revealing the vulnerability of such embayment.

Keywords: Coastal Environment, Paleoenvironment, Sea level rise, Elementary geochemistry, Organic matter

1 INTRODUCTION: THE STUDY AREA AND OBJECTIVE PRESENTATION

Cul-de-Loup Bay (CLB) is located at the northeastern tip of the Cotentin Peninsula (Normandy, France). It is a "back-bay" type environment (Dubois, 2000) covering an area of 3.5 km² and is semi-open to the Baie de Seine (Fig. 1a). The coastline was artificially modified early on with the construction of the Hougue dike in the 17th century, which was built on a former tombolo linking the town of Saint-Vaast-la-Hougue to a granitic spur to the east (Hougue) (Fig. 1b). This seawall protects the bay from dominant northwesterly swells. However, swells from the east-southeast (30% of the year) reach the area. The CLB is an intertidal bay, subject to macrotidal dynamics (maximum tidal range 7 m). The northeastern part of the bay, sheltered behind the Hougue dyke, is characterized by mudflats, evolving toward salt marshes. The rest of the bay, in the center and SE area is occupied by an intertidal sandy platform getting progressively muddier toward the east (i.e., the dyke). CLB is a socio-economic (oyster farming, fish farming, shellfish gathering, tourism, and urban development) and ecological (ZNIEFF 1 and 2, Natura 2000) area of interest. For several years, the bay has been undergoing significant hydro-sedimentary changes, including silting in the back-bay area and coastal erosion (destruction of anthropogenic structures, formation of micro-erosion cliffs, and retreat of sediment ridges). This article is part of the PROTEC project ("D'une alerte DCE à un Projet de Territoire: Anse du Cul-de-Loup, CNAM-Intechmer/AESN"), which aims to understand future changes in the bay by reconstructing paleo-environments and the chronostratigraphic framework. Additionally, this project contributes to the Holocene study of coastal systems in the English Channel (Tessier et al., 2022). As part of the research, 11 surface cores were collected, described, and analyzed in the laboratory. Grain-size, elemental geochemical, and radiocarbon (¹⁴C) dating results helped identify nine sedimentary facies grouped into five chronostratigraphic units, which serve as archives of depositional environment changes. This work highlights both the impact of human activity and sea level rise while underscoring the fragility of back-bay intertidal zones.

2 MATERIALS AND METHODS

Manual interface coring was conducted at eleven stations distributed throughout the study area (Fig. 1b): seven in the open bay (stations 1, 2, 4, 5, 6, 7), two in the inner salt marsh at the foot of the dyke (stations 8, 9), and two on an erosive microcliff incising a lower salt marsh (one at the top, station 10, and one at the base, station 11). After opening the cores, the 'Archive' half-section was photographed and used for X-ray

imaging, which was performed using Ifremer's CT scanner. The 'Work' half-sections were described in detail, with a focus on sediment color, visible granulometry, bioturbation, and apparent laminations, before being photographed. A total of 177 samples, collected at 5 cm intervals, were analyzed for grain-size using a laser diffraction particle size analyzer (Horiba LA-960, 0.011–2000 μm) and for elemental composition using X-ray fluorescence spectrometry (Xsort SPECTRO, Ametek). The results were calibrated using the "Enviro-H" method, which is tailored for rocks and was adjusted through ICP-OES/MS analysis of 60 marine samples (Baux et al., 2019). Twenty-three elements were quantified, ranging from aluminum (the lightest element) to uranium (the heaviest). For this study, two elements were selected: potassium (K), an indicator of terrigenous phyllosilicates (Reynolds, 1963), and organic bromine (BrOrg), a marker of marine organic matter after the removal of interstitial bromides (Mayer et al., 1981). Additionally, 0.05 g of each subsample was used to measure total organic carbon (TOC) via infrared spectrometry (LECO CS 744) after decarbonation with phosphoric acid (H_3PO_4). Eleven radiocarbon (^{14}C) dates were obtained using the AMS method on bulk benthic foraminifera and whole shells (bivalves or gastropods) at the IsotopTech Zrt laboratory (Hungary). Radiocarbon ages were calibrated using the MARINE20 method (Heaton et al., 2020), with the marine reservoir effect measured by Tisnérat-Laborde et al. (2010), estimated at 640 ± 50 years around the island of Tatihou. For cores 10A and 11B, the MARINE20 calibration could not be applied because the sediments were too recent; only the reservoir age correction was directly applied to the raw results. To compensate for the lack of dating in the most recent sediments, accumulation rates were estimated based on the transition level identified in multiple cores. This level is dated between 1972 and 1980, as it contains plastic fragments and coincides with a period of intense anthropogenic activity visible in historical aerial imagery. Since the cores were collected in 2023, sediment accumulation rates were calculated using both 1972 and 1980 as reference years, and the average of these values was retained. In parallel, a cartographic analysis was conducted using archives of aerial photographs (1920–2011) provided by the IGN (Institut National Géographique, <https://remonterletemps.ign.fr>) to highlight historical changes in the study area. This analysis included both anthropogenic structures (oyster farms, dikes) and natural features (Pebble ridge, channels and limit of the salt marsh). Georeferencing accuracy was verified using geological substrate control points.

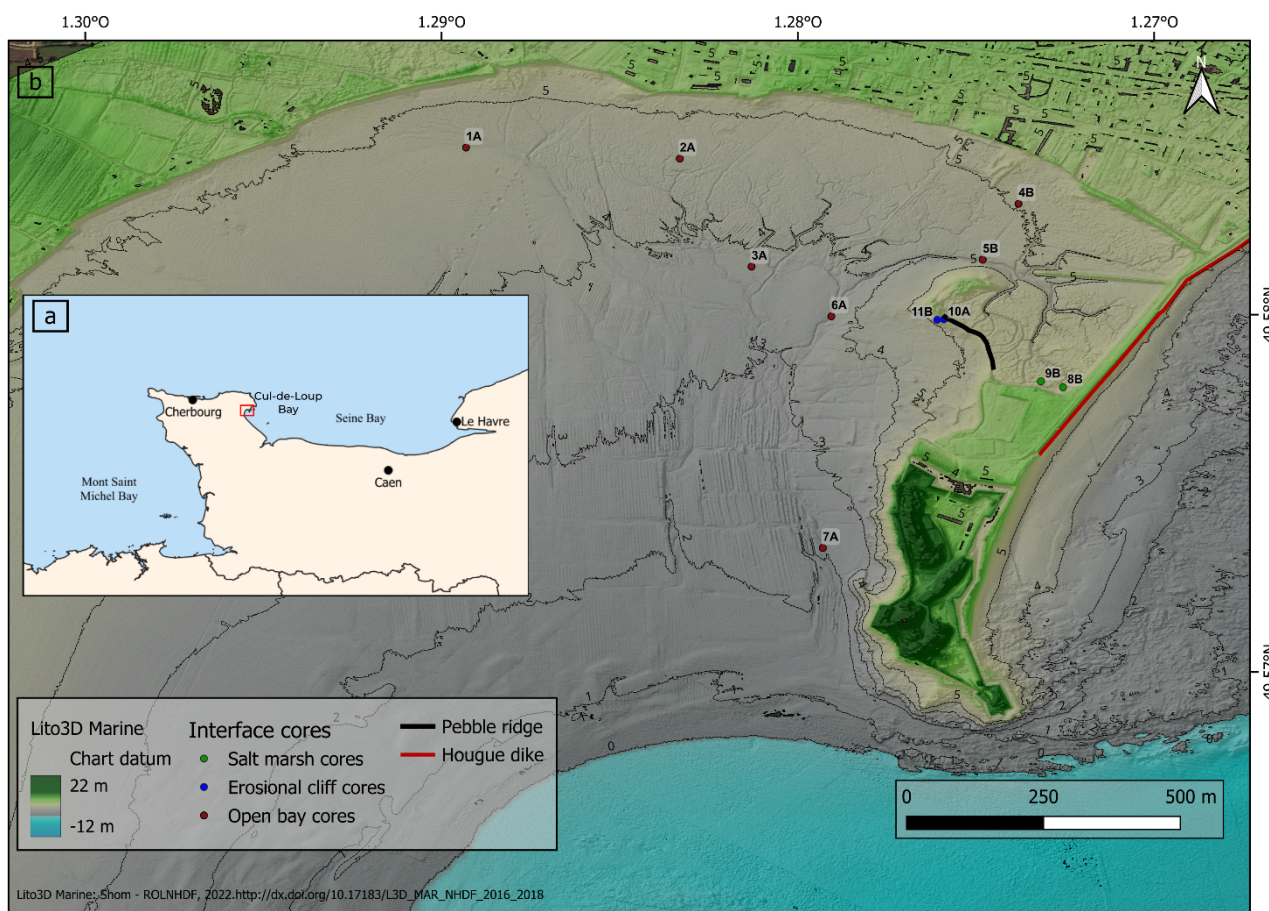


Figure 1. (a) Geographic location of Cul-de-Loup Bay. (b) High-resolution bathymetric and topographic map of the study area. The map also displays sediment cores and geomorphological features include the pebble ridge and the Hougue dike.

3 RESULTS AND DISCUSSION

3.1 Sedimentary facies

Based on grain-sizes, colors (referenced using the Munsell color chart, Nickerson, 1940), bedding, and biological indicators (roots, burrows, shells), confirmed on X-ray imaging, 9 sedimentary facies were identified (A, B, C, D, E, E', F, G, T) (Fig. 2a). The results of particulate geochemistry further allowed the differentiation of depositional environments (Figs. 2b and 2c).

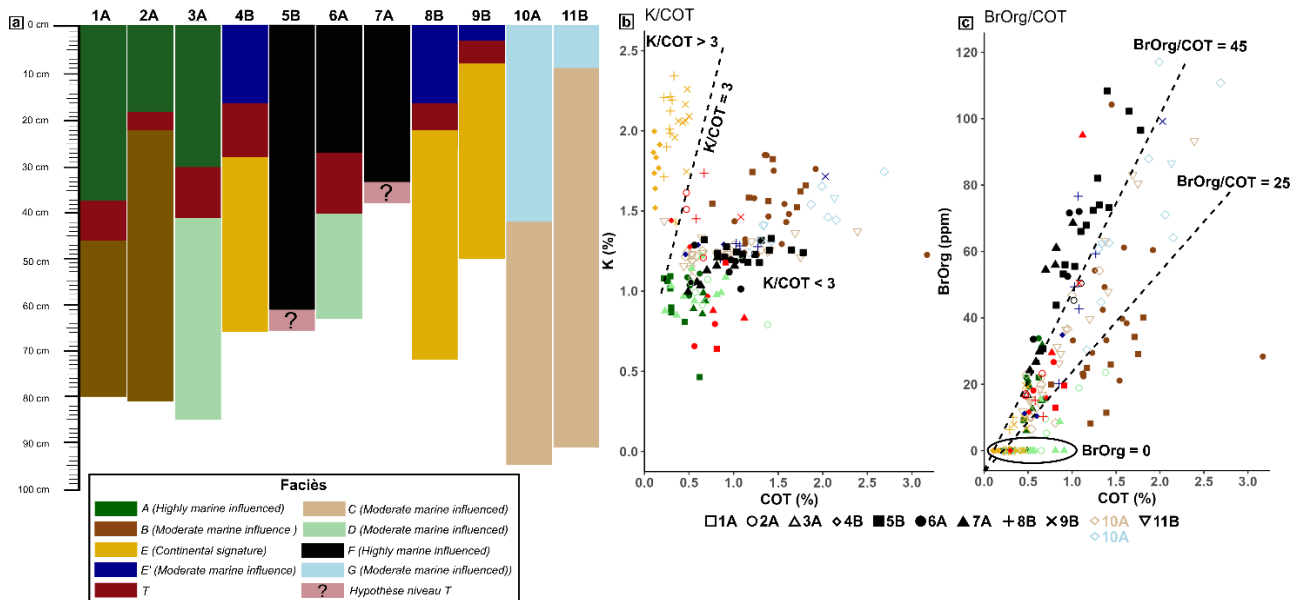


Figure 2. (a) Synthetic log of sedimentary facies organisation. Variations in TOC concentrations as a function of or K (b) or BrOrg (c). On b, colors refer to the sedimentary facies on a, and symbol shapes to core numbers (Fig. 1a for location).

The K/COT ratio defines the marine vs continental signature: K/COT less than 3 signs marine sediment, more than 3, continental sediment. The BrOrg/COT ratio characterizes the degree of marine influence in a transitional “marine to continental” depositional environments such as estuaries or embayments like the CLB. A ratio greater than 45 characterizes maximum marine influence (i.e., the external area), a ratio between 25 and 45 corresponds to intermediate marine influence, and a ratio lower than 25 indicates minimal (moderate) marine influence (i.e. the internal area). However, the BrOrg/COT ratio has limitations, as BrOrg and COT are concentrated in fine-grained fractions, and thus absent in coarser fractions (from sands onward) that are usually dominant in the external marine-dominated areas.

The sedimentary facies T is present in 7 cores over 11 (Fig. 2a). It is characterized by very coarse-grained bioclastic and lithoclastic particles, as well as plastic waste, and by an erosive base. This facies is probably present as well at the base of cores 5B and 7A, characterized by gravel layers as revealed by X-ray images.

The upper sections of cores 1A, 2A, and 3A (Fig. 2a) are characterized by facies A. It consists of sandy-silty sediments enriched with shell debris and lacking visible structures in X-ray images. The absence of fine-grained sediments, and thus of low BrOrg concentration, limits the assessment of the degree of marine influence. However, the four samples containing BrOrg are at the BrOrg/COT = 45 threshold (Fig. 2c). They correspond to sandy deposits in a highly marine-influenced outer environment. In these same cores, two distinct facies were identified below facies T (Fig. 2a). Facies B, in core 1A and 2A consists of silty-sandy-silty sediments with distinct laminations. Although the K/COT ratio (<3) confirms a marine signature of this facies, the BrOrg/COT ratio suggests moderate marine influence (<25) (Fig. 2b and 2c). Facies B signs deposition in a low-energy marine environment (internal areas). This interpretation is corroborated by binocular magnification observations, which revealed an abundance of wood fragments and agglutinated foraminifera, particularly the species *Trochammina inflata* (Montagu, 1808), typical of vegetated salt marsh environments (Rodriguez-Lazaro et al., 2013). Facies D, found at the base of core 3A (Fig. 2a), has a very similar sandy-silty grain-size than the overlying facies A. It is enriched in shells and exhibits numerous laminations identified by X-ray imaging, similar to facies B. Geochemical results are similar to those described for facies B (K/COT <3, BrOrg/COT <25). Facies D is thus non-continental and was deposited in a moderately marine-influenced environment.

At the top of cores 4B, 8B, and 9B, facies E' (Fig. 2a) consists of silty sediments significantly disturbed by the presence of roots. The marine character of this sediment is confirmed by a K/COT ratio lower than 3 (Fig. 1b), while the BrOrg/COT ratio, ranging from 25 to 45 (Fig. 2c), suggests an intermediate degree of marine

influence. At the base of these cores, facies E is distinguished by its fine-grained, silty texture and ochre color. Geochemical analyses indicate a strictly continental signature ($K/COT > 3$, Fig. 2b) with very low values in COT and BrOrg. It is interpreted as loessic deposits, primarily formed during periglacial periods (Giles et al., 2017).

Facies F, identified at the top of cores 5B, 6A, and 7B (Fig. 2a), is characterized by sandy-silty grain-size, and bioturbation. The marine signature of facies F is confirmed by geochemical data. The K/COT ratio is lower than 3 (Fig. 2b), and the BrOrg/COT ratio is greater than 45, indicating a strong marine influence (Fig. 2c) featuring external (outer) environments.

Cores 10A and 11B feature facies G at their top and facies C at their base (Fig. 2a). Facies G exhibits a tri-modal grain-size distribution and is heavily bioturbated by roots and crab burrows. The sediment is silty-sandy, but root implantation generates a medium sand fraction. Facies C is characterized by a sandy-silty texture and is marked by numerous laminations. Both facies exhibit similar geochemical ratios. The K/COT ratio is less than 3 (Fig. 2b), highlighting the marine signature, while the BrOrg/COT ratio varies between 25 and 45, indicating an intermediate degree of marine influence (Fig. 2c). Binocular magnification observations revealed the presence of small marine gastropods and bivalves.

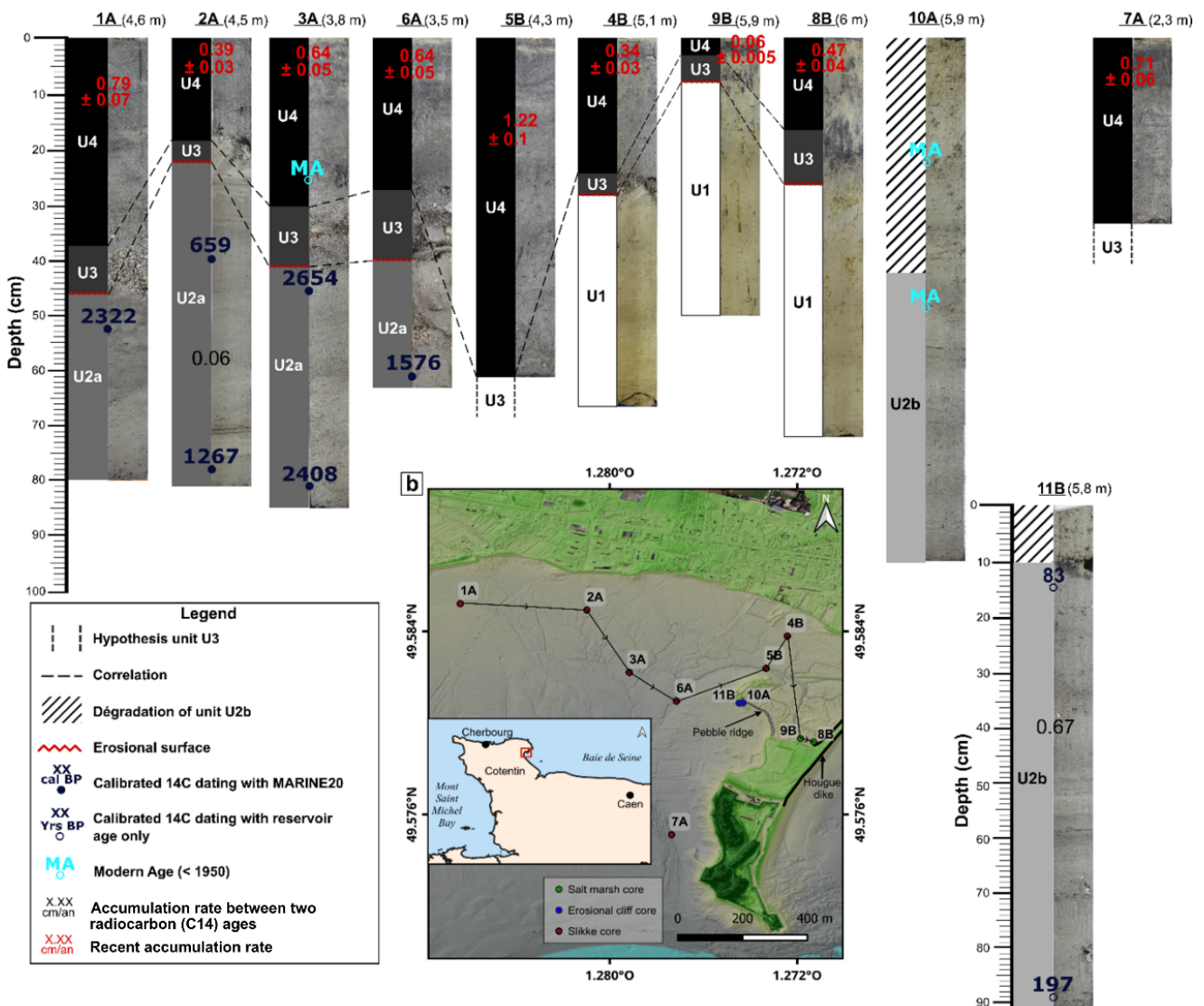


Figure 3. (a) Synthetic log of sedimentary units and photographs. The sampling altitude (marine elevation) of the cores is indicated next to the name.

3.2 Chronostratigraphic units

Five main chronostratigraphic units (from oldest to most recent: U1, U2a, U2b, U3, and U4) have been distinguished on the basis of the combined analysis of photographs and X-ray radiographs, grain-size, and geochemistry data, as well as information on age and accumulation rates. U1 is characterized by facies E, U2a includes facies B and D, U2b is defined by facies C, and U3 corresponds to facies T. Finally, U4

encompasses all surface facies (A, E', and F), except for facies G, which represents the advanced degradation of facies C by current fauna (crab burrows and roots).

Unit U1 (Fig. 3a) is interpreted as loess deposits of periglacial origin, making it the oldest sediment identified in the bay. The absence of datable organic material for radiocarbon dating has prevented a precise determination of its age. An optically stimulated luminescence (OSL) dating (Cordier, 2010) is underway at the CIRAM laboratory on samples collected from a depth of 65 cm in core 8B. Unit U1 is primarily located in the most internal areas of the CDL (Fig. 3b), where root traces suggest more recent reworking during the development of the vegetated salt marsh. Unit U2a corresponds to a depositional environment of sandy-clayey intertidal flat (sand) to salt marsh type (mud), intersected by tidal channels with sandy grain size. Age data in unit U2a range from the beginning of the Iron Age, here 2650 BP, to 659 BP. The west/east profile described by cores 1A, 2A, 3A, and 6A helps to better understand the paleogeography of this environment. In the western part (Fig. 3b), all analyses and the low sediment accumulation rate (0.06 cm/year) recorded from core 2A describe a salt marsh environment with weak marine incursions (only during the highest spring tides). The eastern part of the profile (center of the bay) has similar geochemical characteristics (internal environment) but with coarser grain-size and likely higher sedimentation rate, as indicated by the radiocarbon age in core 3A. These cores are characteristic of an upper tidal flat environment, less vegetated than the salt marsh, and submerged during spring tides. Sedimentation rate is higher and channel migration is rapid (alternation of sand and mud).

Unit U2b is more recent, but the uncalibrated dates do not provide an absolute age, so they are used here for informational purposes. They indicate an age after 1950 at the top of core 10A and 197 to 83 years BP from the base to the top of core 11B (Fig. 3a). A diachronic analysis of aerial images (1940 to 2023) reveals that the erosion of the microcliff sampled by cores 10A and 11B began between the 1970s and 1980s, concomitantly to the landward migration of a pebble ridge making a ling of tombolo (Fig. 3b). By 1990, the tombolo reached the present location of cores 10A and 11B. Radiocarbon dating obtained from core 11B shows a sedimentation rate comparable to the present one, estimated at 0.64 cm/year (Figure 3a). Unit U2b thus corresponds to a salt marsh environment subject to a more pronounced marine influence than the older salt marshes located at the bottom of the bay (U2a) and that develop behind the ridge.

Unit U3 is characterized by the very coarse-grained facies T. Its development is associated to an intensification of anthropogenic activities in the cove. This hypothesis is supported by (1) the presence of plastic waste collected from this level, dated by packaging typology to the early 1980s, and (2) the diachronic analysis of historical aerial images showing an intensification of oyster farming activities between 1970 and 1980 (from 0.07 km² to 0.7 km²). U3 thus formed in a context marked by the expansion of oyster farming areas, the reclamation of the internal salt marshes, and the construction of dikes.

Unit U4 is related to the present-day sedimentation and is characterized by very variable accumulation rates, reaching up to 1.22 cm/year close to the channels and decreasing significantly in the internal areas of the bay (Fig. 3a) (0.06 cm/year). Sedimentation of U4 has followed that of U3 since the 1980s. According to a west-east transect, the environments evolve from an external sandy to an intermediate sandy-clayey intertidal flat, both strongly influenced by marine dynamics. Finally, to the east, a vegetated internal salt marsh sheltered back to a tombolo develops. This environment is subject to daily tidal fluctuations in the channelized parts, the higher vegetated areas being rarely submerged (Fig. 3b).

3.3 Evolution of depositional environments

The overall results allowed for the reconstruction of the depositional environments before and after U3, which corresponds to a sudden change and reconfiguration of the environments in the bay (Fig. 4). Currently, the western part of the bay is characterized by a sandy platform fed by marine sediments due to a combined action of littoral drift and tidal currents (flood tide). This dynamic allows the intrusion of sandy sediments into the bay and the establishment of a sandy-muddy gradient from west to east, until the dissipation of currents and the formation of a mudflat typical of a "bay bottom" environment. It also extends from north to south along the eastern coastline. The most internal sector (northeast), particularly well protected due to the presence of a tombolo and a dike (constructed in 1973) is characterized by mudflat and densely vegetated salt marsh (Fig. 4a). The geographical distribution of pre-U3 environments (from the Iron Age, around 2650 cal BP and 1970-1980) shows the same arrangement (sandy tidal flat, upper tidal flat, and then salt marsh from west to east). However, the extent of the sandy intertidal zone was more restricted than it is now; it did not extend as far into the bay and at the same time the mudflat was not limited only to the eastern part but extended westward, occupying a large portion of the bay. The salt marshes were also much more widespread, covering the entire bay bottom and extending into the eastern part (Fig. 4b). This configuration reflects depositional environments with lower hydrodynamic conditions than present-day ones.

The development of anthropogenic activities, marked by U3, deeply impacted the sedimentary dynamics of the bay and led to a reconfiguration of the depositional environments. The gravel and pebbles found in the cores collected to the east in the bay bottom, are attributed to human paving, which allowed access to the

oyster farms in the muddy flat. It is assumed that this unit is present throughout the bay. The eastward displacement of high energy environments is linked to (1) the establishment of oyster farming parks, now occupying the center of the bay, and (2) a narrow access path to the inner bay bottom. This passage accelerates water masses (tidal currents and littoral drift), promoting the penetration of currents into the bay. This evolution leads to an increase of sediment deposition in the internal areas (1.22 cm/year), and a retreat of gravel ridge and of the sandflat-mudflat limit inducing the erosion of underlying sediments. The recent acceleration of the gravel ridge retreat (from 0.6 m/year to 1.2 m/year between 2000 and 2020) is, however, associated with the acceleration of the sea level rise (from 3 mm/year to 5 mm/year between 2000 and 2020 (IPCC, 2021)).

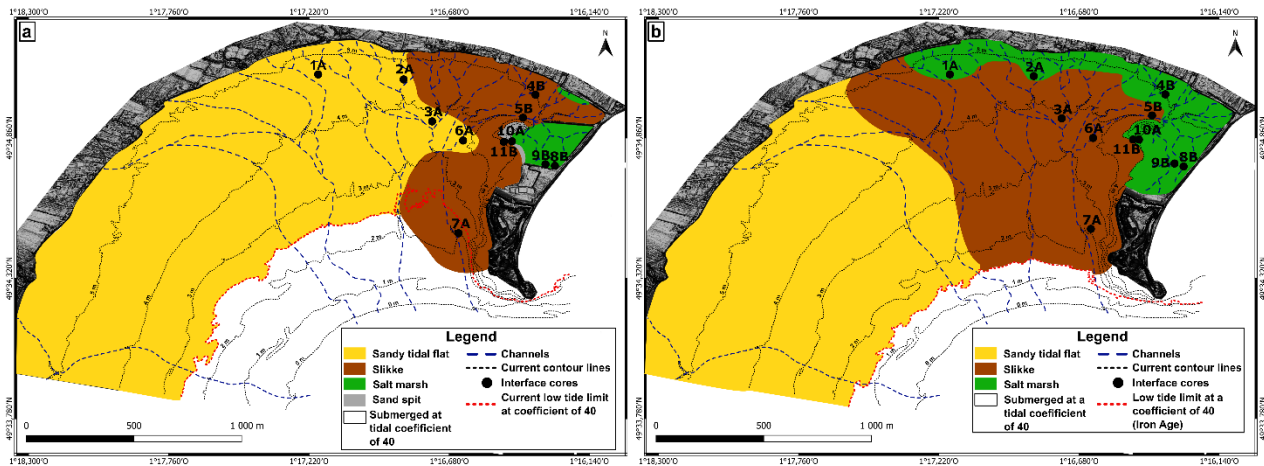


Figure 4. Reconstruction of depositional environments: (a) present-day and (b) during the Iron Age.

4 CONCLUSION

This study highlights the sedimentary and morphological transformations that have occurred in Cul-de-Loup Bay since the Iron Age, in response to significant human influence combined with sea level rise. Human activities, such as the intensification of oyster farming and the construction of dikes, have altered hydrodynamics, depositional environments, and morphologies. The retreat of the pebble ridge by reducing back-bay environments and diminishing its role as a natural barrier, exposes the vegetated salt marshes to increased erosion. Sea level rise reinforces the recently established configuration by intensifying the erosion of exposed areas. In calmer areas, sea level rise promotes sediment infilling by creating new accommodation space, which favors sediment accumulation from eroded sectors. Thus, it acts as a key factor in the reorganization of depositional environments. These disturbances exacerbate the vulnerability of back-bay environments to future changes.

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6 REFERENCES

- Baux, N., Murat, A., Faivre, Q., Lesourd, S., Poizot, E., Méar, Y., Brasselet, S., Dauvin, J.-C., 2019. Sediment dynamic equilibrium, a key for assessing a coastal anthropogenic disturbance using geochemical tracers: Application to the eastern part of the Bay of Seine. *Continental Shelf Research*, 175, 87–98.
- Cordier, S., 2010. Optically stimulated luminescence dating: procedures and applications to geomorphological research in France. *Géomorphologie : relief, processus, environnement*, 16, 21–40.
- Dalrymple, R. W., Zaitlin, B. A., Boyd, R., 1992. Estuarine facies models; conceptual basis and stratigraphic implications. *Journal of Sedimentary Research*, 62, 1130–1146.
- Giles, D.P., Griffiths, J.S., Evans, D.J.A., Murton, J.B., 2017. Chapter 3 Geomorphological framework: glacial and periglacial sediments, structures and landforms. Geological Society London, Engineering Geology Special Publications, 28, 59–368.
- Heaton, T.J. et al., 2020. Marine20—The Marine Radiocarbon Age Calibration Curve (0–55,000 cal BP). *Radiocarbon*, 62, 779–820.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Mayer, L.M., Macko, S.A., Mook, W.H., Murray, S., 1981. The distribution of bromine in coastal sediments and its use as a source indicator for organic matter: *Organic Geochemistry*, 3, 37–42.

Nickerson, D., 1940. History of the Munsell Color System and Its Scientific Application. *Journal of the Optical Society of America*, 30, 575-586.

Pinot, J-P., 1998. La gestion du littoral. *Géographie physique et Quaternaire*. Institut Océanographique, Paris, 759 p.

Reynolds, R.C., 1963. Potassium-rubidium ratios and polymorphism in illites and microclines from the clay size fractions of Proterozoic carbonate rocks. *Geochimica et Cosmochimica Acta*, 27, 1097–1112.

Rodriguez-Lazaro, J., Pascual, A., García, B.M., 2013. Recent benthic foraminifers as indicators of the sedimentary dynamics of the Tina Mayor and Tina Menor estuaries (S Bay of Biscay, N Spain). *Journal of Marine Systems*, 109–110, S213-S232.

Tessier, B., Reynaud, J. Y., Trentesaux, A., Le Bot, S., Grand, E. G., Gregoire, G., Méar, Y., 2022. Evolution of sediment wedges along the French coasts of the English Channel, a synthesis. *Tidalites 2022 International Congress Abstracts*.

Tisnérat-Laborde, N., Paterne, M., Métivier, B., Arnold, M., Yiou, P., Blamart, D., Raynaud, S., 2010. Variability of the northeast Atlantic sea surface $\Delta^{14}\text{C}$ and marine reservoir age and the North Atlantic Oscillation (NAO). *Quaternary Science Reviews*, 29, 2633–2646.