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## Sedimentation on intertidal mudflats in the lower part of macrotidal estuaries: Sedimentation rhythms and their preservation

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### Abstract:

The objective of this study is to propose an original approach to the analysis of the formation of intertidal rhythmites, their preservation, and the evaluation of sedimentation rates on estuarine mudflats. Three mudflats, one from each of three estuaries, were analysed using a combination of long-term (> a year), high-frequency (1 burst/10 or 20 min), and high-resolution (0.2 cm) altimeter datasets and X-ray images of sediment cores collected during topographic surveys. The results highlight the roles played by sediment supply, hydrodynamics, and morphology of the lower estuaries on the sedimentation rhythms. While the sediment-starved Medway estuary (Kent, UK) remains stable at different time-scales, the annual sedimentation rates on the sheltered Authie mudflat (Pas-de-Calais, France) and the open Seine mudflat (Normandy, France) are relatively high at 18 and 15 cm yr<sup>-1</sup>, respectively. On the Authie mudflat, sedimentation rhythms correspond to the semi-lunar cycle, with a good correlation between tidal range and deposit thickness. Sedimentation occurs at the beginning of the recovery (mean value of 0.25 cm per semi-diurnal cycle), and is not disturbed by wind-induced waves. In the lower Seine estuary, semi-diurnal mechanisms of deposition occur mainly when the mudflat is covered by a minimal water height (tidal range threshold value = 7.1 m). Sedimentation rhythms are discontinuous and deposition occurs only during the highest spring tides. Mean deposit thickness is 0.6 cm per semi-diurnal cycle, controlled by the turbidity maximum and the long high tide slack (2–3 h). The fluid mud is sensitive to wind-waves in this open funnel-shaped estuary, which undergoes wind-induced erosion (0.2 to 2 cm) about 10 times per year.

Comparison of altimeter datasets and lithology of the sediments cored at the same points provided improved understanding of the sediment record rhythms and the sedimentation events. On the sediment-starved Medway mudflat, the result of sediment processes is a single superficial lamina. The elementary deposit in the Authie bay corresponds to a semi-lunar-linked layer, typical of sheltered environments. On the lower Seine mudflat, sedimentation rhythms are linked to the highest spring tides (i.e., the lunar cycle), resulting from increased sediment availability related to the high suspended matter concentration in the turbidity maximum. These results underline the complex response of intertidal mudflats to hydrodynamics and sediment supply conditions, from the semi-diurnal to the annual scales.

**Keywords:** morphology; mud; rhythmites; altimeter; X-ray imagery; macrotidal estuary

## 45 **Introduction**

46 Tidal flats in marine or brackish parts of estuarine systems have been the focus of numerous  
47 morpho-sedimentary studies (e.g. Amos, 1995; Perillo, 1995; Black et al., 1998; Dyer, 1998 and  
48 Dyer et al., 2000a, 2000b). Recent works using altimeter measurements have allowed a more  
49 detailed understanding of the morphological evolution of intertidal mudflats over varying  
50 timescales. These studies underline the importance of cyclical evolution of intertidal mudflat  
51 elevation and morphology, controlled either by tidal forcing (Christies et al., 1999; Pritchard et al.,  
52 2002; Deloffre et al., 2006) or by high river discharge (Deloffre et al., 2005). Wind events  
53 (Bassoullet et al., 2000, Fan et al., 2006) and biological activity (e.g., Gouleau et al., 2000;  
54 Andersen and Pejrup, 2002) increase the complexity of the behaviour of these environments.  
55 Similar controls have been identified in studies of cyclic sedimentary facies (i.e. tidal rhythmites) in  
56 ancient and recent environments (e.g: Dalrymple et al., 1978; Tessier, 1993; Kvale et al., 1994;  
57 Archer, 1995; Tessier et al., 1995; Choi et Park, 2000; Stupples, 2002).

58 The sedimentological analysis of cyclical or rhythmic sedimentation on intertidal mudflats  
59 in estuarine systems is frequently complicated however by the relative homogeneity of the material  
60 that settles, intensive bioturbation, and physical removal of settled material as a result of high-  
61 energy events in the water column leading to erosion (West and West, 1991; Kirby et al., 1993;  
62 Schoellehammer, 1996; Bassoullet et al., 2000). Here we combine high-resolution altimeter datasets  
63 with sediment core analysis to examine the sedimentary behaviour of intertidal mudflats in the  
64 lower part of three contrasting macrotidal estuaries: a mudflat in a typical sheltered bay (the Authie,  
65 France), a relatively stable mudflat in a sediment-starved estuary (the Medway, U.K.), and a  
66 mudflat in a system with a highly concentrated turbidity maximum (the Seine, France). The  
67 objective of this paper is to analyse the sediment processes associated with the different cycles on  
68 the mudflats and to compare them on the basis of a long-term (at least one year), high-frequency  
69 and high-resolution topographic study carried out by acoustic altimeter, and on lithologic records in  
70 sediment cores collected from each of the sites during the same survey periods. The altimeter

71 datasets provide information on the role played by the morphology of the intertidal mudflats and the  
72 availability of sediment supply. The comparison of altimeter data and lithologic variations allows  
73 investigation of the occurrence and the preservation rates of tidal-induced mudflat deposits (i.e.  
74 percentage of sedimentary structures preserved). The occurrence and preservation of the laminae is  
75 mainly controlled by the sedimentation and the erosion rates, the sediment properties, the  
76 dewatering, the erosion induced by high energy events (boat passage or wind events) and  
77 bioturbation.

## 78 **Study sites**

79 In order to obtain contrasting sedimentary trends, the sampling strategy was to study  
80 estuarine system characterized by different morphological and sedimentological features at the  
81 mouth (Fig. 1 and Table 1). The mudflat in the Authie bay corresponds to a sheltered system  
82 combined to continuous fine-sediment inputs. The Seine one is an opened system associated with  
83 turbidity maximum inputs. The Medway mudflat corresponds to a sheltered system in a sediment-  
84 starved estuary.

85 The Authie bay is a macrotidal system (maximum tidal range of 8.5 m at its mouth) located  
86 in the northern part of France (Fig. 1B). The mean annual discharge of the Authie River is  $10 \text{ m}^3 \cdot \text{s}^{-1}$ ,  
87 and the river has a  $985 \text{ km}^2$  catchment area. This estuarine system is rapidly filling with silting, but  
88 a chief feature is the penetration of a substantial sand fraction originating from the English Channel  
89 (Anthony and Dobroniak, 2000). Morphologically, the Authie consists of a bay protected by a sand  
90 bar (located in subtidal to supratidal domains) at its mouth, which shelters the estuary from storm  
91 swells (Fig. 1B). The principal hydrodynamic feature is the rapid filling of the bay by the tide:  
92 during low tide, most of the estuary, except the main channel, is sub-aerially exposed, and during  
93 the flood period there is significant resuspension of fine sediment. The Authie bay is considered to  
94 be a relatively “natural estuary”, compared with other local systems, although some polders have

95 been constructed, inducing a seaward salt marsh progression and increased sedimentation (Anthony  
96 and Dobroniak, 2000).

97         The macrotidal Seine estuary (maximum tidal range of 8.0 m at its mouth) is located in the  
98 northwestern part of France (Fig. 1C). It is one of the largest estuaries on the Northwestern  
99 European continental shelf, with a catchment area of more than 79,000 km<sup>2</sup>. The mean annual Seine  
100 river flow, computed for the last 50 years, is 450 m<sup>3</sup>.s<sup>-1</sup>. During the last two centuries, the Seine  
101 estuary has been greatly altered by human activity (Avoine et al., 1981; Lafite and Romaña, 2001;  
102 Lesourd et al., 2001). Intensive engineering works were undertaken between Rouen and Le Havre  
103 to improve navigation. As a result, the lower Seine river was changed from a dominantly natural  
104 system to an anthropogenically-controlled one (Lesourd et al., 2001). Despite the highly dynamic  
105 nature of the system, tidal flats and salt marshes are still developed in the lower estuary, however  
106 the intertidal surface area has drastically decreased during the last 30 years (Lesourd, pers. comm.).  
107 The lower estuary is characterized by the presence of a distinct estuarine turbidity maximum  
108 (Avoine et al., 1981), which has a pronounced control on the sedimentation patterns on intertidal  
109 mudflats at the estuary mouth (Deloffre et al., 2006). One of the principal hydrodynamics features  
110 in the Seine estuary is a 3-hour high-water slack period that can occur at the mouth. The funnel-  
111 shaped estuary is exposed to the prevailing SSW winds, which make the intertidal regions at the  
112 mouth subject to erosion under the combined effect of waves and currents (Verney et al., 2007).

113         The macrotidal Medway estuary (maximum tidal range of ~5.6 m at the mouth) is located in  
114 the southeastern part of England (Fig. 1A) and today forms part of the wider Thames estuary  
115 system. Medway river flow is 35 m<sup>3</sup>.s<sup>-1</sup>, and the river has a 1,750 km<sup>2</sup> catchment area. Extensive  
116 intertidal flats and salt marsh islands characterize the lower part of the estuary, although much of  
117 the salt marsh has been lost through the removal of material for brick-making. From a  
118 sedimentological point of view, the Medway exhibits two distinct characteristics: the absence of  
119 sands on intertidal mudflats and the reworking of fine particles within the estuary. This last feature

120 is a consequence of the absence of significant external sediment supply. While some mudflats are  
121 slowly accreting, erosion processes dominate (Burd, 1989; Kirby, 1990; Pye and French, 1993).

122

## 123 **Materials and methods**

### 124 **1. Oceanographic instrument deployments**

125 A similar sampling strategy was used for each of the three mudflats. A Micrel ALTUS  
126 altimeter was placed at a similar elevation in each estuary (4-6.5 m above the lowest sea level, i.e.,  
127 on the middle slikke). This instrument measures bed elevation at high frequency (1 acoustic pulse  
128 every 10 minutes on the Authie and Seine mudflats, and every 20 minutes on the Medway mudflat),  
129 with high resolution (0.2 cm) and high accuracy (0.06 cm). The altimeter is composed of a 2 MHz  
130 acoustic transducer, which measures the time required for an acoustic pulse to travel from the  
131 mudflat surface to the transducer; which was fixed at a height of ~22 cm above the sediment  
132 surface. Pairs of poles were deployed along a cross-section on each mudflat. Data collected by the  
133 altimeter deployed in the middle of the cross-section is representative of the erosion-deposition  
134 processes along the section (Bassoulet et al., 2000; Deloffre et al., 2005).

135 The datasets acquired by the altimeter on the Medway and Seine estuaries were corrected for  
136 salinity and temperature effects using data from autonomous buoys near the studied sites (Deloffre  
137 et al., 2006) and Coppens (1981) equation for the speed of sound in water. However, for the Authie,  
138 these corrections could not be made because of the absence of an estuarine network. In order to  
139 identify seasonal trends in the sedimentary behaviour of each intertidal mudflat, the altimeter was  
140 deployed for at least one year at each site: 23/09/02-28/11/04 (Authie), 20/06/03-18/08/05  
141 (Medway), and 25/07/01-04/05/03 (Seine). Annual variations in bed level indicated that the most  
142 suitable period for sediment deposition was spring tide, hence additional equipment deployments  
143 were carried out during these periods.

144 The prevailing near-bed current velocities at the sites were measured during several spring  
145 semi-diurnal tidal cycles under low river flow conditions using a 6-MHz Nortek Acoustic Doppler

146 Velocimeter (ADV) (Kim et al., 2000). The ADV measurement cell was located 15 cm from the  
147 transmitter, and was set to measure at a height of 7 cm above the sediment-water interface. This  
148 instrument acquires 3D current velocities near the bed at a 32-Hz frequency. These high-resolution  
149 measurements allow the calculation of bottom shear stress. The turbulent kinetic energy (TKE)  
150 method, judged to be the most suitable to estimate the turbulence generated by tidal currents and  
151 wind-induced waves on intertidal mudflats (Voulgaris and Townbridge, 1998; Kim et al., 2000).  
152 However wave-current interactions are incorporated in the TKE shear stress calculations. The  
153 method used in this study refers to the parametric Wave-Current Interaction (WCI) model proposed  
154 by Soulsby (1995). This model was applied here ( $\tau_{wc}$ ) in order to remove wave-current interactions  
155 in the shear stress calculations (Verney et al., 2007). The backscatter signal recorded by the ADV  
156 allowed estimation of the near-bed suspended solids concentration (SSC) (Kim et al., 2000). The  
157 relationship between ADV backscatter and SSC was derived at each site using surface sediment  
158 samples to minimize errors induced by grain-size variability (Voulgaris and Meyers, 2004).

## 159 **2. Sediment analyses**

160 In order to analyse the processes and to compare the evolution of the intertidal mudflats,  
161 superficial sediment properties were analysed. Surface sediments and short cores (length:~30 cm,  
162 diameter: 10 cm) have been sampled during each field work period (i.e. every two months). The  
163 physical characteristics of the sediment were determined using standard sedimentological  
164 procedures. The water content was measured using a wet-dry weight technique (water content =  
165 water weight/dry weight x 100). The grain-size distribution (sand-to-clay fraction) was analysed  
166 using a Laser Beckman-Coulter LS 230. Organic matter content of the sediment was quantified by  
167 ignition loss at 525 °C.; Carbonate content was measured using a Bernard calcimeter.

168 The lithology of the cores was examined using the SCOPIX X-Ray imagery method  
169 developed by the Bordeaux I University (Migeon et al., 1999). This high-resolution instrument  
170 permits the observation of mm-thick layers of sediment (Lofi and Weber, 2001).

## 171 **Results and interpretation**

### 172 **1. Sediment characteristics**

173 Carbonate content in surface sediments ranged between 9 and 15% on the Medway mudflat.  
174 Higher carbonate content with much more variability was observed on the Authie and Seine  
175 mudflats, with carbonate contents between 25 and 50 %. The organic matter content of these  
176 superficial sediments, however, was similar at each site, ranging from 9.5% to 19%. In each  
177 estuary, there is little temporal variability in grain-size characteristics. The primary grain-size  
178 modes are were: 20 and 40  $\mu\text{m}$  at the Medway site; 15, 40 and 90  $\mu\text{m}$  at the Seine site; and 40 and  
179 90  $\mu\text{m}$  on the Authie site (Fig. 2). Thus the Authie and the Seine sediments generally are coarser  
180 than those for the Medway. The principal granulometric difference between the sites was seen in the  
181 sand fraction: a 200  $\mu\text{m}$ -fraction over the Seine mudflat made up 5-15 % of the sediment, while on  
182 the Authie mudflat the fine-grained sediment was usually associated with a sand fraction of less  
183 than 10% (modes: 200  $\mu\text{m}$  and more rarely 800  $\mu\text{m}$ ). In contrast, no sand was observed on the  
184 Medway mudflat (Fig. 2).

185 The main parameter varying over an annual scale was the water content. While this  
186 parameter was fairly constant over a 1-year monitoring period in the surface samples from the  
187 Medway estuary (70-95%) and the Authie bay (65-90%), it varied widely on the Seine mudflat (80-  
188 200%). Thus in this last estuary fluid mud occurs during periods of sedimentation. Variations in  
189 water content in the superficial sediments of the Seine mudflat result from deposition of fluid mud  
190 (water content = 200%) on the mudflat, and from dewatering processes resulting from consolidation  
191 and from desiccation during neap tides. On the basis of laboratory experiments, Deloffre et al.  
192 (2006) have estimated the impact of dewatering on the altimeter dataset, and variations in bed  
193 elevation induced by dewatering have been removed from the raw altimeter dataset for the Seine  
194 estuary. The present altimeter dataset takes into account only erosion and sedimentation processes.

### 195 **2. Sedimentation rhythms and mechanisms**

196 An annual comparison of bed level measurements on the three intertidal mudflats is shown  
197 in figure 3. Mudflats in the Authie and Seine estuaries received a net deposition of 15-18 cm.year<sup>-1</sup>  
198 during the study whereas the Medway mudflat retained a relatively stable elevation throughout the  
199 year. Although net sedimentation rates over an annual timescale are similar in the Authie and Seine  
200 estuaries, sedimentation rhythms are different (Fig. 3).

201 On the Authie mudflat, topographical variations at a lower scale indicate that the  
202 sedimentation is controlled by the semi-lunar tidal cycle (Fig. 3, Fig 4A): bed level increases during  
203 spring tides, and then decreases or is stabilized during neap tides, when the water level is low on the  
204 mudflat or when the mudflat is subaerially exposed. For each spring tide cycle, the bed level  
205 increases leading to generally continuous sedimentation on the study area of Authie Bay throughout  
206 the year. The threshold between erosion and sedimentation phases corresponds to a water level of  
207 110 cm on the mudflat, which in turn corresponds to a tidal range of 5.5 m. This pattern induces a  
208 lag of a few days between the end of deposition and the maximum water level (Fig. 4A and 4B).  
209 The sedimentation rates observed on the mudflat range from 0.1 to 0.6 cm per semi-diurnal tidal  
210 cycle, with more resuspension of fine particles in the main channel of the bay during spring tides (at  
211 that time current velocities allow the reworking of fine-grained deposits), and a longer duration of  
212 immersion when there is a supply of fine particles (as opposed to during neap tides). Processes  
213 observed at the semi-diurnal scale (Fig. 5A) indicate that particles settle during flood periods, when  
214 the bed shear stress is low ( $\sim 0.20 \text{ N.m}^{-2}$ ) and the SSC near the bed is high ( $\sim 0.4 \text{ g.l}^{-1}$ ). As fine-  
215 grained sediments settle out of suspension, the SSC progressively decreases. After 1 hour of  
216 immersion, most of the sediment have settled out of suspension, resulting in a 0.6-cm-thick deposit.  
217 During the high tide slack water and ebb periods, the SSC and the bottom shear stress are low, with  
218 mean values of  $0.05 \text{ g.l}^{-1}$  and  $0.25 \text{ N.m}^{-2}$ , respectively. Twice during the survey, bottom shear  
219 stresses reached a value of  $0.8 \text{ N.m}^{-2}$  as a result of high energy events (Fig. 5A). However, no  
220 impact on the surface of the mudflat was observed during these two events, which each lasted 30  
221 minutes. It is notable that during the second event, the water was lower on the mudflat and the SSC

222 increased (Fig. 5A). This phenomenon might be linked to erosion of the upper part of the mudflat,  
223 which resulted from the combined effect of waves and tidal currents. However, at the station  
224 studied, the recently-settled sediment was not influenced by the waves: the Authie mudflat surface  
225 remained stable during these events. Apart from these events, all the sedimentary mechanisms  
226 recorded are related to the repetition of semi-diurnal cycles during spring tides (Fig. 5A).

227         The annual sedimentation rate on the Seine estuary mudflat is 18 cm (Fig. 3), however, in  
228 contrast to the Authie mudflat, the main deposition phase occurs during the highest spring tides, i.e.,  
229 according to the lunar cycle, when the water level is > 150 cm above the bed level at the station  
230 (corresponding to a tidal range of 7.1 m). During these periods, the turbidity maximum reaches high  
231 concentrations (>1.95 g.l<sup>-1</sup>) and a maximum volume (Le Hir et al., 2001; Lesourd et al., 2001) in  
232 both the main channel (i.e., the navigation channel) and the northern channel, and the depositional  
233 rate on the mudflat is at a maximum (Deloffre et al., 2006). At these times, the sedimentation rate  
234 on the mudflat is high, from 0.3 to 0.8 cm per tide (Fig. 4B). As on the Authie mudflat, a lag  
235 between the depositional maximum and the water level maximum is observed (Fig. 4B). During  
236 periods of lower water level (< 150 cm water depth on the mudflat), the mudflat undergoes gradual  
237 erosion, with rates ranging between 0.02 and 0.085 cm during a semi-diurnal cycle. Over an annual  
238 timescale, the morphological evolution of the Seine mudflat corresponds to a few periods (6-10 per  
239 year) of high sedimentation, with increases in bed elevation of between 2 and 8 cm, followed by  
240 long periods of slow erosion caused by tidal currents (Fig. 3).

241         At the semi-diurnal scale, particle settling occurs during high water slack periods (Fig. 5B).  
242 During the flood tide, when the Seine mudflat is covered, small wind waves occur, inducing a high  
243 bottom shear stress that reaches 0.8 to 1.0 N.m<sup>-2</sup>. These small wind waves occur even outside of  
244 storm periods. This bottom shear stress prevents deposition, and the SSC in the water column  
245 remains high (up to 1 g.l<sup>-1</sup>). During the early high water slack water, when the bottom shear stress  
246 decreases (~ 0.20 N.m<sup>-2</sup>), the SSC also decreases as fine-grained material settles on the mudflat in a  
247 1 cm-thick layer (Fig. 5B). Once all the material has settled, the SSC in the water column is low.

248 During the late slack and ebb periods, the topographic level decreases; this is interpreted as the  
249 result of dewatering and erosion of the soft/fluid mud deposit by tidal currents. In the Seine estuary,  
250 the duration of high water slack is up to 3 hours during spring tides, with a well-developed double  
251 high tide that favours settling of fine particles and dewatering/consolidation processes just after  
252 deposition.

253 The Medway mudflat has little topographical variations in comparison to the Seine and  
254 Authie mudflats (Fig. 4C): bed-level variations at the annual scale are +/- 1 cm (Fig. 3). This  
255 amplitude is consistent with results from earlier studies that report a low sediment supply in the  
256 Medway estuary (Kirby, 1990; Pye and French, 1993). This range of bed level elevation change is  
257 close to the altimeter accuracy, and thus is difficult to evaluate. However, on this mudflat the SSC  
258 is always low  $\sim 0.1 \text{ g.l}^{-1}$  (Fig. 5C), and the principal feature of the estuary is the lack of sediment  
259 supply. This low sediment supply, combined with the low impact of wind events (bottom shear  
260 stresses is always less than  $0.20 \text{ N.m}^{-2}$  (Fig. 5C), leads to a topographic equilibrium at the annual  
261 scale (Fig. 3).

### 262 **3. Erosion events**

263 Altimeter measurements at a high resolution and high frequency were used to evaluate bed  
264 level changes at the tidal scale, and determine the impact of wind-generated waves on the mudflat.  
265 Compared to continuous slow tidal erosion, the wind-induced reworking of intertidal mudflats  
266 occurs rapidly.

267 The Authie and Medway mudflats show no evidence of wind-generated erosion events (Fig.  
268 3; Fig. 5B and 5C), consistent with the sheltered morphology of these estuaries. In contrast, the  
269 Seine mudflat undergoes strong erosional phases induced by westerly to northwesterly swells and  
270 by local southerly to westerly waves in the Bay of the Seine (Lesourd et al., 2001). Such winds  
271 occur on the mudflat about 10 times per year, and are more common during the winter (Deloffre et  
272 al., 2006). At the study site, the amplitude of the wind-induced erosion was 0.2-2 cm, corresponding  
273 to wind speed intensities ranging from 12 to 20  $\text{m.s}^{-1}$  (Deloffre et al., 2006). A direct correlation

274 between wind speed and erosion on the mudflat is difficult, however, as the consolidation state of  
275 the sediment must be taken into account. For example, for the same wind event, a fluid mud bottom  
276 (such as that found during a depositional period) will undergo more erosion than will a consolidated  
277 muddy bed (such as that found during tidal erosion periods).

#### 278 **4. Coupling of altimeter datasets and lithologic analyses**

279 The SCOPIX X-ray images of cores allow the identification of physical structures, such as  
280 layers and surfaces, and biological structures, such as burrows, tracks, and shell remains, that make  
281 up the deposits. The images of the cores from the intertidal mudflats studied show that burrows  
282 always occur, and that shells are found at the Medway station only. As far as physical features, the  
283 Seine and Authie mudflat deposits are made up thin layers, whereas the Medway mudflat has no  
284 internal structure except for a single superficial layer. If only the data from the SCOPIX X-ray  
285 imagery is used, an interpretation of the sedimentary facies of the intertidal mudflats is difficult, as  
286 single layers can be interpreted as the result of semi-diurnal, semi-lunar, or lunar depositional  
287 cycles. To resolve this problem, for this study we interpreted sedimentary cores images in relation  
288 to the altimeter dataset. This approach allowed us to determine the duration of deposition for each  
289 layer, and to estimate deposition rates for each site, on the basis of the number and thickness of  
290 layers.

291 In the Authie mudflat, there is a great deal of bioturbation, mostly resulting from the activity  
292 of polychaetes (*Nereis*) at depth and of crustaceans (*Corophium*) in the superficial subsurface.  
293 Physical facies, however, also are easily observed at this site as thin layers of fine sediment (Fig.  
294 4A). The occurrence of thin sediment layers is consistent with the observed bed-level variations  
295 (Fig. 4). At this site, where deposition is driven by the semi-lunar cycle, the depositional phases are  
296 recorded in the cores, and correspond to cm-thick layers; however, all the semi-lunar cycles are not  
297 preserved in the cores (Fig. 4A). This indicates that even in protected settings, water current  
298 velocities are high enough to rework some deposits corresponding to fortnightly cycles and, as a  
299 result, gaps occur on the neap-spring recording time.

300 In the Seine estuary mudflat, freshly deposited sediments can clearly be identified in X-ray  
301 images of cores collected a few days after the highest spring tide period (Fig. 4B). They are  
302 characterized by erosion surfaces at the base of the elementary deposits, which result from tidal- or  
303 wind-induced phases. Above this erosion surface, the fresh deposits are characterized by a low  
304 consolidation state and low bulk density (water content on the order of 200%). The fresh deposits  
305 are seen in the positive X-ray images as light grey colours (Fig. 4B). The layer thicknesses  
306 indicated by the altimeter dataset and the sedimentological variations in the cores are consistent:  
307 when the core sampled a thickness of freshly deposited sediment of ~ 2.5 cm-thick, the altimeter  
308 dataset indicated a bed-level elevation of 2.7 cm (Fig. 4B). The lithological analysis of the  
309 uppermost part of the cores is more complicated, however, at sediment depths exceeding 10 cm,  
310 mainly because of strong mixing by bioturbation and the erosion of part of the deposits by waves  
311 and/or tidal currents (Fig. 3).

312 No apparent physical structure is seen in the X-ray images of the sediment core collected  
313 from the Medway mudflat. This is consistent with the monotonous altimeter record, which indicates  
314 that the mudflat elevation is stable throughout the year (Fig. 3). The X-ray image of the core does,  
315 however, show that the top centimetre of the sediment is very light, indicating that it corresponds to  
316 material that is less consolidated than the underlying muddy sediment. This thin superficial layer  
317 corresponds to the part of the sediments that is continuously reworked by tidal currents (Fig. 4C).

318

## 319 **General discussion**

320 The sedimentation processes on the three tidal mudflats examined here are strongly influenced  
321 by sediment supply and of the morphology of the estuary at various time-scales (Table2). No trend  
322 of net erosion or sedimentation occurs at the Medway station, whereas the mudflats examined in the  
323 Seine and the Authie estuaries have a similar sedimentation rate at an annual scale (15-18 cm.year<sup>-1</sup>).  
324

325 In the Medway estuary, Cundy et al. (2005) demonstrated that sedimentation rates are low and  
326 that processes are reproducible. In this environment, hydrodynamic conditions such as tidal currents  
327 and turbulence are minimal and thus do not cause erosion of the mudflat. Furthermore,  
328 sedimentation phases are not recorded. No source of sediment has been identified for this mudflat.  
329 These patterns are consistent with literature citing the reworking of fine particles inside the estuary  
330 and little erosion of tidal flats and salt marshes (Burd, 1989; Kirby, 1990; Pye and French, 1993).

331 The morphology of the estuary mouth controls the impact of wind-generated waves. In the  
332 open lower Seine estuary, wind-generated waves result in rapid erosion (0.2 to 2 cm) of the mudflat  
333 studied. Erosion by waves is controlled by wind direction and intensity, the water level on the  
334 mudflat, and the sediment characteristics. The erosion on the Seine mudflat during the survey  
335 occurred preferentially when the water level on the study site was low and was greater following the  
336 deposition of fresh, unconsolidated mud.

337 The sheltered Authie mudflat shows no evidence of wind-induced erosion: on this mudflat,  
338 tidal currents are the only cause of erosional phases at the study site. On the Seine and Authie  
339 mudflats, although long-term sedimentation rates are similar, the rhythms of deposition are different  
340 (Fig. 3, Table 2). On the Authie mudflat, sedimentation is continuous, with sedimentation rate  
341 controlled by the semi-lunar cycle. A linear relationship exists between the tidal ranges and the  
342 resulting deposit thickness, as determined from the altimeter data (Fig. 6). On the Seine estuary  
343 mudflat, no sedimentation occurs under neap- to medium spring-tide conditions. Rather,  
344 sedimentation on this mudflat occurs when a tidal range threshold value of 7.1 m is reached  
345 (Deloffre et al., 2006; Fig. 6). Sedimentation is thus discontinuous, occurring only during the higher  
346 spring tides, and leading to only a few (< 10) depositional episodes over the course of a year (Fig. 3  
347 and Table 2).

348 Sedimentation on the Authie mudflat corresponds to a semi-lunar rhythm, typical of most  
349 modern sheltered mudflats. The lower Seine estuary mudflat, however, exhibits a distinct pattern of  
350 deposition-erosion. This unusual pattern is nota result of the altitude of the study site, as its

351 elevation is the same as that of the Authie mudflat, and this pattern is recorded on other locations on  
352 the Seine slikke, including at lower altitudes (Deloffre et al., 2006). The difference between the  
353 rhythms of sedimentation on the Authie and Seine mudflats likely is linked to sediment availability  
354 and to sediment properties. On the Authie mudflat, the fine particles originate from the reworking  
355 of sediment from the lower parts of the slikke during the rapid filling of the estuary during the flood  
356 tide. During each spring period, the fine material is resuspended and sedimentation occurs on the  
357 mudflat at the location studied, which is on the middle slikke. In the Seine estuary, the delivery of  
358 sediment to the mudflat is related to the turbidity maximum (Deloffre et al., 2006). Because of the  
359 characteristics of the suspended particulates and the hydrodynamic conditions, development of the  
360 Seine estuary turbidity maximum is higher during tidal ranges that exceed 7.1 m (Avoine et al.,  
361 1981; Le Hir et al., 2001), which is the threshold value for deposition (Fig. 6). The control of  
362 sedimentation by the turbidity maximum also results in differences at the annual scale.  
363 Sedimentation rates are higher when river discharge is low, under which conditions the position of  
364 the turbidity maximum in the estuary is in the area of the mudflat (Lesourd et al., 2001; Le Hir et  
365 al., 2001). When river discharge is high, the turbidity maximum is expelled outside the estuary into  
366 the Bay of the Seine. During a lunar cycle (Fig. 3), high sedimentation rates result from some  
367 specific characteristics of the Seine estuary. Because of a high silt content (quartz, calcite) and a  
368 low clay mineral content (Lesourd, pers. comm.), the settling velocity of particles in the lower Seine  
369 estuary is higher ( $\sim 1 \text{ mm.s}^{-1}$ ) than in other estuarine settings (Delo and Ockenden, 1992). These  
370 high settling velocities combined with the long high tide slack (up to 3 hours) in the Seine estuary  
371 lead to the high sedimentation rates observed on the mudflat during the highest spring tides. These  
372 conditions result in the settling of fluid mud, a phenomenon that is observed only in this estuary  
373 among the three estuaries studied; thus on this mudflat, dewatering processes must be considered.

374 The properties of cohesive material play an important role in controlling deposition (formation  
375 of laminae) and preservation of fine-grained sediments. The sediment of the Medway estuary  
376 mudflat, as analysed in the cores, is characterized by little variation in grain size. This feature,

377 combined with insignificant sedimentation rates, results in the absence of physical structures in the  
378 cores collected from this mudflat. Sediment properties such as grain-size, water content, and  
379 settling velocities play a role in determining the thickness of deposits on intertidal mudflats. The  
380 depth of wind-induced erosion is related to the cohesion of surface sediments as well as to wave  
381 amplitude. As a result, erosion occurs on the open Seine mudflat where the mud is soft or even fluid  
382 (Fig. 4B), whereas on the sheltered Authie mudflat, where the sediment is coarser-grained and less  
383 fluid, only a small amount of wave-related erosion is observed (Fig. 5A).

384 Interpretation of tidal structures via investigation of the lithology of modern intertidal  
385 estuarine mudflats presents many challenges. By interpreting altimeter datasets and X-ray images  
386 concurrently, we can better understand the deposition and preservation of rhythmites in superficial  
387 deposits. On the Authie and Seine mudflats, where deposition is driven by tidal cycles (Fig. 3 and  
388 Table 2), sediment is deposited in mm- to cm-thick layers. However, because of the biological  
389 activity and the tidal or wind induced erosion occurring on these mudflats, rhythmites are rarely  
390 preserved in the cores. The comparison of several mudflat settings enhances the plurality of  
391 sedimentation tendencies, in particular when considering the superficial material (Table 2). In the  
392 uppermost 5 cm of the cores, the age of sediment for the three estuaries studied ranged from 3 days  
393 to 10 years (Table 1). For the Seine estuary, the age of the uppermost part of the sediment varied  
394 from a few days to a month, largely related to the unique behaviour of this system, i.e., high  
395 sediment supply and sedimentation rates, but only during the highest spring tides. On the Authie  
396 mudflat, where sedimentation is driven by the fortnightly cycle, the age of the top 1 cm of surface  
397 sediment was in the range of 1-10 days. For the Medway estuary, Cundy et al. (2005), using  
398 radionuclide methods, indicated a mean sedimentation rate of  $4 \text{ mm}\cdot\text{year}^{-1}$  in the upper 13 cm of the  
399 cores; this value is consistent with a single surface lamina and the absence of physical structures in  
400 this layer.

401 Based on altimetric measurements, the percentage of preserved sediment (preservation rate)  
402 on the mudflat can be calculated:

403 Preservation rate (%) = 
$$\frac{\Sigma (\text{thicknesses of deposit episodes during one year}) (\text{cm})}{\text{Annual sedimentation rate (cm)}}$$

404

405 On the Medway mudflat, the annual sedimentation rate is not enough significant in order to  
406 calculate a preservation rate (table 2). On the Authie mudflat, the preservation rate is high: 90%  
407 (Table 2). This high preservation rate is consistent with the morphology of the bay: few erosion  
408 episodes are recorded in this system (Fig. 3). On the contrary, in the Seine estuary, the preservation  
409 rate is lower (50%). This value implies that half of the fine sediment deposited on this mudflat  
410 during the year is stored temporally because of the erosion induced by current and waves. As a  
411 consequence, the lithology observed in the cores correspond to a discontinuous record, controlled  
412 by the turbidity maximum inputs and the erosion events (Fig. 3).

413 This paper demonstrates that high-resolution, high frequency and long term altimetric  
414 measurements can be used in order to better apprehend fast infilling mudflats. Most of the studies  
415 on intertidal mudflats deal with the sedimentary processes on the mudflat's surface, including  
416 studies based on altimetric measurements (Christies et al., 1999; Bassoulet et al., 2000; O'Brian et  
417 al., 2000; Andersen et al., 2002; Andersen et al., 2006). None of these studies is concerned by the  
418 lithological records in the mudflat's sediment. However many researchers are involved in recent or  
419 ancient tidal rhythmites lithological records (e.g: Dalrymple et al., 1978; Tessier, 1993; Kvale et al.,  
420 1994; Archer, 1995; Tessier et al., 1995; Choi et Park, 2000; Stupples, 2002; Mazumder et Arima,  
421 2005). This paper proposes a sampling strategy based on high resolution techniques that allow to  
422 make the link between sedimentary processes at the mudflat's surface and the lithological recording  
423 in depth (i.e. tidal rhythmites). Such sampling strategy brings new insights on the occurrence and  
424 the preservation rate of tidal rhythmites on rapidly infilling intertidal mudflats.

425

## 426 **Conclusions**

427 For estuarine intertidal mudflats, sedimentation and erosion processes are controlled by a  
428 complex combination of fine sediment availability, sediment properties, local morphology,  
429 hydrodynamics parameters (including tidal cycles, river flow, and wind-generated waves), and  
430 biological activity. These parameters shape the morphological evolution of intertidal mudflats at  
431 several time scales.

432 For this study, a combination of altimeter measurements at high resolution and high frequency  
433 over one year and collection of sediment cores along the survey led to a better understanding of the  
434 mechanisms controlling sedimentation and erosion at quasi-instantaneous (e.g., wind-generated  
435 erosion), semi-diurnal, and seasonal scales. For the three mudflats investigated, deposition and  
436 erosion occurred at the semi-diurnal tidal scale, whereas the sedimentation rhythms were driven  
437 either by fortnightly and lunar cycles. The analysis of the sedimentation rhythms confirm that the  
438 Authie mudflat is in a typical sheltered environment, where the deposition of fine-grained material  
439 occurs on a fortnightly-scale; that the Medway mudflat is in a sediment-starved system that is  
440 dominated by the reworking of autochthonous material; and that the mudflat in the mouth of the  
441 Seine estuary is characterized by a unique pattern of sedimentation, in which sedimentation occurs  
442 only during the highest spring tides, when suspended sediment concentrations in the turbidity  
443 maximum are higher. Lithological analysis coupled to altimeter measurements demonstrates that  
444 the sedimentation is nearly continuous (following the neap-spring cycles) on the Authie Bay, while  
445 it is discontinuous on the Seine estuary: the sedimentation occurs at lunar scale only during highest  
446 spring tide while erosion of the deposited sediment is controlled by tidal currents and waves.

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458

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## Caption (6 figures)

Figure 1 : Location of the areas studied (modified from Cundy et al., 2005)

(A) Medway estuary (Kent, UK)

(B) Authie estuary (Pas-de-Calais, France)

(C) Seine estuary, (Normandy, France)

Figure 2 : Typical grain-size of the surface sediment on the studied mudflats,

Figure 3 : Annual bed-elevation on the intertidal mudflats of the studied estuaries

Figure 4 : Sedimentation rhythms: comparison between monthly bed level evolution and recorded lithology

A: Authie; B: Seine and C: Medway

E.S.: Erosion Surface

Figure 5: Semi-diurnal mechanisms; sedimentary and hydrodynamics condition during similar spring tide conditions. A: Authie (07/05/03); B: Seine (10/05/03) and C: Medway (10/04/05)

These trends have been observed during several semi-diurnal surveys on each mudflat.

Figure 6 : Relationship between tidal range and maximal deposit thickness on the Authie and the Seine mudflats

LRF : Low River flow

HRF : High River Flow

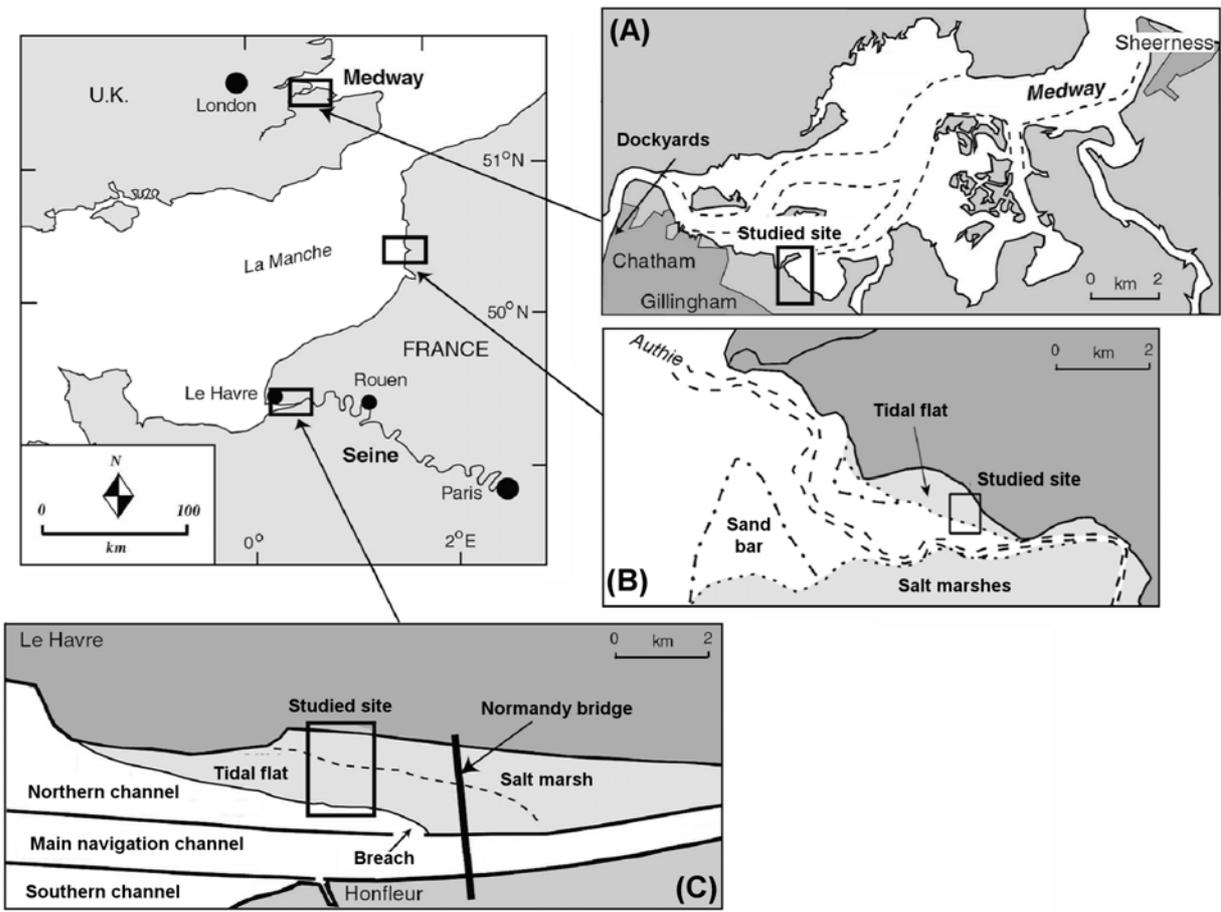


Figure 1

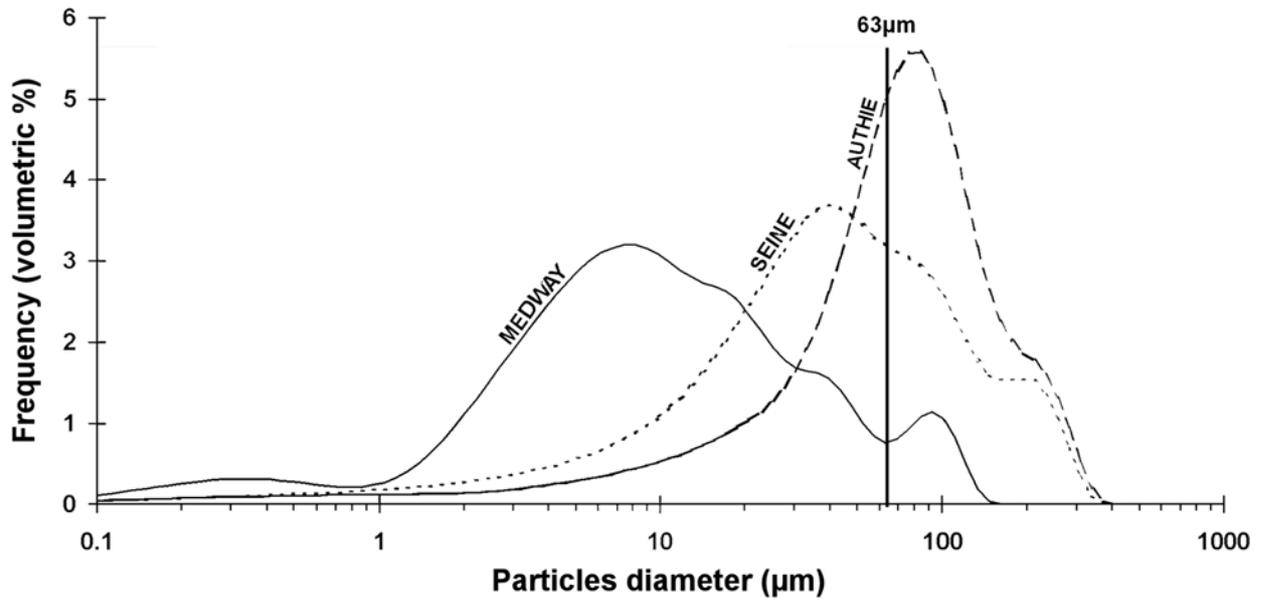


Figure 2

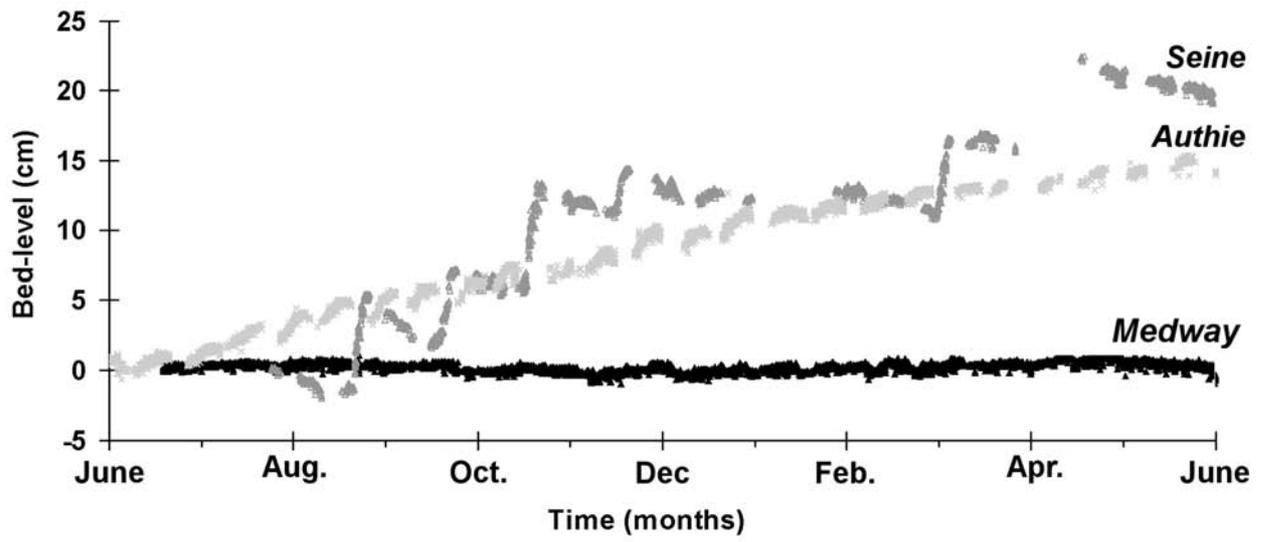


Figure 3

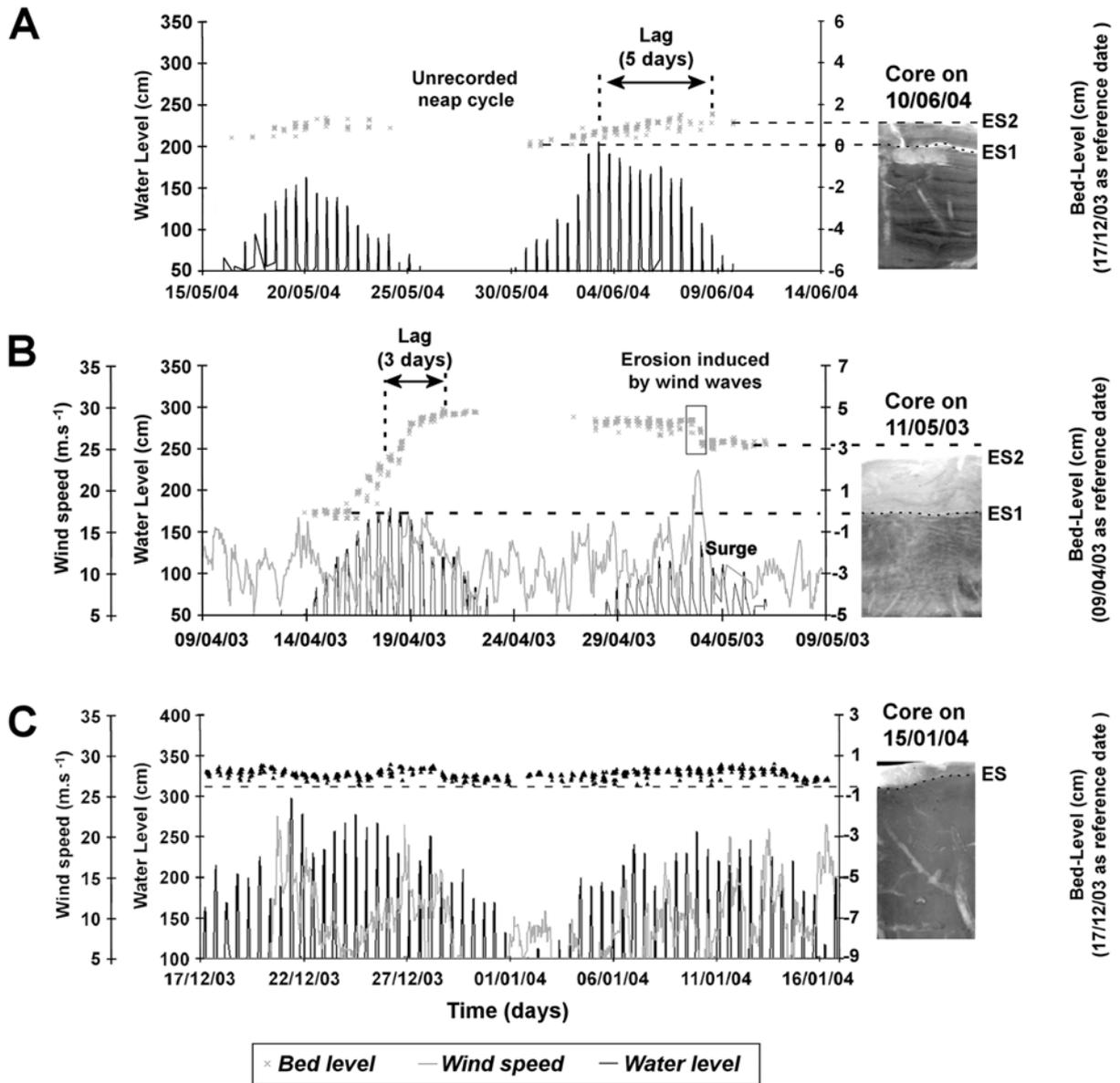


Figure 4

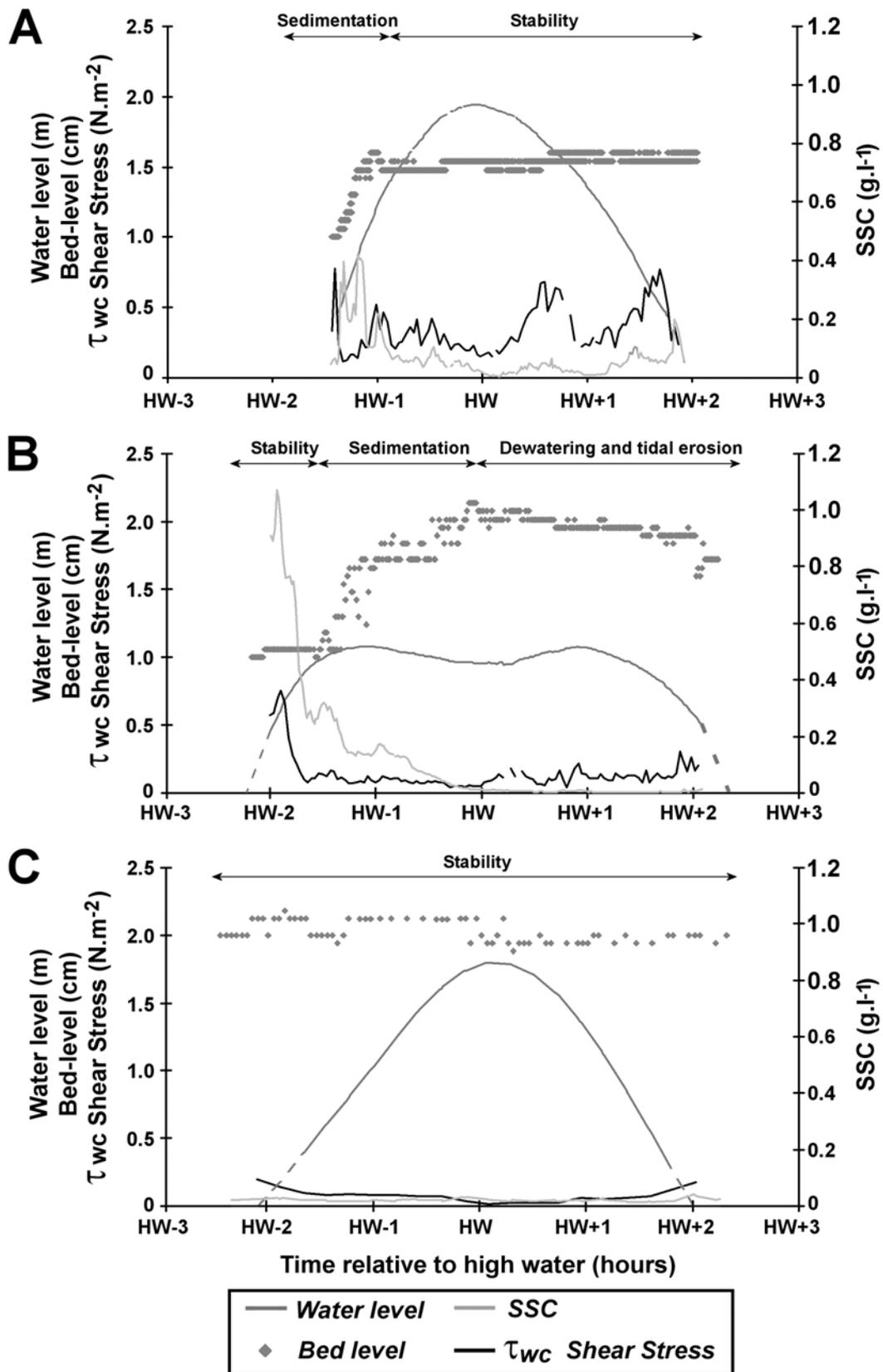


Figure 5

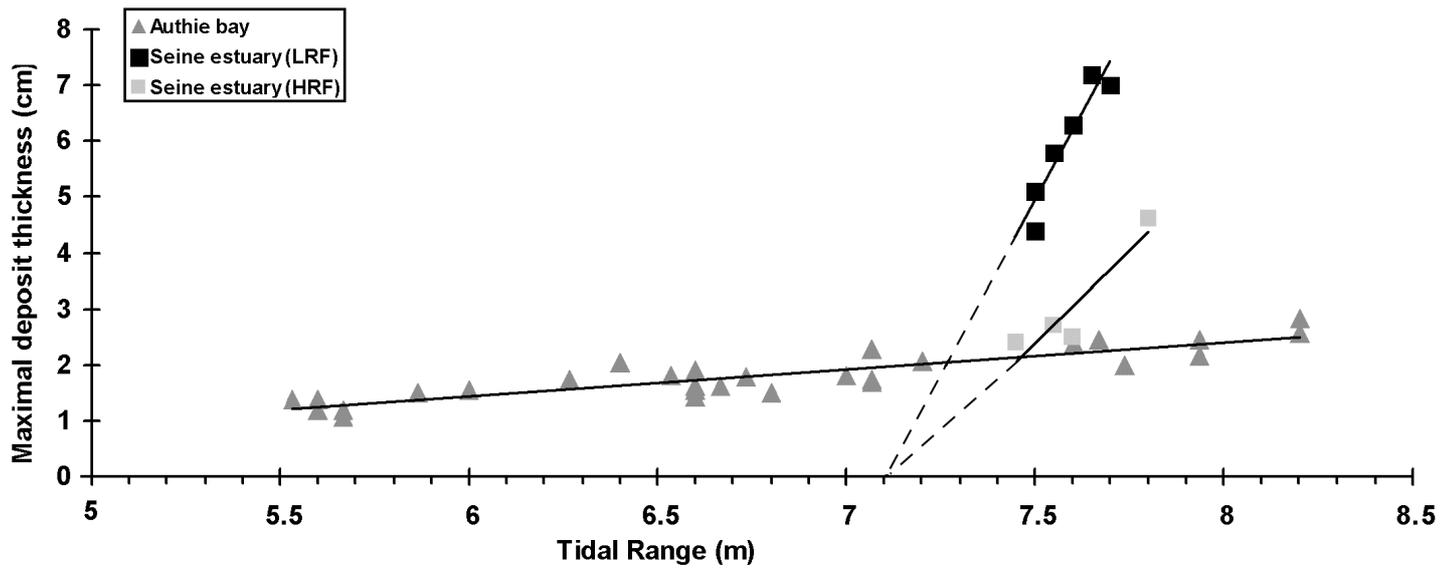


Figure 6

## Caption (2 tables)

Table 1 : Main characteristics of the studied mudflats (N/A: not available).

Table 2 : Comparison of the main sedimentological results on the studied mudflats.  
SD : semi-diurnal; FC: fortnightly cycle; LC: lunar cycle; TM: turbidity maximum

		Seine	Authie	Medway
Estuaries	Mean river discharge ( $\text{m}^3 \cdot \text{s}^{-1}$ )	430 (200-2,000)	10 (4-15)	35
	Annual solid discharge (tons)	500,000	N/A	N/A
	Tidal range at the mouth (m)	6.0 to 8.0	6.0 to 8.5	5.1 to 5.6
	Catchment area surface ( $\text{km}^2$ )	79,000	985	1,750
Mudflats	Maximum bottom SSC ( $\text{g} \cdot \text{l}^{-1}$ )	~2.5	1.5	0.25
	Maximum [Flood-Ebb] current velocities ( $\text{m} \cdot \text{s}^{-1}$ )	[0.5-0.45]	[0.5-0.45]	[0.35-0.25]
	Maximum Twc shear stress ( $\text{N} \cdot \text{m}^{-2}$ )	1.5	1	0.5
	Mean water temperature ( $^{\circ}\text{C}$ )	5-20	N/A	4-22

**Table 1**

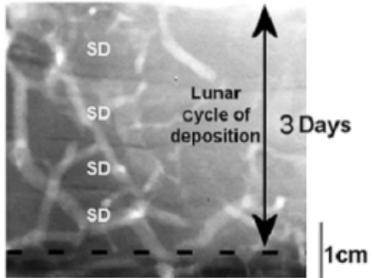
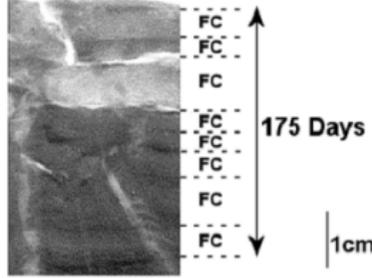
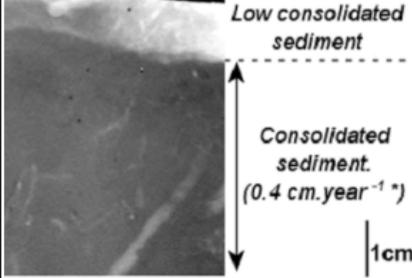
	Seine	Authie	Medway
Morphology at the Mouth	Opened estuary	Protected Bay	Opened estuary
Sediment Supply	Turbidity Maximum	Resuspended sediment inside the estuary	Low : Recycling in the estuary
Forcing parameter(s)	- Strongest Spring tides (TM development) - Wind (>15 m.s-1 westerlies)	Tidal Cycles	-
Sedimentation rates at semi-diurnal scale (cm)	0.3 to 0.8	0.1 to 0.6	-
Main sedimentation cycles (deposit sequence)	Lunar	Fortnightly	None
Max. sedimentation during one deposit episod (cm)	8	5	-
Number of sedimentation episod/year	7 to 10	15 to 22	-
Annual sedimentation rates (cm)	18	15	0
Preservation rates (%)	50%	90%	-
Typical Facies and Estimated duration based on bed-level evolution			 <p>Base on radionuclides measurements proposed by Cundy et al., 2005.</p>

Table 2

