

# CARBONATE SOURCES AND DYNAMICS IN COASTAL ENVIRONMENTS: APPLICATION OFF THE COAST OF SAINT-VALÉRY-EN-CAUX (SEINE-MARITIME)

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**Abstract**: The Seine-Maritime coastline, shaped by constantly eroding Mesozoic chalk cliffs, experiences significant and poorly understood sandy siltation, particularly to the east of Saint-Valéry-en-Caux. To better determine the origin of this siltation and to follow the sedimentary dynamics, 45 surface sediment samples over a 10 km<sup>2</sup> area off the coast of Saint-Valéry-en-Caux were collected. Elemental chemical analyses (Ca, Sr, Si, BrOrg) were carried out: (i) on the bulk sediment, and (ii) on separate fractions. The GSTA (Geochemical Sediment Trend Analysis) method was applied to the bulk sediment, while the COVA (COmposition Variability Analysis) method was used for separate fractions. Carbonates produced in situ and likely to be fragmented during transport are excellent indicators of local dynamics. Their stock dynamics were monitored using an innovative approach (PASTA: PArticulate Stock Trend Analysis). The result is a complete picture of sediment dynamics. Three zones can be distinguished: (i) a steeply sloping western zone, in dynamic swell/tide equilibrium, where shells make little cross-shore transport towards the coast, (ii) a gently sloping eastern zone, also in dynamic swell/tide equilibrium, where shells and quartz migrate coastward through the minimum energy zone located at -15 m, and (iii) an intermediate zone, which appears to be much more mixed, with disrupted cross-shore exchange.

**Keywords:** Sediment sources and stocks, carbonate dynamics, coastal environment, COVA method, PASTA method.

## **1 INTRODUCTION**

Sediments are mainly composed of two types of particles: silicates and carbonates. Although these two types are often mixed in coastal environments, they differ in both origin and dynamics. Unlike silicate particles, carbonate particles can have multiple origins. They can be lithoclastic, resulting from the erosion of carbonate substrates such as chalk cliffs, or derived from biological in situ production, like shells. Due to their fragility and low density, carbonate particles are prone to fragmentation and are more easily transported by currents. The Seine-Maritime coastline, characterised by Mesozoic chalk cliffs (Letortu et al., 2015; Costa et al., 2019) in constant erosion (from -0.1 to -0.5 m/year), has undergone significant, yet poorly understood, sandy silting, particularly east of Saint-Valéry-en-Caux (Peuziat et al., 2021). To better determine the origin of the siltation and to trace the dynamic of the carbonate particles, this study proposes a dual approach: quantifying carbonates (traced by Ca) and assessing their qualitative variability (Sr/Ca ratio). Strontium and calcium are two quantitative markers of carbonates and are correlated. The Sr/Ca ratio can be used to identify different carbonate origins (Treese et al., 1981; Stoll & Schrag, 2001; Bayon et al., 2007). The variability of these two markers in granulometric and geographical space makes it possible to trace the geographical sources and dynamics of different types of carbonate particles. The first part of the results, based on the GSTA method (Geochemical Sediment Trend Analysis: Baux et al., 2022), presents the analyses carried out on the total sediment. The second part analyses the individual granulometric fractions and their geographical variability (COVA method: COmposition Variability Analysis). Finally, the last section examines carbonates stock dynamics using PASTA (PArticulate Stock Trend Analysis), an innovative approach to sediment transport analysis.

## 2 MATERIALS AND METHODS

The bathymetry of the studied area ranges from 12 to 21 m depth. Analysis of the morphology reveals the presence of two distinct zones: a steeply sloping western zone and a gently sloping eastern zone. A total of 45 subsurface sediment samples were collected with a Shipek grab off Saint-Valéry-en-Caux over a 10 km<sup>2</sup> area (Fig. 1). The samples were separated by sieving into 20 particle size fractions ranging from less than 50  $\mu$ m to 2500  $\mu$ m (log scale of 1.26) (NF ISO 3310-1, 2016). Elemental geochemical analyses were carried out on both the total sample and the separated granulometric fractions using X-ray fluorescence spectrometry.

Around sixty marine sediment standards were used to calibrate the analytical method. Additionally, 0.05 g of each subsample was used to measure total organic carbon (TOC) on the fine fraction (<50  $\mu$ m) by infrared spectrometry (LECO CS 744) after decarbonation with phosphoric acid (H3PO4).

The results obtained on total sediment using the GSTA method and those from the COVA method are presented in the form of maps of spatial variability of element concentration or element concentration ratio. For the PASTA method, calcium stock data were determined using the following formula: (sieve mass (%) × sieve Ca concentration (ppm)). Introducing the mass of the granulometric fractions gives access to the stock of a type of particle. These data describe the geographical variability of the granulometry (mean) of this type of particle. A field of "Finer" vectors indicates the direction of refinement, which can be interpreted as a direction of decrease in particle transport energy.



Figure 1: Location of study area and sampled stations.

## **3 RESULTS AND DISCUSSION**

### 3.1 Contributions of the GSTA (Geochemical Sediment Trend Analysis) method

The spatial variability in the concentrations of; (i) silicon (Si), an indicator of silicate content, (ii) calcium (Ca), an indicator of carbonate content, (iii) organic bromine (BrOrg), an indicator of organic matter content, and (iv) the Sr/Ca ratio which qualifies the origin of carbonates, is illustrated in figure 2. The variability of the Sr/Ca ratio enables the distinction between carbonates of chalky origin (approximately 1.5) and carbonates derived from shells (greater than 4) (Peuziat, 2022). The concentration ranges of the major elements Si and Ca are identical, varying in opposition from 28 to 7%, corresponding to 60 to 15% SiO2 and 70 to 18% CaCO3. The deposits are therefore primarily composed of carbonates and silicates. The highest silicon concentrations are in the South, but at varying depths, and there is no pattern to the variability of calcium. The Sr/Ca ratio is always greater than 4, indicating that the dominant carbonates are derived from shells throughout the zone. The amount of BrOrg in the total sediment is low, often close to zero with a maximum of 32 ppm. Values above 20 ppm are localised in three patches, which also show an enrichment in silicon. The results obtained on the total sediment do not allow any interpretation of the sedimentary dynamics of the study area.

### 3.2 Contributions of the COVA (COmposition Variability Analysis) method

Carbonates represent a target of interest for the COVA methodology, as it allows for the monitoring of both their quantitative (Ca) and qualitative (Sr/Ca) variability in granulometric and geographical spaces.

Figures 3 and 4 illustrate the spatial variability of Ca and Sr/Ca for six distinct granulometric fractions. For the Sr/Ca ratio, the scales remain constant across all granulometric fractions. However, for clarity, each fraction has its own scale for Ca concentration.

A twofold change is evident from 2500  $\mu$ m to 125  $\mu$ m, characterized by a decrease in both the range and the maximum value (from a range of 35-9% Ca for the 2000-2500  $\mu$ m fraction to 9-1% for the 125-160  $\mu$ m fraction). The coarsest fractions exhibit a greater abundance of carbonates and higher geographical differentiation. The homogenisation of concentrations could be interpreted as indicating more frequent transport of the smallest grains; however, the Sr/Ca ratio provides a different perspective. The three coarsest fractions (Fig. 3, 2500 to 315  $\mu$ m) are uniformly composed of shells (Sr/Ca ≥ 4), while the finer fractions reveal two origins (Fig. 4, 315-125  $\mu$ m): shells and chalk. Consequently, there is an absence of

homogenisation for the finest fractions. The decrease in the maximum Ca concentration is associated with the presence of quartz in these finer fractions. The fraction <50  $\mu$ m is distinguished by high Ca concentrations (range 28-19%) and a higher proportion of chalk than shells.



Figure 2: Spatial variability in the concentration (total sediment) of Si (%), Ca (%), BrOrg (ppm) and the Sr/Ca ratio (x1000).

The geographical variability of the 2500  $\mu$ m to 125  $\mu$ m fractions generally exhibits higher calcium concentrations offshore in the east (shells) and along the coast in the west (shells for fractions >315  $\mu$ m and chalk for those <315  $\mu$ m). The carbonate enrichment of the <50  $\mu$ m fraction corresponds to the development of a source of coastal chalk to the west, likely originating from the coastal cliffs.

The COVA approach identifies two significant localised sources of carbonates: 315 to 800  $\mu$ m shells in the offshore area to the east, and 315 to <50  $\mu$ m chalk from the cliffs on the coast to the west.



Figure 3: Spatial variability of Ca concentration (%) and Sr/Ca ratio (x1000) for fractions 2000-2500 μm, 630-800 μm and 315-400 μm.





Figure 4: Spatial variability of Ca concentration (%) and Sr/Ca ratio (x1000) for fractions 250-315  $\mu$ m, 125-160  $\mu$ m and < 50  $\mu$ m.

## 3.3 Contributions of the PASTA (PArticular Stock Trend Analysis) method

The PASTA methodology facilitates the visualisation of the current granulometric gradients within the stocks of a specific grain type using vectors. Figure 5 illustrates the 'finer' gradients of the carbonate stock. Inshore vectors are indicated in red, offshore vectors in blue.



Figure 5: Finer gradients of the carbonate stock: inshore red vectors correspond to the prevailing action of tides; offshore blue vectors correspond to the prevailing action of swells. Spatial variability BrOrg/TOC (10-4) on fractions < 50 µm. The dashed line indicates the dominant swell/tide boundary.

The area of convergence between the two vectors fields is delineated by a black dotted line, indicating the region where carbonates are the finest in size, at an approximate depth of 15 metres. This zone of reduced energy activity is characterised by the convergence of two distinct refinement gradients: (i) a gradient originating from the open sea and terminating at the coast (red vectors), which corresponds to the prevailing action of tide (Larsonneur, 1971; Levoy and Larsonneur, 1992; Guillen and Hoekstra, 1996; Baux et al., 2019), and (ii) a gradient extending from the coast to the open sea (blue vectors), which corresponds to the prevailing action of swells. It appears that a state of dynamic equilibrium has been established for both hydrological parameters. Geographically, three zones can be distinguished: (i) in the west, the dominant swell/tide boundary is at a depth of approximately 15 metres, (ii) in the east, it is at the same depth, (iii) in the centre, it approaches the coast. Baux et al. (2019) previously identified a similar dynamic equilibrium with two gradients related to the bathymetry which converge towards the 15m depth in the south of Antifer Harbour (70 km further south).

A comparison of the spatial evolution of the carbonate stock with that of BrOrg/TOC (fraction < 50  $\mu$ m) reveals that the distributions are highly analogous, except in the central zone. The BrOrg/TOC ratio can be used to trace the marine or continental origin of organic matter (Mayer et al., 2007). Marine organic matter is enriched in bromine. A BrOrg/TOC ratio greater than 100.10<sup>-4</sup> corresponds to marine organic matter and less than 20.10<sup>-4</sup> to continental organic matter. Organic matter of continental origin is enriched in the coastal zone, while organic matter of marine origin is enriched in the offshore zone. Mixing is minimal in the eastern and western zones, and higher in the central zone. Two independent parameters (carbonates stock and organic matter content) demonstrate a change in the behaviour of sediment dynamics at Saint Valery-en-Caux.

The carbonate stock is in dynamic equilibrium and displays two gradients that converge at a depth of about 15 metres, irrespective of the bottom slope.

The variability in organic matter, as depicted by BrOrg/TOC ratio, reveals that the mix of marine and continental organic matter is less pronounced in the eastern and western zones. This phenomenon can be attributed to the well-marked gradients of dominant wave/tide action in these regions. In contrast, the central zone exhibits a higher degree of mixing between these two sources of organic matter.

### 4 CONCLUSIONS

The GSTA method applied on total sediment does not provide meaningful insights into the sources and sedimentary dynamics of the particles making up the deposits. In contrast, the COVA approach provides more interpretable data revealing the presence of two distinct carbonate origins: shell debris and chalk. The local sources and the particle sizes of these two types of carbonates were determined.

The PASTA method then complemented these approaches by assessing the dynamics and trajectories of the carbonate stock.

As a result, a comprehensive diagram of sedimentary dynamics can be established, distinguishing three distinct zones: (i) a steeply sloping western zone, in dynamic swell/tide equilibrium, where marine shells make little progress coastward (cross-shore transport); (ii) a gently sloping eastern zone, also in swell /tide equilibrium, where shells and quartz migrate coastward through the minimum energy zone at -15 metres; (iii) an intermediate zone which appears to be much more mixed, with disrupted cross-shore exchanges.

The sandy siltation observed east of Saint-Valéry-en-Caux corresponds to the influx of a sedimentary stock composed of shells and quartz. These sediments move shoreward through cross-shore transport and successfully traverse the threshold of dominant swell/tide action, likely facilitated by the gentler slope.

## 5 ACKNOWLEDGMENTS

This research was supported by a grant from the Région Basse Normandie and the Communauté d'Agglomération du Cotentin. Sediment samples were obtained during the CAUXySTA cruise. The authors would like to thank the Flotte Océanographique Française and the crew of R/V Côtes de la Manche that make the CAUXySTA cruise possible (<u>https://doi.org/10.17600/18002491</u>). They also thank Alain Trentesaux for reviewing the manuscript.

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