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THE DYNAMICS OF SILICA SEDIMENT AT THE ECUSED SITE IN THE BAIE DE SEINE BASED ON THE COVA METHODOLOGY: (1) GLAUCONITE TRACED BY ARSENIC

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Abstract: The English Channel, and specifically the Baie de Seine, is one of the maritime areas hosting the most human activities in Europe. The ECUSED project focuses on the cumulative impact of marine aggregate extraction activities (“Granulats Marins du Havre” concession) and dumping of dredged sediment by the Normand harbours (“Grands Ports Maritimes”) for the maintenance of navigation channels (MACHU site), which are concentrated at the outlet of the Seine estuary. To achieve this goal, we used an innovative methodology (ELCOVA) on 114 surface sediments samples according to a regular grid of 2 stations per km². Samples were separated by sieving into 16 particle size fractions and elemental geochemical analyses were carried out on the separated granulometric fractions using X-ray fluorescence spectrometry. The present work focuses on identifying the movements of the various grain sizes naturally present at the site. The mineral considered is glauconite, an alumino-silicate, traced in the elemental analysis by arsenic. The study zone reveals a complex history in terms of granulometry, geography and time. We identify two sources of material, underwater erosion, river input, transports on the seabed and in suspension and a dynamic equilibrium sedimentary state. An essential point of the results obtained is that each granulometric fraction has its own history. Grains belonging to the same sediment sample do not come from the same sources, have not been transported in the same direction, and have not been deposited at the same time under the same energy conditions. It is possible to find grains of the same size and mineralogy from different sources in the same surface sample. This directly challenges the view of sedimentologists on sedimentation.

Keywords: Sediment dynamics, Glauconite, COVA methodology, Baie de Seine.

1 INTRODUCTION

The English Channel is a shallow epicontinental basin characterised by slow litho-bioclastic sedimentation established since the last transgression. Sediment distribution is controlled by tidal currents, with waves only interfering effectively in coastal areas. As the Bay of the Seine is relatively sheltered from long ocean swells, the distribution of surface sediments is directly linked to the action of tidal currents (Larsonneur, 1971; Gentil et Cabioch, 1997). Loose sediments generally form a thin layer. The siliceous sedimentary stock comes from contributions during regressive phases by various periglacial agents: fluvial and eolian transport, mudflows, sheets of cryoclasts from basement rocks and glacial rafts. The characteristics of this terrigenous material reflect a long evolution with successive contributions and repeated reworking (Auffret et al., 1975).

Assessing the cumulative impacts of human activities on the environment remains a major challenge for marine ecosystem conservation and management (Foley et al., 2017; Stelzenmüller et al., 2020). The English Channel, and specifically the Baie de Seine is among one of the maritime areas hosting the most human activities in Europe (Marmin et al., 2014; Dauvin et al., 2020). Among these activities, marine aggregate extraction and the dumping of dredged material from ports and waterways have increased in recent years, representing a challenge to coastal zone management (Le Bot et al., 2010; Duclos et al., 2013; Marmin et al., 2014). The cumulative sedimentary impacts of aggregate extraction and dredged material dumping, however, remain largely unknown, mainly due to a lack of methods allowing to trace sedimentary dynamics. The ECUSED project focuses on the cumulative impact of marine aggregate extraction activities (“Granulats Marins du Havre” concession) and dumping of dredged sediment by the Normand harbours (“Grands Ports Maritimes”) for the maintenance of navigation channels (MACHU site), which are concentrated at the outlet of the Seine estuary.

Geochemistry is most often used to trace the origins of particles in total sediment (Baux et al. 2022). In coastal environments, the results obtained depend on the granulometric variability of the samples, which essentially reflects the energy conditions of the environment studied. By analysing grain size fractions, we can bypass this granulometric variability. It is then possible to access the spatial variability of the composition of grains of the same size, i.e. the geographical sources of these grains (Peuziat 2022; Grégoire et al., in press). The elemental chemical composition of grain size fractions enables us to obtain two types of information: (i) identification and quantification of the different grain types: quartz, calcium carbonates, zircon... and (ii) the spatial variability of each grain type for each grain size fraction. We have developed a new methodology COVA (COmposition Variation Analysis) that combines: (i) elemental analysis of sediment fractions and (ii) a sampling strategy organised according to a regular grid, with a sampling density adapted to the research objective. This approach provides 'ground truth' data that complement predictive numerical models which are limited when confronted with sediment heterogeneity and the complex hydrodynamic forcing characteristic of the Baie de Seine.

We use the term origin to designate the general conditions of particle formation. For example, it is accepted that quartz comes from the erosion of granites, and calcium carbonates from current to sub-actual marine biogenic production. The term source refers to a specific geographical location in the study area. A quartz grain sampled on a beach, that was initially crystallised in a granitic magma (origin), may have been brought to the beach from offshore by cross-shore transport (source). The study of spatial variability in the chemical composition of a single fraction provides information on the sources of the different types of grain that make it up. It is possible to identify the relationships that exist or do not exist between these different sources (mixing gradient between two sources, for example), thus obtaining information on the transport dynamics of these grains.

Sediment dynamics result from the dynamic of the water mass (tide and swell) modulated by a pre-existing morphology and applied to sedimentary grains likely to be in motion. This work focused on identifying the movements of the different grain sizes naturally present at the site. The mineral considered is glauconite, an alumino-silicate, traced in the elemental analysis by arsenic (Mumford et al., 2012; Baux et al., 2019).

2 MATERIALS AND METHODS

2.1 Study area

The study area (43 km^2) is located in the Baie de Seine off the Seine estuary (Fig. 1) and was chosen because two distinct anthropogenic activities were taking place only 4 km apart. The Granulats Marins du Havre (GMH) concession is in the northern part, and at the time of the mission in April 2022, extraction started approximately 3 months before. Extractions of between 10,000 and 50,000 m^3.yr^{-1} are planned. The Machu dredge disposal area is located south of the study area, on the southern edge of the Banc de Seine. It consists of 6 series (labelled A to F) of boxes that will be used successively over a period of about 10 years. Each series is used for 2 to 3 years, during which deposits accumulate to a thickness of several metres and are then abandoned. At the time of the mission (2022), serie F has been used between 2017 to 2019 before being abandoned. The C serie has been in operation since 2020. The deposited sediments come from dredging carried out by the Grand Port Maritime de Rouen (GPMR), which oversees navigation in the Seine estuary up to the port of Rouen. The sediments amount to 5 million m^3.yr^{-1}.

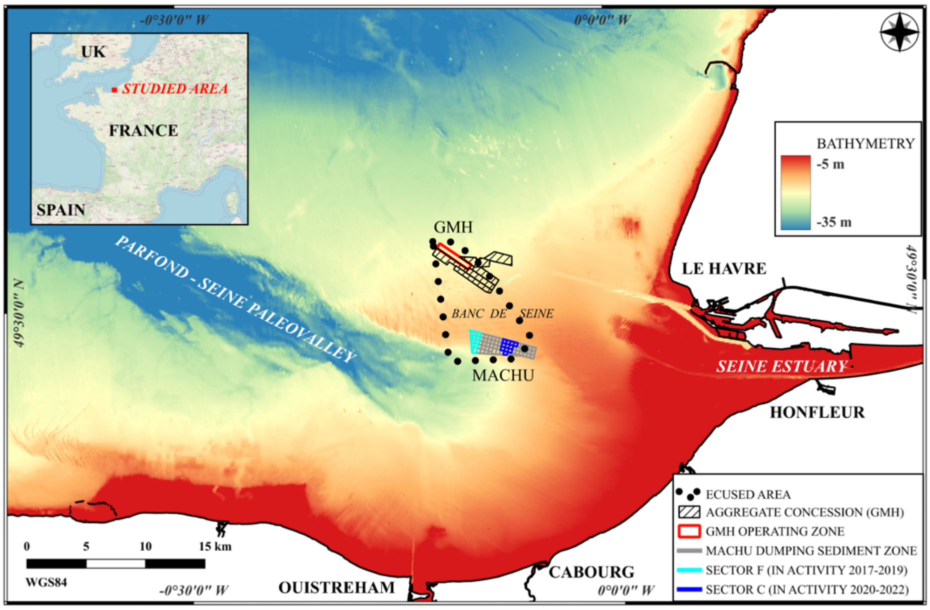

Figure 1: Location of the ECUSED study area, the Granulats Marins du Havre (GMH) concession and the Machu dredge deposit area.

2.2 Methodology

The ECUSED mission (April 2022) collected surface sediment at 114 stations on a regular grid of 2 stations per km^2, with a higher station density in areas influenced by anthropogenic activities (Fig. 2A).

The samples were separated by sieving into 16 particle size fractions, ranging from less than 50 µm to 2000 µm (log scale of 1.26) (NF ISO 3310-1, 2016). Elemental geochemical analyses were carried out on the separated granulometric fractions using X-ray fluorescence spectrometry. Sixty marine sediment standards were used to calibrate the analytical method.

The granulometric mean is based on dataset obtained using a Horiba laser particle size analyser with a measuring range from 0.01 µm to 2000 µm. Residual tidal currents were obtained using the MARS 2D (Model for Application at Regional Scale in 2D) numerical model. This model simulates the horizontal movement of oceanic water masses to study and predict the dynamics of coastal and estuarine waters (Lazure and Dumas, 2008).

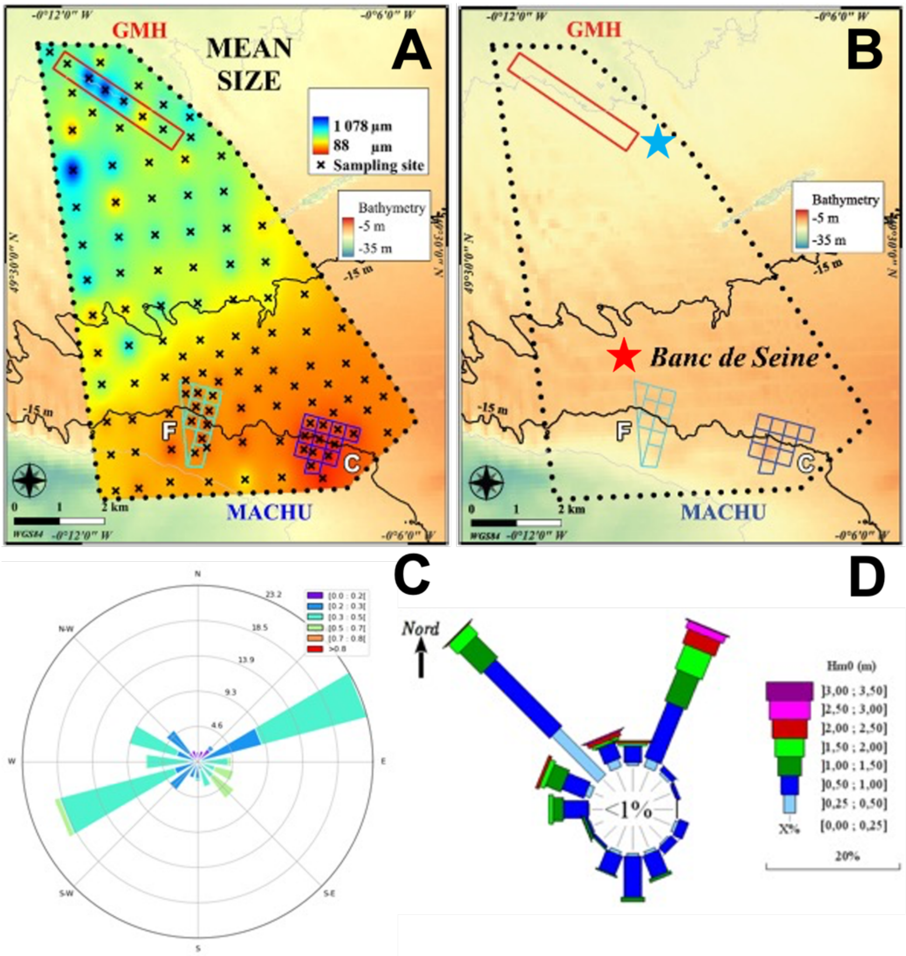

Figure 2: Physical data: 2A, location of the 114 sediment samples collected and granulometric mean variability; 2B, bathymetry of the study area, blue star for swell station (2D) and red star for position of tidal currents rose (2C); 2C, tidal currents rose; 2D, swell data, Hmo from Cerema CANDHIS 07605-Le Havre2 buoy at - 17m depth, recorded between 10/01 and 05/03/2010.

3 RESULTS AND DISCUSSION

3.1 Results

The natural bathymetry of the study area ranges from -21 m in the north to -14 m at the top of the Banc de Seine, a relief bounded by the -15 m isobath (Fig. 2B). In the extreme south-east, the Parfond corresponds to the paleo-valley of the Seine (Fig. 1). Dredged sediments from the F serie of boxes have reached the -12 m bathymetric level.

In this area of the Baie de Seine, tidal currents are northeasterly during the flood and south-westerly during the ebb, generally reaching 0.4 m.s^{-1} with a maximum of 0.8 m.s^{-1} in the Parfond (Fig. 2C). The dominant swells come from the northwest and the northeast (Fig. 2D).

The map in Fig. 2A shows the granulometric mean variability of the ECUSED zone. The sediments are sandy, with a refinement gradient from north (very coarse sands at -21 m) to south (fine to medium sands on the Banc de Seine). The finest sediments (silty sands) are found in the serie of active MACHU boxes C.

Glauconite is a specific clay that forms at the water-sediment interface in a marine environment, forming grains within the sandy particle size range. Glauconite is generally assumed to occur within fine-grained marine (Amorosi, 1997) outer shelf and slope deposits, at an average depth between about 50 m to 500 m (Odin and Matter, 1981) under warm climatic conditions (Banerjee et al., 2020). These formation conditions do not correspond to the current environment of the Baie de Seine. Here it is allochthonous detrital (Amorosi, 1997) derived and eroded from the Mesozoic chalk and glauconitic sandstone of the Bassin Parisien. The marine origin of glauconite means that it remains stable in the marine environment and is enriched in modern sands. Figure 3 shows the geographical variability in the amount of arsenic (As), the quantitative tracer of glauconite, for nine granulometric fractions. Each fraction has its own concentration scale, with a maximum value ranging from 79 ppm for the coarsest fraction to 15 ppm for the finest. Interpretation of the results is essentially based on the geographical position of the samples with the highest glauconite content for each fraction examined.

The two coarsest fractions, 800 - 1000 µm and 630 - 800 µm, could not be analysed at certain stations in the south of the zone due to insufficient material quantity.

For the 800 - 1000 µm fraction, the zone of maximum concentration is located on the northern flank of the Banc de Seine, slightly north of the -15 m isobath. This zone is considered as source 1 of glauconite grains, all the more so as glauconite grains >1000 µm were also identified. There is no glauconite grains at the northern and southern ends of the studied zone.

From 800 to 315 µm, the zone of maximum concentration moves south-eastwards, widening at the top of the Banc de Seine. Each finer fraction moves further, being transported upslope. This « shallower = finer » refinement gradient indicates the prevailing action of the tide on the swell (Larsonneur, 1971; Levoy and Larsonneur, 1992; Guillen and Hoekstra, 1996; Baux et al., 2019). Each fraction finds a depth on a slope where it reaches dynamic equilibrium. The F and C series become increasingly distinct because the sediments deposited there do not contain glauconite of these sizes.

Below 315 µm, a new source of glauconite grains appears in the south-east. The black circle on the 250 - 315 µm map identifies it as source 2. This source 2 probably corresponds to sub-actual inputs from the Seine River. For the 250 - 315 µm fraction, the extension zone progresses to south and west, bypassing the F and C series.

For the 200 - 250 µm fraction, the extension restricts to the west and reaches the F series of boxes, a 2m morphological obstacle which the glauconite grains can cross only by suspension. As the C boxes series is still free of arsenic, except in the north, kinetics must be used to interpret this difference. The use of the two series of boxes has been delayed by two years. There are two possible and compatible hypotheses: (i) the active C series is constantly receiving deposits that cover any glauconite grains deposited from suspended load, (ii) suspension occurs occasionally, for example during a storm, when swell and tidal currents combine to allow transport, and only the F series of boxes and the northern part of the C series can record these events.

For the 160-200 µm fraction, the regression area is wider to the west, south, and even north. Most of the source 1 zone no longer contains glauconite grains. The source 2 zone is dominant, but despite possible suspension, the area of extension remains limited. This may be because the very small amount of glauconite grains in suspension makes it unidentifiable in the deposits. Analysis of the deposits in the C series of boxes shows that some of the boxes, with no geographical connection between them, contain glauconite grains of this size. It is likely that some of the dredged areas are glauconite grains sources.

The last fraction in which glauconite grains can be identified is 125 - 160 µm. The extension is limited to the source 2 zone, which shows that even if some of the glauconite grains of this size are transported in suspension and dispersed, some are still transported in contact with the seabed.

3.2 Discussion

The study of the glauconite grains in the ECUSED zone reveals a complex history in terms of grain size, geography, and time. Two sources of material were identified.

Source 1 contains coarse glauconite grains (> 800 µm) that were not transported under the current energy conditions. It corresponds to a deposition that occurred several thousand years ago. Based on seismic data, Benabdellouahed et al. (2013) interpreted the Banc de Seine as consisting of glacial alluvial deposits from the Seine River. Part of these fluvial terraces, located on the northern flank, is not covered by modern sedimentary deposits and, for certain granulometric fractions, is even undergoing erosion.

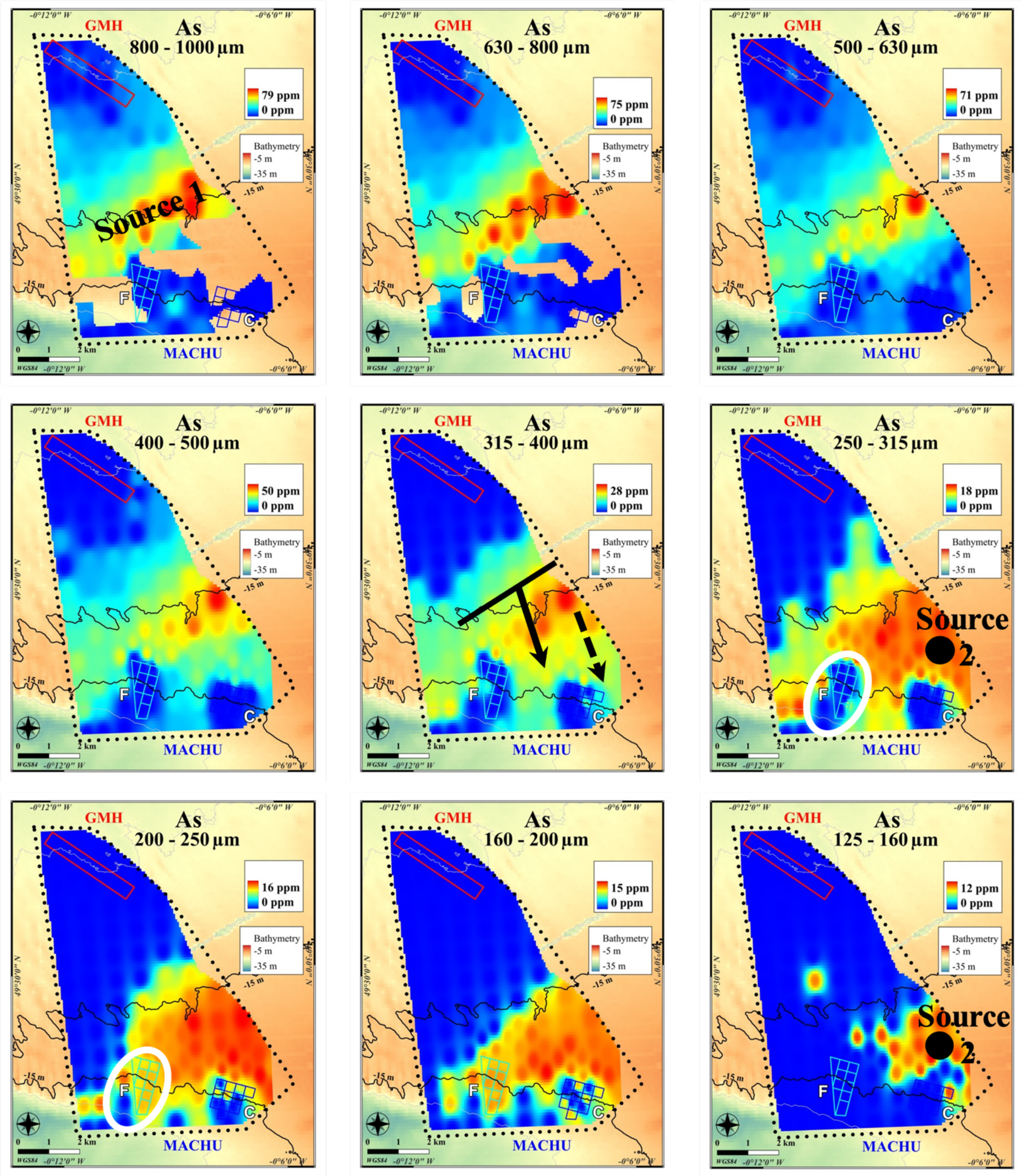

Figure 3: Geographical variability of As concentration (ppm), the quantitative tracer of glauconite, for nine granulometric fractions. The black line on the 315 - 400 microns map indicates the position of source 1 and arrows the south-eastward movement of the glauconite grains. The black dot on the 250 - 315 and 125 - 160 microns maps represents the position of source 2. The white oval on the 250 - 315 and 200 - 250 microns maps highlights the evolution of the F series of boxes.

The 800 to 200 µm fractions are transported on the seabed by tidal currents up the northern slope of the Banc de Seine, with finest fractions being transported further south-east. Each granulometric fractions finds its zone of dynamic equilibrium and remains there. This dynamic equilibrium may have existed for thousands of years. The south-eastward transport may seem surprising, given that the dominant tidal currents are those from the north-east flow (Fig. 2C). Auffret and d'Ozouville (1986) reached to the same conclusion of a south-easterly transit and areas of underwater erosion based on side-scan sonar data. An analysis of the tide roses for different parts of the study area shows that currents with velocities greater than 50 $cm.s^{-1}$ flow to the south-east. It is probably these higher energy currents that make this transport possible. From 250 µm, glauconite grains can be transported in suspension during high-energy events (exceptional tides or swells) and dispersed much further and in other directions.

Source 2 consists of glauconite grains arriving at the study site already sorted (315 - 125 µm) from the south-east. It is possible that their transport dynamics are related to the current flooding of the Seine. Our data do not allow any further interpretation.

4 CONCLUSION

The COVA method makes it possible to: (i) interpret the history of a mineral in detail, (ii) distinguish bedload and suspension transport of particles, (iii.) identify the directions of transport in contact with the seabed, and (iiii) reconstruct the sedimentary dynamics of a particular grain type in the present coastal environment on the basis of a single sampling campaign. An essential point of the results obtained is that each granulometric fraction has its own history. Grains from the same sediment sample do not come from the same sources, have not been transported in the same direction, and have not been deposited at the same time under the same energy conditions. It is possible to find grains of the same size and mineralogy from different sources in the same surface sample. This directly challenges the view of sedimentologists on sedimentation and explains the difficulties encountered by hydrosedimentary models in reconstructing bedload transport.

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