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Structural effects of tidal exposures on mudflats along the French Guiana coast

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Abstract

Wetting and drying cycles on intertidal mudflats vary considerably with altitude, modifying the physical characteristics of surface sediment in ways favoring (or not) plant colonization. In this context, sediment properties were investigated by means of laboratory experiments and field surveys on a wide range of fluid to desiccated muds from the highly dynamic coastline of French Guiana. Changes in physical parameters, such as sediment erodability (yield stress), water loss and pore water salinity indicated a long term compaction of mudflats as well as fluctuations related to the successive wetting and drying cycles. Mudcracks constituted a spectacular feature representative of the contractional stress. They (re)opened after a few days of dewatering and (re)healed during the subsequent wetting. From the analysis of field data, the trapping of *Avicennia germinans* propagules in ephemeral mudcracks turned out to be responsible of 95% of the sprouting on the coastal fringe. Thus, desiccation process, usually considered as a typical feature of erosion, revealed herein to be a major mechanism of colonization. This mechanism undoubtedly affects the 1600 km long Amazon coastal system and is believed to exist in many other tropical environments submitted to important siltation.

Keywords: Amazon; French Guiana; coastal dynamics; mudflat; desiccation; mangrove

1. Introduction

During the last decade, several surveys carried out over temperate mudflats have demonstrated the spatio-temporal variability of intertidal cohesive sediment stability under the combined influences of physical, geological and biological processes (Friend et al., 2003; Lesourd et al., 2003; Widdows et al., 2000; among others). For example, Widdows et al. (2000) gave evidence of the reactivity of an intertidal mudflat at Humber Estuary (UK) with regard to the changing immersion time over a single spring-to-neap tidal cycle. More recently, a clear effort has been made to understand the short-term structuring processes of tropical intertidal mud, particularly along the mud system of the northeastern coast of South America (Baltzer et al., 2004). The present study aims at further constraining the complex interactions that exist between sediment stabilization, duration of air exposure episodes and mangrove settlement in this unique environment.

The S. American system, which extends from Amapá (NE Brazil) to the Orinoco River delta (Venezuela), is the longest muddy coast fronting the open ocean in the world. This extremely complex and unstable coast is constantly affected by the huge mud discharge of the

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Amazon River, estimated at some 1.1–1.3 × 10^9 tons year^{-1} (Meade et al., 1985). While about half of this fine-grained sediment supply settles on the continental shelf in the vicinity of the Amazon mouth, 15% to 20% migrates northwestward to the Guianas coastal plain. The huge mudbanks so formed along the northwestern coast of Amapá (Allison et al., 2000) then transit rapidly along the Guianas coast, resulting in successions of depositional and erosional phases that considerably alter the morphology of this highly dynamic shore. The extremely smooth slope of the intertidal fringe (averaging 1 : 1600) explains the considerable offshore extension of the mudflats. These deposits are exposed to air during more or less prolonged low-tide periods, and display different aspects depending on their location on a given mudflat (Fig. 1b). Thus, sectors adjacent to the coast (upper mudflat), are characterized by visco-plastic sediments having reached significant states of firmness, whereas others are composed of soft, bare muds likely to be transported (Allison and Lee, 2004). On the lee side of the banks, which also are accreting faces, massive arrivals of fluid mud in the form of mud lakes are frequently observed (Lefebvre et al., 2004; Baghdadi et al., 2004). Important mass transfers occurring under the combined action of tidal currents and mud liquefaction promote the accumulation of these thixotropic fluid muds along the coastline. Wave energy is strongly damped over the sheltering mud lakes, so that the complex hydro-sedimentary dynamics may produce a progressive stabilization of muds, followed eventually by initial plant colonization. From a remote-sensing-based analysis, Gardel and Gratiot (in press) estimated a two-and-a-half-year-period between the arrival of the maximal extension of the intertidal zone and the initiation of mangrove settlement processes at the same site. In the pioneer zones, where a dense recruitment of mangrove propagules occurs, the survival of small plants in their initial phase of development depends above all on the number of consecutive days of continuous air exposure (Chapman, 1976; Wells and Coleman, 1981). The structural states of the sediment bed, which are strongly variable over the mudflats, appear to be closely related to the establishment and maturation stages of mangroves.

The main objective of the present study is to assess the effects of emergence durations on the consolidation and structuration of intertidal mudflats in the meso-tidal semi-diurnal coastal system of French Guiana. More specifically, it aims at investigating the evaporation processes that are particularly strong in this tropical environment where the mean annual total insulation reaches 2200 h and the monthly average air temperature oscillates between 26 and 29 °C (Donet, 2004). To that end, the settling of fluid mud in glass prisms subject to immersion regimes based on different tidal rhythms was investigated in the lab and a field campaign was carried out over several major mudflats of the Guianese coastline to examine the interrelationship between fluid mud evolution, vegetation and tidal regime.

2. Materials and methods

2.1. Study sites

The mudflat areas studied are located on five large mudbanks of the French Guiana coast that are presented on Fig. 1a. They are listed as follows in the chronologic order of the missions: (1) on the right bank of the

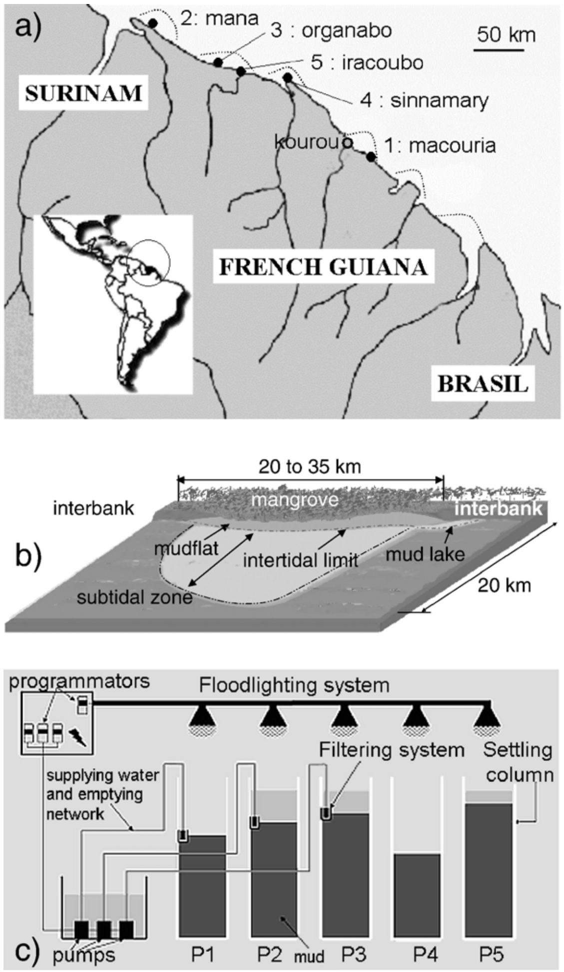

Fig. 1. Field and laboratory investigations. (a) Location map of the field sampling stations. Dotted lines correspond to the approximate position of the main intertidal mudflats in 2004. (b) Schematic representation of a mudbank (adapted from Baghdadi et al., 2004). (c) Schematic representation of the experimental set up. On this picture, muds in P1 and P4 are exposed to air, P1 because of a phase of emergence.

Macouria rivermouth, 25 km southeast of Kourou, (2) on an isolated mudbar of the bank of Mana, 140 km northwest of Kourou, (3) at the mouth of the Organabo river, 90 km northwest of Kourou, (4) at the Iracoubo river mouth, 70 km northwest of Kourou and lastly, (5) at the mouth of the Sinnamary river, 40 km northwest of Kourou. These areas were investigated in June 2004, during the rainy season, when surface water salinities can periodically fall to about 10. The outer side of soft mudbanks, being wave exposed and very shallow even at high tide, was not accessible in four cases and measurements had to be performed near the mouths of the river leading to the mudflats concerned. For the mudbank of Mana (n°2), an appropriate boat made possible the study of an isolated bar, separated from the shoreline by a distance of about 400 m. The scarcity of precisely georeferenced points in the coastal zones of French Guiana combined with the difficulties of using leveling instruments or differential GPS in the field, caused problems with vertical referencing; to that end we used the tidal signal registered by a pressure tranducer (©NKE) which, once readjusted with the local tidal harmonic components, provided the altitude (error of about 10 cm) of each point over the mudflat according to the exact hour of its flooding by the tide (Gratiot et al., 2005). The tidal harmonic components were provided by the Service Hydrographique et Océanographique de la Marine (SHOM; www.shom.fr). Since 1992, a tidal gauge was moored on the 'Iles du Salut' islands during 892 consecutive days by the SHOM. 94 frequency components were extracted and are currently used to predict the tidal signal. Atmospheric pressure being almost constant in French Guiana (≈1011 hPa, Donet, 2004), it has no influence on the tidal signal. Finally, the additional effects of other parameters such as wave secondary currents and on-shore wind stress, do not seem to modify significantly the propagation of tides over mudflats, as reported by Gratiot et al. (2005).

At the exception of the organic content, all of the parameters that are described in Section 2.3 were measured in situ and in the laboratory. To link the evolution of those parameters to the observed geomorphic features, an arborescent classification was defined (Fig. 2). Three criteria were chosen for this classification, namely: the presence or the absence of desiccation cracks, of phytobenthos or algal films, and of mangroves. The first criterion characterizes the level of contractional stress over the mud bank while the two others characterize the existence of micro and macro-flora, respectively. The assignment of a measured point to some class or another was assessed using a catalogue of photographs made during the field campaign (Fiot et al., 2004, available online at www.lthe.hmg.inpg.fr/~gratiot/).

2.2. Experimental set-up

The mud used for our settling prisms experiments was collected at the Macouria rivermouth, during the 'short summer' season on March 31, 2004 (site 1 in Fig. 1a). The experimental material was a natural fluid mud having a mean particulate concentration of 250 g l^{-1} (dry weight/total wet volume). The collected mud was

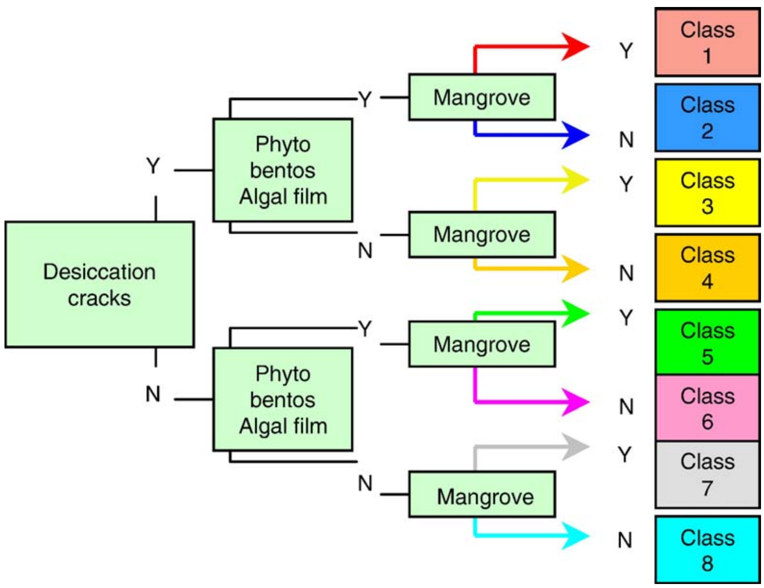

Fig. 2. Scheme for the classification of in situ measurements based on mud conditions and present vegetation.

hermetically sealed in opaque cans, carried to the laboratory, and transferred into the settling prisms within 2 days. The inorganic sediment particle density is 2.656 kg m^{-3}.

The experiments consisted in following the structuring processes occurring in fluid mud suspensions ($C \approx 250$ g l^{-1}) submitted to planned immersion–emersion cycles. These cycles were ultimately tuned to the tidal signal existing along the coast. The complete experimental set up is depicted in Fig. 1c. Fluid mud samples were set into five transparent settling prisms each with inner dimensions of $24 \times 24 \times 80$ cm (internal base area = 0.0576 m^2). These transparent prisms are ideal for observation and their glazed sides allowed for good sediment settling conditions free from lateral resistance. Each fluid mud prism—namely P1, P2, P3, P4 and P5—had an approximate mass of 11.6 kg. The regime applied to P1 simulated that of a point located at an altitude of 2.95 m, just at mean high water level (MHWL), where air exposure phases of 7 or 8 days long could be observed. Prism P2 simulated a height of about 2.60 m, in the vicinity of mean neap tide high water level (MNTHWL), and therefore experienced 2 to 3 days of continuous air exposure during neap tides. Conditions in P3 simulated a regular immersion—emersion cycle, so that air exposures and flooding phases were uniformly time-spaced like a semi-diurnal tidal rhythm. It corresponded to a height of 2.05 m, equal to mean water level (MWL). P4 and P5 prisms reproduced extreme situations corresponding to continuous air exposure and immersion, respectively. Within the three prisms associated to particular flooding regimes (P1, P2 and P3), the characteristic heights where deduced from the tidal signal provided by the SHOM and referenced on the 'Iles du Salut' station (French Guiana). Programmed pumps automatically controlled the filling up and emptying of prisms. At the ending of immersion cycles, emptying was initiated by briefly turning pumps on and continued by hydrostatic siphoning. Analyses of the tidal signal for year 2003 (Fig. 4c.) provided the inundation cycles applied to the settling prisms. Diurnal floodings occurred in P1 and P2 only, not in P3 (MWL). Flooding durations were lasting from 2 to 6 h per tidal cycle, depending on the semi-diurnal or diurnal character of the tidal cycle applied to the prism. Semi-diurnal floods (majority) began at 8 a.m. and 8 p.m.; single floods began at 8 a.m. During inundations, the water height above the muddy surface was roughly 10–15 cm, so that the effect of the water column weight on the compaction of the mud could be considered as negligible. Inundation cycles were carried out with seawater sampled on a mudflat (directly accessible from our laboratory), in order to roughly reproduce conditions of turbidity and salinity and to ensure the renewal of nutrients over the mud surface.

Periods of lighting and insulation were chosen in concordance with the local climatology (360 h of sunlight per month and 180 h of insulation, Donet, 2004). Lighting was from 6 a.m. to 6 p.m. with an intense period of insulation of 6 h, from 11 a.m. to 5 p.m. Insulation was simulated by means of five 300-W floodlight projectors placed just above the settling prisms. Prior tests showed that during insulation, 5 to 7 mm of free-water evaporate daily, depending on the distance between projectors and the water surface in the prism (Fig. 3b). This evaporation rate fits with values measured over wet tropical mudflat (Hollins and Ridd, 1997). Additional tests showed that the sediment surface temperatures reached during insulation periods were of the same order as those observed in situ (ranging from 25 to 40 °C approximately). The reproduction of conditions of daily sun exposure aimed at accelerating the consolidation

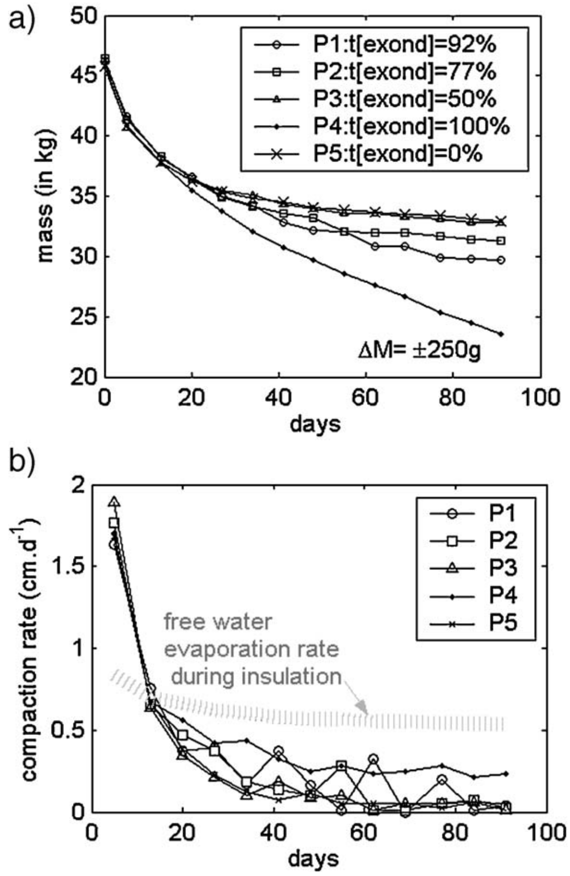

Fig. 3. (a) Mass loss by evaporation and compression in the settling prisms during the 3-month experiments. (b) Corresponding rate of water loss and free-water evaporation rate during insulation.

processes by evaporation while maintaining realistic forcing conditions. These experimental conditions led to the development of an algal film in very similar way to that observed during the field survey.

2.3. Parameters obtained in experimental and natural settings

Sediment erodability was quantified both on natural mud-banks and in settling prisms, measuring the shear stress τ_s by means of an Eijkelkamp shear vane. This vane tester supplies a shear resistance value measured as the torque sufficient to provoke bed rupture when applied to the spring head. An empirical calibration (provided by the constructor) relates the shear vane rupture value to an equivalent critical bed shear stress (kg cm^{-2}). The small size of the shear vane made measurements possible inside the settling prisms. The footprint of the vane on the mud surface is a disc of 2.4 cm radius. On the mudflats, the test is rapid, allowing repetition and calculation of an average value. Pore water salinity S was determined using an ATC refractometer loaded with a drop of water extracted from a core subsample (through filter paper in a hand press). The concentrations of surface sediment C_s (dry mass/total wet volume, in g l^{-1}) were calculated after drying to constant mass at 105 °C for 72 h and correcting for initial dissolved salt content based on pore water content and salinity. The masses of wet sediment M_{tot} (in kg) in settling prisms were measured weekly, using a KERN balance ([0–150 kg], d=50 g). Surface sediment temperature was monitored by a thermic probe inserted within the first centimeters of the mud. Organic content was quantified as weight loss on ignition after heating to 450 °C for 6 h, a procedure made possible by the scarcity of calcium carbonate and sulphides in the mud. Vertical profiles of concentrations $C(z)$, as well as total carbon and total nitrogen contents were determined at the ending of the 3-month period of experiments (by combustion at 1800 °C with a THERMOQUEST NA2100 PROTEIN apparatus).

3. Results

3.1. Time-dependent sediment compaction

Total fluid mud mixture mass, M_{tot}, is the most representative parameter to describe the overall sediment compaction, i.e., the elimination of pore water. It has been observed that water elimination occurred primarily through gravitational compression and evaporation. When evaporation became important, desiccation cracks appeared along the glazed sides of prisms. During more intense phases of evaporation, cracks were observed to be as wide as 2–3 cm. For that reason, we consider that the thickness of fluid mud mixture does not characterize precisely the elimination of water, whereas the mass M_{tot} does. The evolution of M_{tot} during the whole period of experiments within the five prisms is depicted in Fig. 3a. Another interesting parameter, directly obtained from M_{tot}, is the compaction rate. It is reported in Fig. 3b. Sediment compaction evolved similarly in the different prisms during the first 2 weeks, after which the curve obtained for P4 diverged significantly from the others because of evaporation. The other curves remained similar until approximately the 25th day. This initial period of about 20 days corresponded to the period during which the recently deposited fluid muds released large quantities of water through gravitational compression (5–20 mm day^{-1}), so that the effects of the various immersion regimes were not substantially different in prisms P1, P2 and P3. After that period, the evaporation rate during insulation (rate of 5–7 mm day^{-1}) then became higher than the compaction rate in every prisms, as reported in Fig. 3b. It means that the evaporation started to become efficient during the air exposure cycles. After day 25, M_{tot} decreased extremely slowly in P3 (immersed during 50% of time) and P5 (continuously immersed), until they reached an asymptotic trend. This gave evidence that compaction processes were quasi-unengaged at the ending of the 3-month-experiment period. In the mean time, masses in P1 and P2 evolved in an intermediate way, and were clearly affected by the immersion–emersion cycles. They exhibited a temporal variability indicating the effects of evaporation during emersion cycles, especially on bed surface parameters.

As shown in Fig. 4, surface parameters measurements (C_s, and τ_s) indicated a strong response to alternating phases of immersion and air exposure. After day 25, those parameters systematically reached peak values during periods when continuous air exposure exceeded 2 consecutive days. This was the case on days 27, 41, 62 and 77 for P1 and on days 27 and 55 for P2. For example, on day 77, after mud surface in P1 had been air exposed for 7 days, shear resistance value was twice as high as 1 week before, increasing from 0.0562 to 0.1087 kg cm^{-2} (+93%). This strong increase was associated with an over-consolidation of sediment of 20% (from 675 to 812 g l^{-1}) and an increase in pore water salinity (from 75 to >100). The renewal of immersion cycles after prolonged air exposure caused an immediate and significant decrease of surface concentration C_s and salinity values. This was the case in P1 on day 31. As a consequence

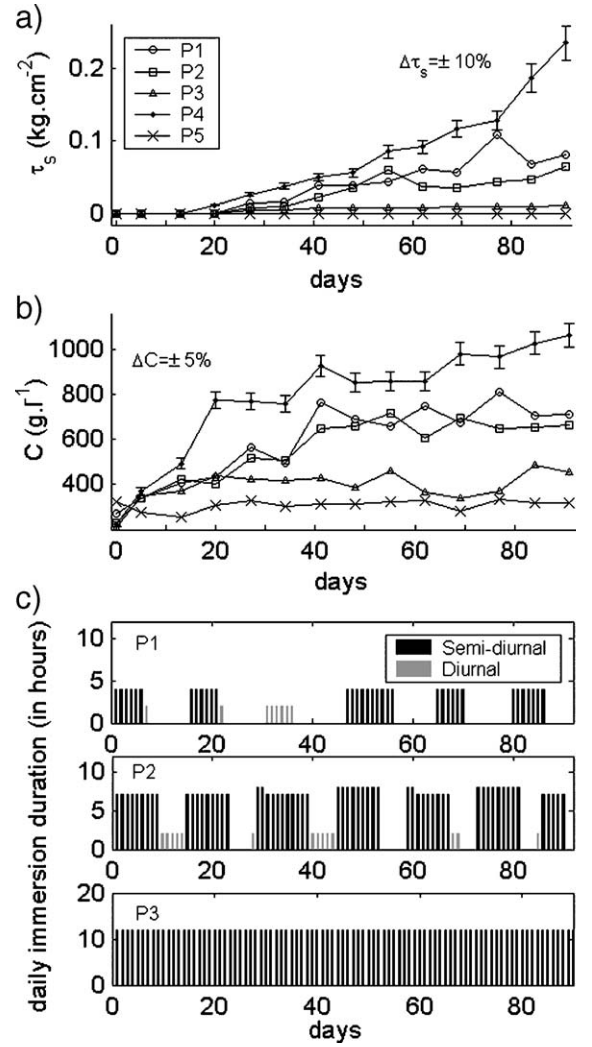

Fig. 4. Time series of the bed sediment parameters under the influence of programmed cycles of immersions. (a) Shear resistance τ_s; (b) Mud concentration (% dry weight/wet volume); (c) immersion–emersion cycles in prisms P1, P2 and P3.

of the beginning of diurnal immersions, the increase in water content in the surface sediment was associated with a decrease in salinity (from 90 to 69) and a decrease of C_s from 563 to 495 g l^{-1}.

These oscillations are an expression of the reversible character of surface compaction processes. They are qualitatively similar to the ones reported by Yesiller et al. (2000) from laboratory experiments. The corresponding time response can be quantified by intercomparison of sediment prisms of P1 and P2. Surface compaction in P2 slightly exceeded that in P1 on day 55, as a consequence of a unique episode of continuous air exposure which started on day 53 in P2, while semi-diurnal immersions were maintained (permanently) in P1 in the meantime. During this episode, 2 days of continuous evaporation were sufficient to generate a noticeable surface compaction in P2 while surface parameters in P1 remained quite stable. This duration, $t_R \approx 2$ days, gives an estimation of the characteristic time of reversibility when optimal conditions of evaporation are met.

At the ending of the 3-month-experiment period, the continuously immersed sediment (P5) did not reach a significant stage of consolidation, τ_s remaining almost equal to zero. This lack of change demonstrates the very long timescale over which gravitational compaction processes occur. The daily immersed sediment in prism P3 also demonstrates a quasi unengaged compaction. We may conclude that semi-diurnal air exposure is insufficient to provoke a noticeable effect of evaporation on compaction. As a consequence, the resistance of sediment surface to shear stress remains very low ($\tau_s \approx 10^{-2}$ kg cm^{-2}). In contrast, evaporative processes in prism P4 (continuously air exposed) were still very active at the ending of the experiment, as shown by the gradual increase of C_s and τ_s. The final shear stress measured at the sediment surface of P4 was as high as 0.235 kg cm^{-2}. Settling sediment in prisms P1 and P2 demonstrated the most dynamic response. Beyond day 90, data presented in Fig. 4 indicate that sediment surface parameters reached asymptotic values suggesting that the time dependence associated with the 2–5 days emersion–immersion cycles would remain the most important phenomenon.

3.2. Altitude-dependent sediment compaction

Vertical profiles of particulate concentrations were measured at the end of the 3-month-experiment period. The five profiles, labelled $P_i = 1:5(z)$, are presented in Fig. 5. These experimental results, compared subsequently

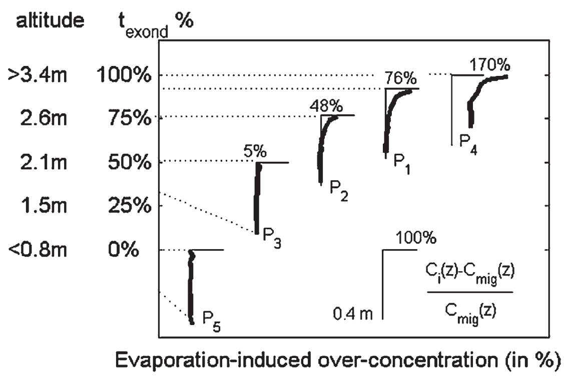

Fig. 5. Over-concentrations in surface sediment: vertical profiles corresponding to various durations of emergence, i.e. various altitude.

with field measurements, provide insight on the role of altitudes and correlative duration of emergence on mudflat compaction.

As highlighted in the previous section, the vertical profiles are not representative of an equilibrium state of compaction. Nevertheless, the 90 days duration of the experiment is believed to be representative of the maximum duration during which compaction processes can determine mudflat dynamics. It is almost certain that beyond this limit (and probably before), hydrodynamic forcing by waves and/or currents can also become important.

With the view to emphasizing the influence of air exposure times on the superficial structuring of the muds, experimental profiles $P_{\mathrm{i}=1:5}(z)$ were compared with the predictions of the empirical law proposed by Migniot (1968) for fluid mud compacting under gravitational compression effect alone:

$$C_{\mathrm{mig}}(z) = C_{\mathrm{s}} + n \cdot \log(z) \tag{1}$$

where $C_{\mathrm{s},5} \approx 440$ g l^{-1} is the particulate concentration of superficial sediment in prism P5 at the end of experiments, n is a parameter dependent on the nature of the soil–water complex. In this study, the best fit was obtained for $n \approx 40.3$.

Profile C_5 (continuously immerged) fits exactly the y-axis, a convincing indication that the experimental run involving only gravitational processes fitted the logarithmic z-dependence presented in Eq. (1) ($r^2 = 0.92$). Profile C_3 is similar, with a surface over-concentration of only 5% ($C_3(0) \approx 460$ g l^{-1}). This indicates that compaction by evaporation at MWL ($t_{\mathrm{exond}} = 50\%$) is hindered by frequent and prolonged periods of immersion (semi-diurnal water flooding regimes, with immersion during about 6 h). Prism P2, which corresponded to a total fractional emersion time of 77% (and an altitude close to MNTHWL) had a surface over-concentration ten times higher than that of P3 (48%, $C_2(0) \approx 650$ g l^{-1}). This clearly confirmed the increase in dewatering processes produced by prolonged air exposures. Evaporative over-concentration were significant from surface to a depth of 0.15 m. The surface mud in P1 was highly consolidated, with an over-concentration about 76% ($C_1(0) \approx 770$ g l^{-1}) with respect to the mud that remained continuously immersed during the same period. The depth reached by dewatering increased to 0.25 m. The over-concentration profile for P4 ($t_{\mathrm{exond}} = 100\%$) was the only one in which evaporation modified the sediment concentration over the whole prism. In the surface mud, over-concentration reached 170% ($C_4(0) \approx 1200$ g l^{-1}).

As expected, profiles corresponding to higher altitudes on the mudflat were associated with increasing evaporation processes and higher consolidations. These increases were directly linked with air and light exposure periods. Surface over-concentration data (dots) are reported from Figs. 5 to 6 to reveal the altitude-dependent sediment compaction. From the statistical analysis of the tidal signal over the year 2003 (raw data supplied by the SHOM; www.shom.fr), one can calculate the proportion of time during which a point at a given altitude is flooded. The black curve shows a linear relationship between 'global immersion time' and height on the mudflat for heights ranging from 1.2 to 3.0 m (of the form: $y = -48.4x + 150$). This rules out the existence of any threshold level above which overall immersion time would decrease rapidly. Comparing cumulative immersion times with surficial over-concentration we note that the effects of air exposure duration on surface over-concentrations increased tremendously above the MWL ($h \approx 2.1$ m) while the overall time of immersion did not show any inflexion for the corresponding altitude.

Thus, the experimental study demonstrated that the duration of immersions did influence the compaction of surface mud. However, this interrelationship is not a simple linear dependence. This conclusion was subsequently confirmed by field data.

3.3. Correlation between altitude and compaction in the field

Fig. 7 displays the altitude-dependent compaction of surface sediment for the field survey. A double

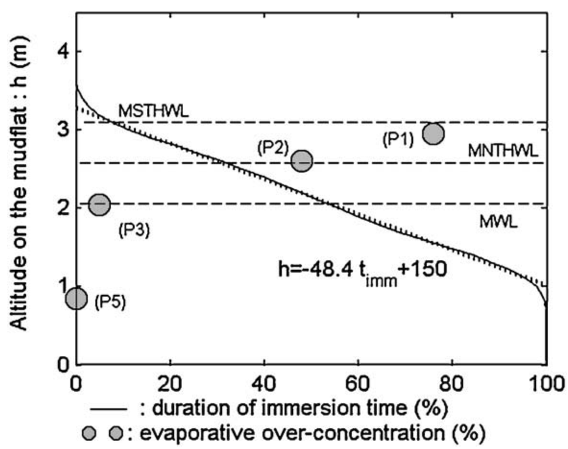

Fig. 6. Evaporative over-concentrations in surface muds and duration of immersions during tidal cycles: comparison of their reactions to altitude.

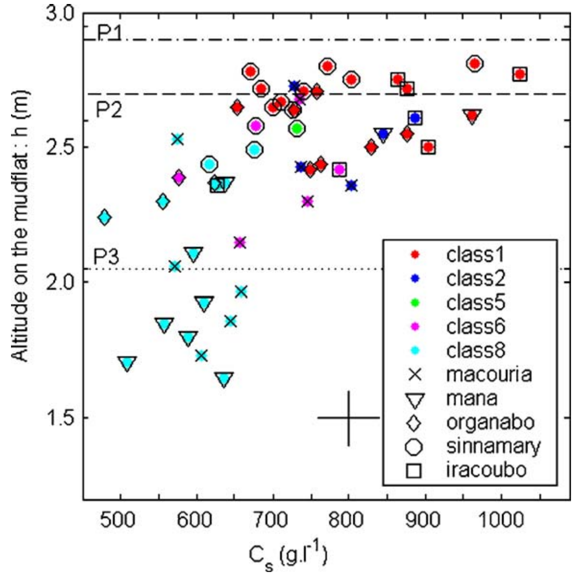

Fig. 7. Plot of in situ particulate concentrations against altitudes on intertidal mudflats with indication of sampling localities and physiographic classes.

representation allows for the reading of the sites the points were taken from, in addition to the class to which they belong. In situ field investigations are consistent with the experimental trends by indicating the existence of two main groups of points. Below a critical height of about 2.35 m (intermediate value between MWL and MNTHWL), 《purely physical》 conditions dominate the mud surface. The influence of macro biological activity is almost non-existent. As a result of tidal flooding conditions, structuring processes do not happen and the mud remains poorly consolidated. There is a transitional concentration, $C_{crit} = 650$ g l^{-1} that appears to be the limit beyond which the points belonging to class n°8 are almost lacking. This class represents soft mud with neither desiccation cracks nor visible vegetation (Fig. 2). This critical concentration was identified previously as the boundary between mud in 《fluid》 and 《plastic》 states (Gratiot et al., 2003). These primary observations indicate a fundamental change of structural response with altitude on the mudflat. Vegetation is completely absent within this margin of altitudes: the conditions for the initiation of plant colonization are not attained. For altitudes higher than $H_{crit} = 2.35$ m, C_s is in most of cases higher than 650 g l^{-1} (Fig. 7), implying well-structured plastic muds. A large majority of points in this group are associated with mangrove shoots or young trees, and therefore belong to class 1, extreme opposite of class 8 in our arborescent classification (class 1 = presence of mud cracks, algal films and mangroves). Finally, when considering the points associated with the presence of mangrove shoots or young trees (classes 1 and 5; 3 and 7 being never observed), it appeared that in 95% of cases, the sediment surfaces were or had been desiccated. This observation confirms the importance of desiccation as a fundamental factor for mangrove settlement.

As a first conclusion, the presence of macro biological activity becomes significant above the critical height of 2.35 m, and of primary importance in the neighbourhood of MSTHWL (beyond MHWL mudflats systematically appeared strongly carpeted with phytobenthos and algal matter, at the feet of mature and senescent mangrove forest).

3.4. Additional influences: biological and chemical effects

The relative influence of biological activity on the compaction of the sediment and the capacity of our experimental set-up to simulate this compaction can be inferred from the analysis of the geochemical and rheological properties.

The sedimentary organic matter measured in the prisms at the end of the experimental investigation is characterized by low carbons/nitrogen ratios (C/N ratio, from 7 to 11). Such values are typical of pioneer mangrove substratum (Marchand et al., 2003) while C/N ratios measured on substratum of mature mangroves are much higher, of the order of twenty or more (Meyers, 1994). This provided some elements showing the capacity of our experimental set-up to reasonably simulate the geochemistry of mudflats.

The rheological behaviour of laboratory and field samples was examined by plotting the shear resistance τ_s against concentration C_s of the surface sediment. On Fig. 8, the black symbols correspond to laboratory experiments (except first 20 days for the reason explained in Section 3.1) and colored symbols correspond to field data. Both groups follow the same trend with an exponential link between shear resistance and sediment concentration. This common trend (delimited by dotted lines) validates the transposability of our laboratory results to the field observations and turns out the overall similarity of the rheological behaviour of these two datasets.

A particular group of points is observed sticking out of the general trend around concentrations of nearly 700 g l^{-1}. They are associated to in situ measurements for which the mudflat surface was intensely carpeted with phytobenthos or algal matter, as confirmed by the iconographic catalogue. These high values of shear resistance are easily explained by the filamentous structure of the

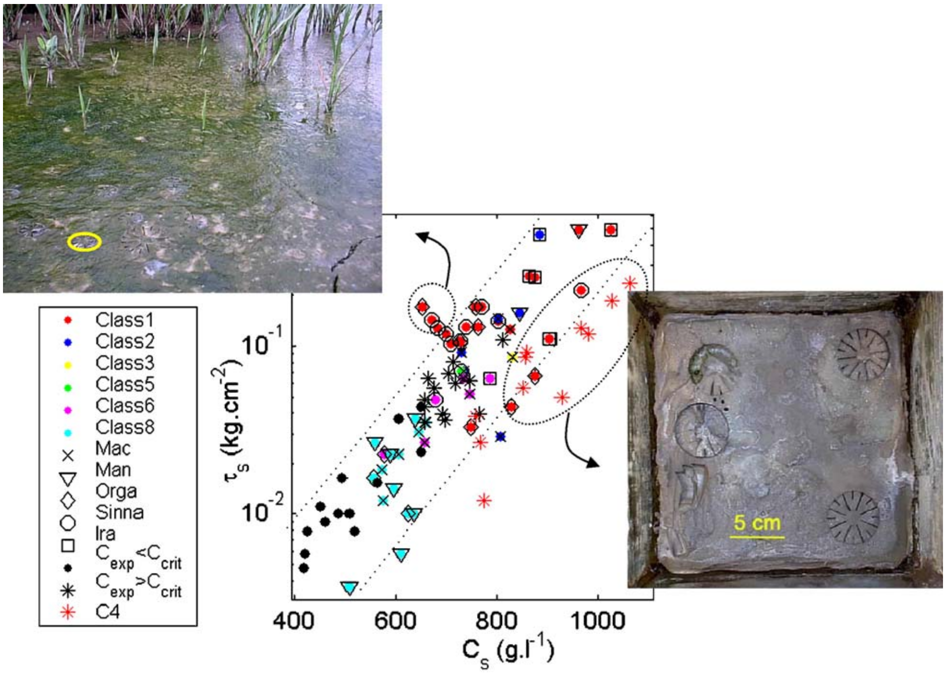

Fig. 8. Shear resistance of surface mud as a function of particulate concentration (dry mass / wet volume). Upper left photograph (Organabo mudflat, 06/15/2004) shows a thick algal carpet at the base of *Avicennia* young trees with a desiccation fissure on the right side. The lower right photograph shows white salt precipitates as a result of the over-saltiness of surface mud on top of P4 prism. The footprint which appears in yellow in the upper photograph measures 4.8 cm in diameter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phytobenthos and by the presence of algal matter that contributes to enhance the cohesion of the surface sediment. In the same way, surface over-saltiness may structure the sediment and make it less erodable provided it does not alter the chemical structure of the mud deposit, a process that probably caused the divergence of P4 data (red stars).

4. Discussion

The complex structural response of intertidal mudflats to air exposure periods reveals a strong temporal and spatial dependence that is a result of the interplay between physical and biological factors. The stability of the sediment in a particular point is thus highly variable depending on the overall duration of exposure period, and on the degree of modification by macro flora, or by phytobenthic and algal activity.

Desiccation phenomena turn out to be of primary importance for explaining mangrove settlement, because desiccation is an indication that the sediment has reached a mature structural stage, and because mud cracks constitute a major mechanism for trapping mangrove propagules.

4.1. Structural reversibility

During the course of our laboratory investigations, reversible variations were observed when immersion and air exposure alternated for short periods, resulting in only transient desiccation.

Reversibility occurred over characteristic response times of roughly 2 days, giving evidence of the strong temporal dynamics of the surface structure of the intertidal mudflat. As observed by Yesiller et al. (2000), sediment often re-heals during the flooding cycles following a prolonged dewatering period. Desiccation initiated at the mud surface can be interrupted by a new immersion and, in the case of experimental prisms, sometimes followed by a complete resticking of the sediment to the glazed sides.

As a result of the field survey, desiccation appears to be an essential element for *Avicennia germinans* recruitment on a mudflat exposed to the open sea. It can be inferred from our laboratory results that for soft muds subject to reversible effects, the field conditions favoring propagule trapping may vanish. In addition, small plants having settled over a soft mud plain at an early stage of consolidation can be rapidly destroyed during subsequent spring tide flooding. However, Steinke (1975) indicated that regular inundations have little effect on mangrove growth when their root system was firmly established.

4.2. Critical height

The importance of altitude on the intertidal mudflat and the corresponding air exposure periods is clearly demonstrated in this study, and several significant concordances between laboratory results and field observations can be shown. As previously demonstrated, a clear change of regime is observed between levels MWL and MNTHWL. Our laboratory experiments revealed that the action of evaporation on superficial consolidation was negligible for sediment located at MWL. In contrast, at MNTHWL, the increased duration of dewatering periods allowed the sediment to become well-structured within the 3-month duration of our experiments (Figs. 5 and 6). This information about the role of evaporation, directly dependent on the air exposure times and frequency, corroborates the mudflat response scheme described by Widdows et al. (2000). After measuring the erodability over an estuarine mudflat in a temperate climate, located just above MNTHWL, the authors showed that the exposure times contributed to the《protection of the bank》by sediment consolidation.

The combination of field and laboratory studies shows how a change in regime effectively occurs between MWL and MNTHWL. First, we suggest not to consider H_{crit} (2.35 m) as a real threshold altitude, but rather as an altitude in the vicinity of which there is an inflexion of the bed sediment response, in terms of structuring processes. The general trend of the distribution of immersion times vs. altitude of the mudflat surface (Fig. 6) does not show any sharp change in decrease rate at a given altitude. Actually, immersion times decrease linearly with rising altitudes increase, up to 3 m; for altitudes higher than 3 m a perceptible inflexion of the curve indicates a progressive accentuation of decrease. It has been shown above that surface sediment structures could be highly variable over a lunar tidal cycle and that conditions for the outbreak of desiccation cracks could be reached fleetingly in a given area. This suggests that the overall emersion time, percentage of long period of time during which a given height on the bank stays exposed to air, is not the most relevant parameter to explain the structuration of sediment under dewatering processes. This led to an analysis of the tidal signal based on the frequency of exposure events exceeding a given duration at a given altitude on the mudflat (Fig. 9). In the light of experimental results, 2 days are considered as the minimal duration permitting the formation of desiccation interstices (under the optimal insulation conditions considered in this paper). Fig. 9 shows that 2-day-emersion-periods occur only above an altitude of roughly 2.40 m, the number of such events reaching a maximum around 2.90 m with about 24 occurrences during a year. This indicates that the probability for desiccation, and then, for potential mangrove settlement, are reached

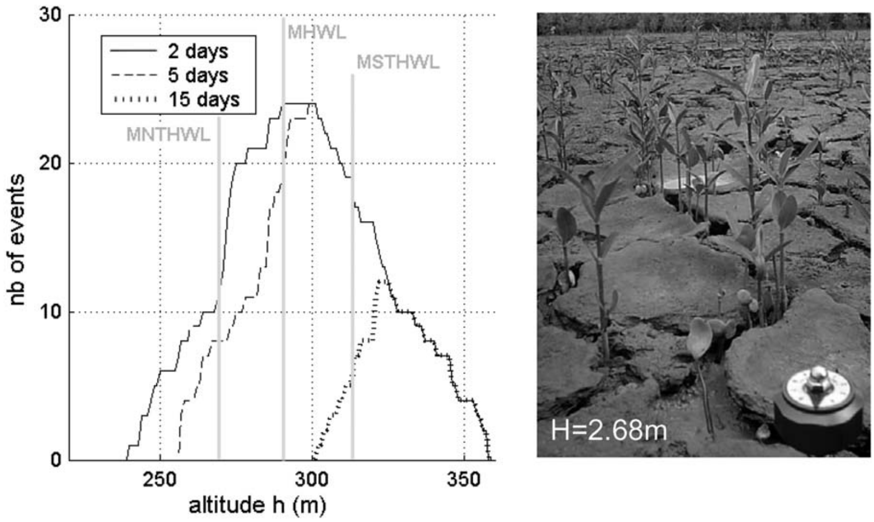

Fig. 9. Statistical distribution of emergence events of a given duration in relation to altitude on mudflat. Curves obtained from the analysis of the tidal components supplied by the SHOM over the year 2003 (www.shom.fr). The photograph (Mana muflat, 06/14/2004) shows strongly desiccated patterns. It gives evidence of the fundamental influence of mud cracks as traps for *Avicennia* propagules. The shear vane is 2.4 cm in radius.

from altitudes near the previously defined critical height 2.35 m and are maximum for heights of nearly 3 m. Longer emersion periods (5 days) are observed for a height of about 2.55 m, that is in accordance with the increasing density of observed vegetated points (H=2.55/2.60 m, Fig. 7). Actually, within the interval [H_{crit}−MNTHWL], mangroves keep undergoing semi-diurnal immersions which lessen plant colonization without stopping it. Besides, the number of reported events of 5-day-air-exposures is maximal at $H \approx 3$ m, just below MSTHWL. Such emersion periods next to MSTHWL are associated with very effective evaporation processes, as previously demonstrated in Fig. 5, with an over-concentration exceeding by 76% that of a continuously flooded mud surface. The conditions for the settlement of a durable mangrove are optimal there. Our results bring a functional explanation to observations by Baltzer (1969), Steinke (1975), and Diemont and Van Wijngaarden (1975). According to these authors mangroves settle principally between MNTHWL and MSTHWL. It also corroborates nicely the observations of Lefebvre et al. (2004) who reported the formation of patches of colonization for altitudes higher than 2.5 m. Fig. 9 eventually indicates that exceptional air exposures of 15 consecutive days may occur at MSTHWL.

4.3. A concrete explanation for the absence of vegetation below $H_{crit} \approx 2.35$ m

Our critical height corresponds also to a critical dried concentration of the bed sediment of about 650 g l^{-1}, below which the mud is considered as “fluid”. The shear resistance in this state, being close to nil, allows tidal currents, sometimes accompanied by incident breaking waves, to massively remobilize sediment. The sensitivity of *Avicennia* propagules and young shoots to tidal flooding has been described by various authors (Davis, 1940; Baltzer, 1969; Chapman, 1976; Marchand et al., 2003, among others). Among them, Baltzer explains that the lack of oxygen and the light obstruction caused by the particles that settle onto the leaves of youngest shoots drastically reduce their survival chances. This may be part of the explanation for the absence of vegetation in areas of high sedimentary supply and remobilization. Moreover, it should be emphasized that many of the measurement points present under H_{crit} (and concentration C_s<650 g l^{-1}) were collected on the *Mana* and *Macouria* sites; both represent a bumpy facies characteristic of the erosion induced by waves in a fluid mud sector. A great quantity of sediment is remobilized by every flood tide in these areas.

5. Conclusion

We undertook laboratory and field investigations to determine the dynamic of a tropical mudflat under the influence of air exposure periods. Even though various in situ investigations have dealt with problems of mudflat stability over temperate climate (Anderson and Howel, 1984; Dyer, 2000), very few have examined this aspect on tropical systems (Perillo and Kjerfve, 2005) and to our knowledge, almost no study details the trapping mechanisms of seeds by mudcracks.

According to the previous discussion, suitable conditions for plant colonization are dependent upon the structural state of the sediment and are closely related to the frequency and duration of mudflat emergence periods. The combination of laboratory experiments and in situ measurements indicate that the structuring regime of sediment shows an inflexion between MWL and MNTHWL, above which extensive desiccation episodes may occur and allow for the initiation of mangrove settlement. Below this altitude, mud remains soft because frequent re-immersions prevent extensive dewatering phases. For this reason, overall emersion time is not the best parameter to account for the spatio-temporal evolution of surface mud structure. A proper analysis of the structural evolution of sediment must be based on the frequency of prolonged air exposures at a given height.

The follow-up of several physical surface parameters within the framework of laboratory investigation gave evidence of an important temporal variability which is a result of the reversible aspect of bed sediment properties. As a consequence, the superficial consolidation of relatively soft muds exhibits oscillations that may be a significant reason for the temporary appearance of desiccation cracks (during dewatering periods). Despite high spatial and temporal variability, there is a direct relation between the sedimentary and vegetation structuring of the intertidal mudflat and the emersion times, explaining why the major influence of altitude on these processes.

The in situ sampling was carried out in June, during the rainy season. The impact of rains on the behaviour of the intertidal muds is considerable, with salinities and shear resistances over the sediment surface revealing a strong sensitivity of the bed to the intensity and duration of rain showers. It would be of a great interest to carry out a campaign during the dry season, in order to assess the sediment-mangrove interactions over a complete annual cycle. Concerning the laboratory experiments, future improvement should consider the effect of drainage reported by many authors as an important effect, largely governed by animal burrowing (Anderson and Howel, 1984; Kazanci et al., 2001; Perillo et al., 2005).

Ephemeral mudcracks undoubtedly play a major role for mangrove colonization along the 1600-km Amazon dispersal coastal system, and may be significant in many other mangrove systems suffering high rates of sedimentation. From a coastal management point of view, mangroves offer greenbelts that protect the shore from oceanic storm events (Danielsen et al., 2005). By pointing out mudflat areas that present the best physical conditions for the settlement of a dense and protective mangrove fringe, this study may help in developing appropriate mangrove rehabilitation strategy.

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