

Tidal rhythmites of the Marais Vernier Seine estuary, France and their implications for relative sea-level

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Abstract

The Marais Vernier, located in the upper reaches of the Seine River Estuary (northern France), preserves a thick Holocene succession of laminated detrital deposits and peats. The spectral analysis of one laminated deposit suggests that tidal processes were largely responsible for supplying sediments to this system. Two periods (16 and 32 laminae per cycle) were identified. These cycles can be related to either both the synodic neap–spring cycle (the so-called “fortnightly cycle”) and the anomalistic monthly cycle or both the semiannual and annual tidal cycles. The recognition of tidal influence on these deposits provides insight into the likelihood of some relative sea-level fluctuations previously inferred from these sediments. The depositional rates calculated for the laminated deposits, based on the recognition of these tidal cycles, suggest that the time interval required to deposit the sediments was far shorter than is implied by considering rates based on regional sea-level rise alone.

Keywords: tidal rhythmites; spectral analysis; wetlands; Holocene; Seine estuary

1. Introduction

Since the Last Glacial Maximum, the Flandrian transgression induced by a global climatic warming has profoundly affected coastal landscapes. Studies in northwestern Europe have described the influence of this transgression on the depositional environments (*i.e.*

wetland network development) and the sedimentation (*i.e.* alluvial prism settlement) in vast fluvial corridors (Allen, 2000). More recently, these environments have also been affected by the increasing development of human activities (Lafite and Romaña, 2001; Berglund, 2003).

The Marais Vernier, which is located within the lower Seine Valley, lies in an abandoned meander (Fig. 1). As part of a study to understand the Holocene evolution of the Marais Vernier, a 20 m thick core was drilled in the southwestern part of the area. This core is composed of alternating detrital and peaty deposits (Fig. 1). Palaeoecological markers (Huault and Lefebvre, 1983; Huault, 1985) and radiocarbon dates (Huault and Lefebvre, 1983) obtained from this core provided important information

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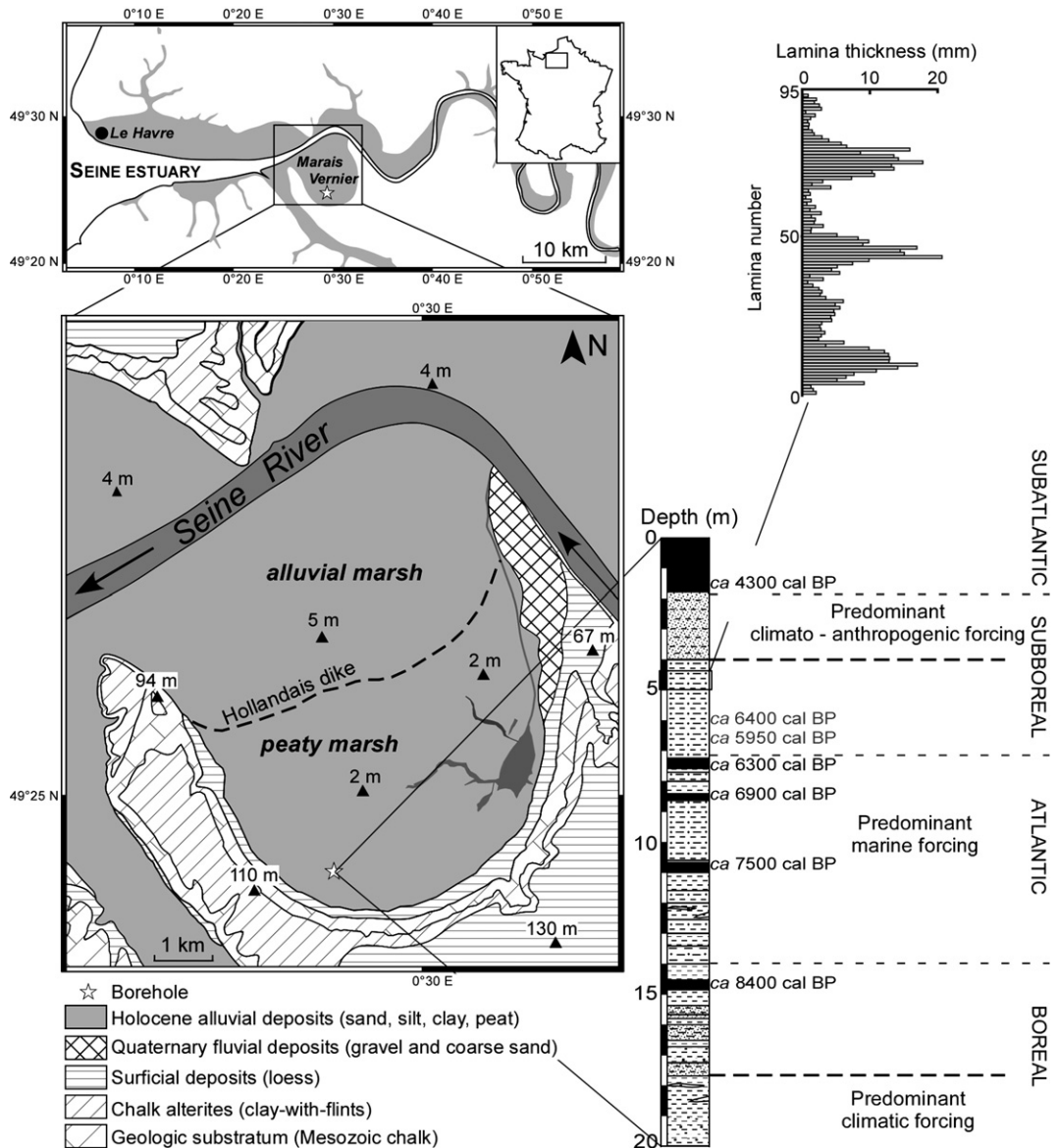


Fig. 1. Maps showing the location of the Marais Vernier in the lower Seine Valley of France and a graphic log of the 20 m core described for this study. The bar chart reflects the lamina thicknesses of the laminated sediments studied. See text for discussion.

on the Holocene evolution of the site. These studies showed that the peaty deposits are likely associated with either relative decreases in sea-level or periodic pauses in the Flandrian transgression, whereas the detrital deposits can be correlated with relative sea-level increases. Huault (1985) interpreted changes in the influx of allochthonous marine diatom valves as a marker of the record of relative sea-level increases in the site during the Holocene.

The present work aims to decode the processes, which controlled the sedimentological features in the median

part of the core, which is dominated by laminated silt and clay. Laminated sediments can result from a succession of random events (*e.g.* storms, floods) or a periodical process (*e.g.* tidal cycles). To check the likelihood of both hypotheses, the deposits were examined to see if lamina thicknesses varied in a systematic way. This approach helped us to determine the time represented by the detrital laminated deposits and thus put into question some relative sea-level increases previously described by Huault (1985).

2. Regional setting

2.1. Current situation

The Marais Vernier (European Datum 1950 coordinates lat: 0°27'16" E; long: 49°25'26" N) lies 30 km from the mouth of the Seine estuary (France; Fig. 1). It constitutes the largest remaining wetland system in the lower Seine Valley (about 4500 ha) making it one of the largest wetland systems in France. The area is affected by an oceanic climate characterized by a mean annual temperature of 10.5 °C and a mean annual rainfall close to 800 mm. The vegetation varies from (1) *Typha* and *Phragmites* in the wet part; (2) *Juncuns*, *Carex*, and some *Graminae* in the meadows; to (3) *Quercus pedunculata* and *Fagus sylvatica*

on the slope (Huault and Lefebvre, 1983). The bedrock underlying the site consists of Upper Cretaceous chalk and associated bedded and nodular flints. Varying in altitude between 2 and 5 m above mean sea-level, it is surrounded to the west, the south and the east by an abrupt concave slope. This slope is composed of Cretaceous chalk overlain by Pliocene–Quaternary chalk alterites (*i.e.* clay-with-flints) and in turn, by Quaternary loess (Fig. 1; Lautridou, 1985; Laignel et al., 1998; Laignel et al., 1999; Quesnel et al., 2000; Laignel et al., 2002). The landscape of the Marais Vernier is also marked by the presence of colluvial fans (Lefebvre, 1998).

During the Flandrian transgression, fine-grained sediments comprised of marine sands and silts and peats accumulated in the area (Huault and Lefebvre,

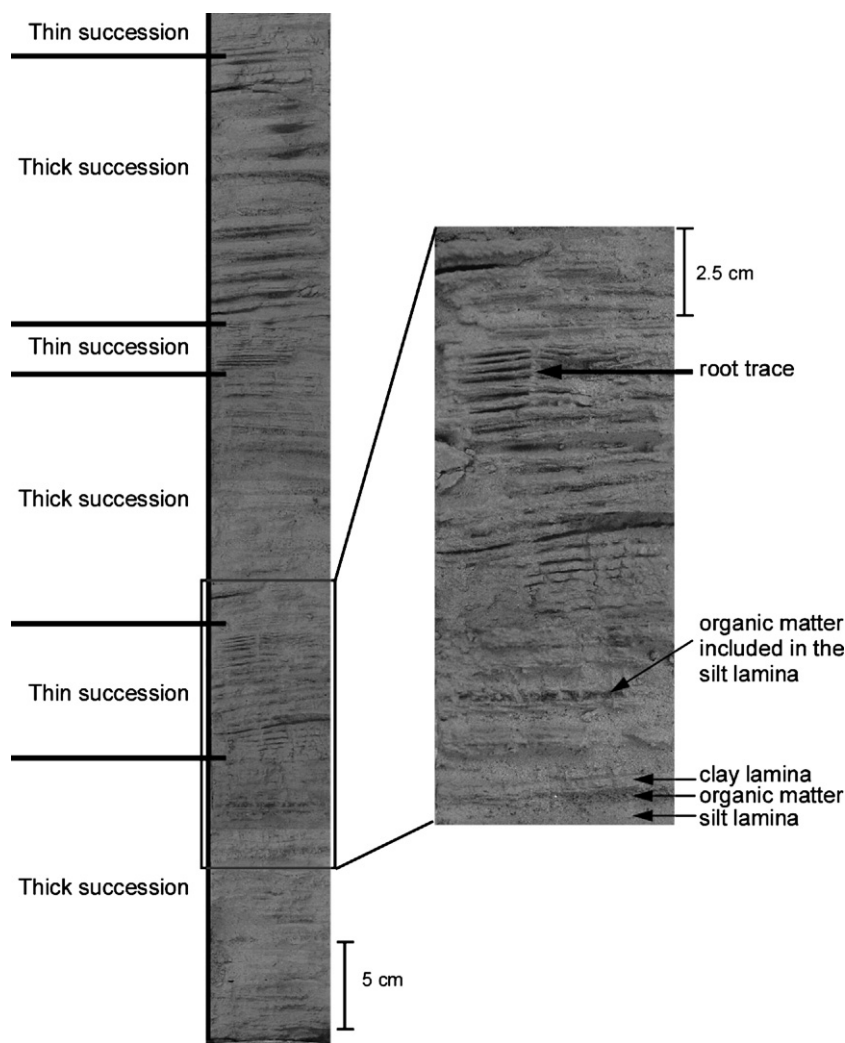
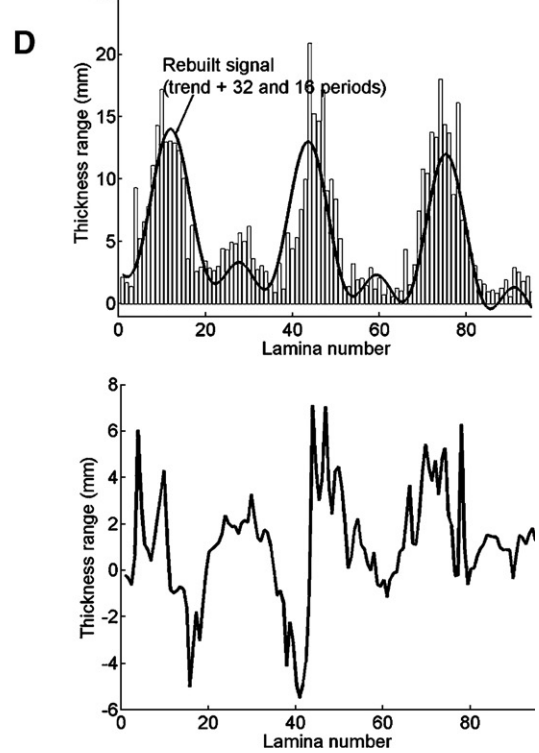
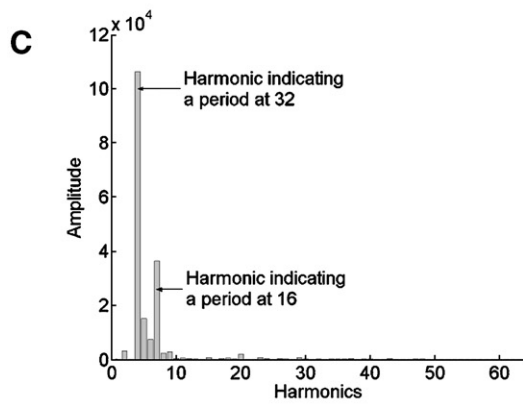
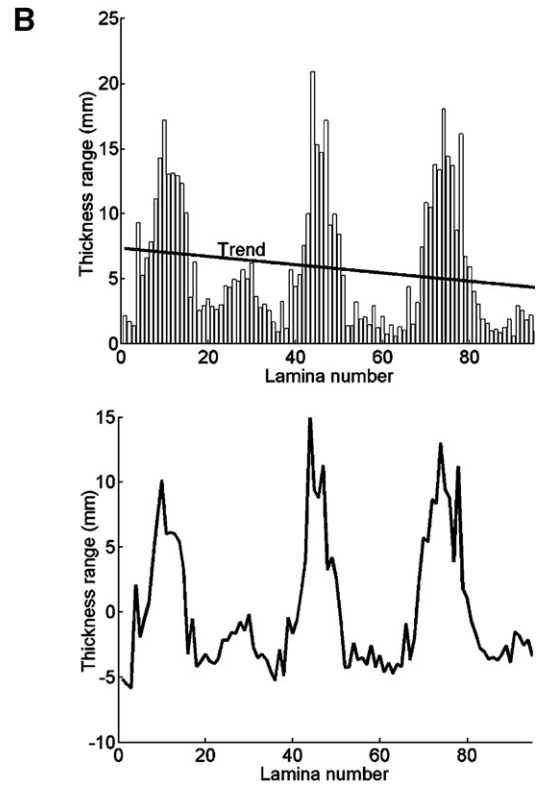
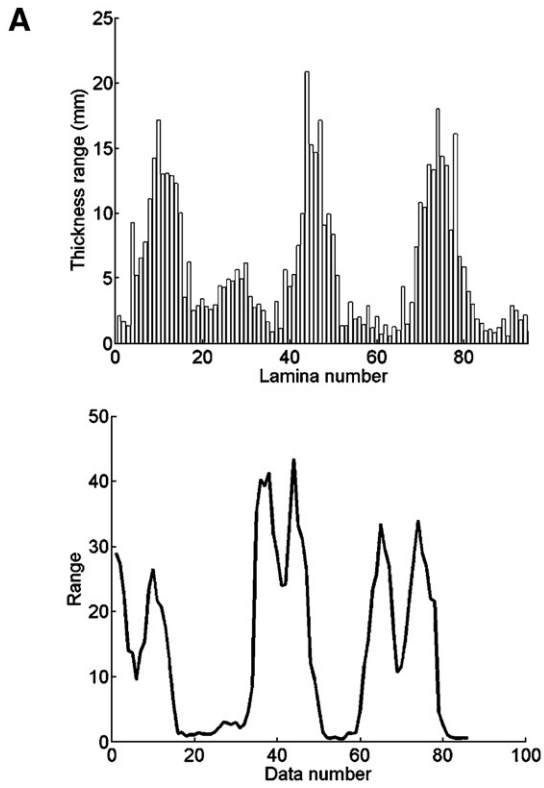


Fig. 2. Photographs of the studied sequence. Interval dominated by relatively thick laminae and thin laminae are noted. The clay laminae, which are in relief, appear as the light layers, whereas the silt laminae, which lie in depressions, appear as the darker layers. The enlarged photo, on which the organic matter present in the silt lamina may be distinguished as the black material, shows features described in the text.



1983). Huault and Lefebvre (1983) showed that the Flandrian transgression resulted in the deposition of sand and silt with peaty intercalations to form an offshore bar that isolated the southern part of the Marais Vernier from the river. This offshore bar was used as the foundation of the current Hollandais dike that crosses the Marais Vernier. The area north of the dike currently is the site of an alluvial marsh and polders while the area to the south shelters a peaty marsh (Fig. 1).

2.2. Holocene sedimentation

A sedimentological investigation was carried out on detrital deposits in the core in order to more accurately describe the Holocene evolution of the site (Frouin et al., 2003; Frouin et al., in press). Grain-size distribution was considered as an indicator of the depositional environment, while the composition of the clay was used to identify the origin (marine versus continental) of the sedimentary material.

Based on a synthesis of palaeobiological and sedimentological data, the core can be divided into three parts (Fig. 1). The core bottom is composed of 2.3 m thick interbedded clay with sand deposit containing few flint clasts. This part is characterized by wood pollens (Huault and Lefebvre, 1983) and sediments enriched in smectite and carbonate that originated from the erosion of continental deposits (*i.e.* loess; Frouin et al., 2003; Frouin et al., in press). The median part is composed of a 13.7 m thick thinly laminated silt and clay sequence that contains four peats. This part is characterized by sediments richer in illite reflecting an estuarine source (Frouin et al., 2003; Frouin et al., in press). The uppermost part of the core is composed of a detrital sandy deposit capped by a peat, which is characterized by pollens and spores derived from herbaceous plants (Huault and Lefebvre, 1983). Detrital sediments in the upper part, like those in the lower portion of the core, are enriched in smectite derived from the erosion of continental deposits (*i.e.* loess; Frouin et al., 2003; Frouin et al., in press). According to these studies (Huault and Lefebvre, 1983; Huault, 1985; Frouin et al., 2003; Frouin et al., in press), each part of the core can be related to different predominant forcings: the bottom to a

predominantly climatic forcing (strong erosion of the watershed), the median part to a predominantly marine forcing (estuarine supplied sediments) and the top to a predominantly climato-anthropogenic forcing (natural and human-induced erosion of the watershed).

3. Spectral analysis of a laminated sequence

3.1. Problematic

Previous studies on the diatom content of the Marais Vernier core (Huault, 1985) assumed that regional transgressive events were the cause of the detrital material deposition. In fact, the sedimentological analysis carried out on the same core showed that these detrital deposits originated from an estuarine source (sediment enriched in illite; Frouin et al., 2003; Frouin et al., in press). The estuarine origin of the sedimentary material thus attests to the marine character of these detrital deposits; however, the material origin does not necessarily directly imply regional transgressive events. Sediments might have been brought into the site because of other processes. For example, peat compaction, caused by dewatering, results in the creation of accommodation space and thus can mimic a regional sea-level rise (Allen, 1999; Baeteman, 2005).

By the time the peat layer developed in the Marais Vernier (5500 ± 150 yr 14C BP, *i.e.* ca 6300 yr cal BP, end of Atlantic period), coastal barriers formed across northwestern Europe (Beets et al., 1992; Long et al., 1996). These constructions took place during the climatic optimum (*i.e.* period of the highest moisture and mildest winters around 6000 yr cal BP; Roberts, 1998). The climatic changes, and the associated sea-level fluctuations that followed, caused the break-up of these barriers, thus enabling the re-entrance of detrital material (Beets et al., 1992; Long et al., 1996).

The remnants of the coastal barrier, on which the Hollandais dyke is built in the Marais Vernier (Fig. 1), may also have originated during the climatic optimum. The record of detrital material within the site likely indicates a break in the coastal barrier. This break can be related to either climatic changes (e.g. storms) or the

Fig. 3. Graphs representing the successive phases of the spectral analysis carried out here. Before the spectral analysis: (A) The bar chart represents the thickness variation of the organic-silt and clay couplets. The line chart represents the calculated variance of the signal expressed in the thickness variation, where 10 organic-silt and clay couplets were considered at once. (B) The bar chart, on which the line indicates the trend identified, represents the thickness variation of the organic-silt and clay couplets. The line chart beneath shows the trendless signal, on which the FFT was performed. Spectral analysis: (C) The bar chart represents the Fourier spectrum of the trendless signal, on which two periods at 16 and 32 were determined according to their amplitudes. (D) The bar chart, on which the rebuilt signal that comprises both periods and the trend was superimposed, represents the thickness variation of the organic-silt and clay couplets. This rebuilt signal represents more than 80% of the raw signal. The line chart beneath represents the remaining signal that corresponds to white noise.

associated relative sea-level fluctuations recorded in several sites across northwestern Europe (Beets et al., 1992; Long et al., 1996). A spectral analysis of the fine-grained laminae present in the intermediate and thickest part of the core was thus conducted in order to determine which process (*i.e.* periodical or not) is more likely responsible for the material deposition.

3.2. Materials and methods

This work focused on a 3.2 m thick portion of a laminated sequence of the core, dated as Subboreal in age according to pollens (Fig. 1). This sequence shows a rhythmic succession of silt laminae, which includes organic matter, covered by clay laminae (Fig. 2). The laminae varying in thickness from 30 to 0.3 mm exhibit a vertical pattern of thickening and thinning of the organic-silt/clay lamina bundles.

Within the 3.2 m thick interval, spectral analysis was conducted on lamina thickness variability within a 55.45 cm long segment of the core. This segment preserves the longest unbroken and best developed rhythmites.

The thickness of each organic-silt and clay lamina was measured using a calliper to an accuracy of 0.01 mm (Damnati and Taieb, 1995). Almost 95 lamina couplets (*i.e.* organic-silt and clay laminae) were measured (Fig. 3A). Their thicknesses formed a raw signal from which a mobile variance (*i.e.* 10 couplets considered at once) was calculated.

The first step of the rhythmite spectral analysis was the identification and removal of a linear trend using a 1st order polynomial fitting (Fig. 3B). In fact, the Fourier series are based on the assumption that the time series is periodic. The analysis of a data set results in the characterization of a series that matches that data but then repeats the series periodically beyond the measured data set. A trend can modify a data set in such a way that the series may not be repeated correctly beyond the measured set, which explains the need for removal of any trend before applying a Fourier analysis. However, it is important to note that a long record of tidal rhythmite deposition may show a regular deviation from the predicted tidal cycles that may be equated to palaeoclimatic influences (Kvale et al., 1999).

A fast Fourier transform (FFT) was then performed on the trendless signal. The FFT required a data set of an order of magnitude of 2^n , with n being a positive integer. The trendless signal was oversampled to achieve 128 values (*i.e.* 2^7 , Fig. 3C), instead of being supplemented by zeros, which modifies the raw signal. According to the Fourier spectrum obtained, the main harmonics (*i.e.* the highest amplitude) and the trend previously removed were

then used to rebuild a signal. The comparison between the rebuilt signal and the raw signal enables the determination of the quantity of information contained within this rebuilt signal. The remainder obtained from the removal of this rebuilt signal from the raw signal was also analysed to determine whether or not it contained information.

3.3. Results

The signal presents an important variability and thus provides enough information to carry out a spectral analysis (Fig. 3A; Davis, 2002; Stupples, 2002). The spectral analysis resulted in the identification of a linear trend (Fig. 3B) and two main periods (lamina number per cycle) at 32 and 16 (Fig. 3C). The 32 and 16 periods have the greatest amplitudes (1.06×10^5 and 3.6×10^4 , respectively) and were used as well as the linear trend to rebuild a signal. This signal represents more than 80% of the information contained in the raw signal. The remaining signal corresponds to white noise that may be attributed to the error margin of the analysis ($\approx 5\%$).

4. Overview of tidal characteristics

The identified spectral cycles indicate that tidal cycles may have been responsible for the observed lamination. To understand this it is necessary to first provide an overview of the potential tidal cycles that may have been recorded. Then the deposition of the organic-silt and clay laminae will be discussed in regards to the current tidal processes operating in the Seine estuary.

4.1. Tidal cycles

The oceanic tides result from the gravitational fields of the moon and sun and vary with the positions and distances of those bodies with respect to the earth (Kvale et al., 1999). Though many tidal cycles having periods ranging from semidaily to multiyearly have been described (Kvale et al., 1995; Kvale et al., 1999; Mazumder and Arima, 2005), the most common tidal periods identified in the rock record span half-days to months (Kvale et al., 1999). The half-day period, or semidiurnal cycle, can be explained in the context of equilibrium tidal theory. In this model, semidiurnal tides are the result of the rotation of the earth through two tidal bulges formed on opposite sides of the earth produced by the combined gravitational attraction of the moon and sun on the earth (Kvale et al., 1995; Kvale et al., 1999; Mazumder and Arima, 2005).

The most familiar half-month period, the so-called half-synodic month, is a result of the phase changes of

the moon. When the earth, moon, and sun are aligned, higher tides known as spring tides are produced. When the alignment of the moon and earth is at a right angle to the alignment of the sun and earth, smaller tides known as neap tides are produced. Another semi-monthly period to consider is the so-called half-tropical month, the result of changes in the moon's declination in its orbit around the earth. The interval of time required for the moon to move from its maximum northerly declination to its maximum southerly declination and return is called the tropical month. It causes the diurnal inequality of the tides in semidiurnal systems. The effect of this tide in northern France is minimal.

Tides can be affected by a monthly tidal cycle that results from changes in the earth–moon distance caused by the slightly elliptical orbit of the moon. This change in earth–moon distance produces spring tides of unequal magnitude (*i.e.* high-spring and low-spring tide). The period of time required to go from one high-spring tide to the next is called the anomalistic month (Archer, 1996; Kvale et al., 1999). Tides can also be influenced by a semiannual tidal cycle. Twice a year, the monthly periods constructively amplify each other and induce a maximum in the tidal forces. In northern France, the semiannual tidal maxima occur around the equinox periods.

4.2. Seine estuary current pattern

To understand the processes responsible for the lamina formation, the current behaviour of the macrotidal Seine estuary was studied. As the tidal wave propagates upstream in the relatively shallow system, it is deformed and a marked ebb–flood asymmetry occurs. It results in a short-term (4 to 5 h) flood with high current velocities and a long-lasting ebb (7 to 8 h) with lower current velocities (Avoine, 1981). Deloffre et al. (2004)

showed that sedimentation at a semidiurnal scale takes place during the late flood and slack period when the shear stress is low.

During a tidal cycle (*i.e.* flood/ebb), silt was likely supplied to tidal channels in the Marais Vernier during the flood period. To understand the origin of the organic matter included in the silt laminae, two laminae 1.2 m apart were dated by an Accelerator Mass Spectrometry (AMS). The AMS analysis (Fig. 1) provided two dates 5745 ± 35 yr ^{14}C BP (*ca* 6400 yr cal B.P.) around 5.7 m depth and 5250 ± 35 yr ^{14}C BP (*ca* 5950 yr cal B.P.) at 6.7 m depth. Both dates fall within the age range of the underlying peat. The organic matter included in the silt laminae may thus have originated from the reworking of the surrounding peat by the flow. This kind of organic-silt laminae has also been described in Holocene tidal channels of the Belgian coastal lowlands (Baeteman, 2005). As the oldest date was found in the shallower part of the laminated deposit, the reworking of the underlying peat was progressive. The clay laminae that draped the organic-silt laminae probably settled during the slack water period, which followed the flow. During the ebb period, the flow was not strong enough to erode the deposited clay. Thus, the organic-silt and clay laminae likely formed during a single tidal cycle (*i.e.* flood/ebb).

5. Tidal record in the Marais Vernier

5.1. Neap–spring cycles and anomalistic month

Based on an understanding of the various tidal cycles, the thin–thick succession shown in Fig. 2 may have resulted from tidal cycles ranging from semidaily to multiyearly. However, the rhythmite analysis helps to constrain which of the cycles are likely recorded within the rhythmite succession. The lamina deposition during

Table 1

Summary of calculated parameters for each tidal cycle such as the hypothetical time span represented by the sequence studied (55.45 cm), the cycles recorded (according to the periods at 16 and 32), a mean sedimentation rate and the time span represented by the entire laminated deposit (320 cm)

Tidal record	CD	TS1	1st period	2nd period	MSR (cm.yr ⁻¹)	TS2	
Semidiurnal	2D	0.5 day	48 days	16 days	8 days	422	≈ 0.76 yr
Diurnal	1D	1 day	96 days	32 days	16 days	211	≈ 1.5 yr
Fortnight	2M	14 days	≈ 3.7 yr	≈ 1.2 yr	≈ 0.6 yr	15	≈ 21.3 yr
Lunar month	1M	28 days	≈ 7.3 yr	≈ 2.4 yr	≈ 1.2 yr	8	≈ 40 yr
Semiannual	2Y	182.6 days	≈ 48 yr	≈ 16 yr	≈ 8 yr	1	320 yr

CD: cycle length.

TS1: time span represented by the sequence studied (55.45 cm).

1st spectral period: 32 laminae per cycle.

2nd spectral period: 16 laminae per cycle.

MSR: mean sedimentation rate.

TS2: time span represented by the entire laminated deposit (320 cm).

the Subboreal in the Marais Vernier may have been the result of a tidal system characterized by either a semidiurnal (2D) or a diurnal (1D) tide and a half-month (2M), a month (1M), a semiannual (2Y) tidal cycle or a combination of these. To assess the likelihood for preservation of each tidal period, we determined the time span represented by the laminated deposit studied (55.45 cm), the periods recorded (*i.e.* time unit per cycle) and a mean sedimentation rate. A time span was also extrapolated for the entire laminated sequence (320 cm; Table 1). No erosion was assumed in the calculations.

The current tidal pattern of the modern Seine estuary is semi-diurnal with neap–spring cycles controlled by the synodic month. The number of laminae deposited during a neap–spring cycle and the anomalistic month would thus be around 29 and 55, respectively, if one

assumed no deposition on the ebb tide and that every flood tide resulted in a deposit. Yet, the cycles identified by our analysis from the Marais Vernier correspond to 16 and 32 depositional events. However, it has been shown that the deposition on the northern mudflat of the Seine estuary mouth takes place only during the highest spring tides (Deloffre et al., 2004). If Seine estuarine tides were similar during the deposition of the Marais Vernier rhythmites, then, the studied succession of lamina record only the strongest flood tides that entered the area (*i.e.* high- and low-spring tides). Neap tides are therefore likely not recorded at this site.

The incomplete record of the tidal cycle may also be the result of disturbances of the flood tides in the area. In fact, some authors (de Boer et al., 1989; Stupples, 2002) have shown that a basin's natural resonance enhanced

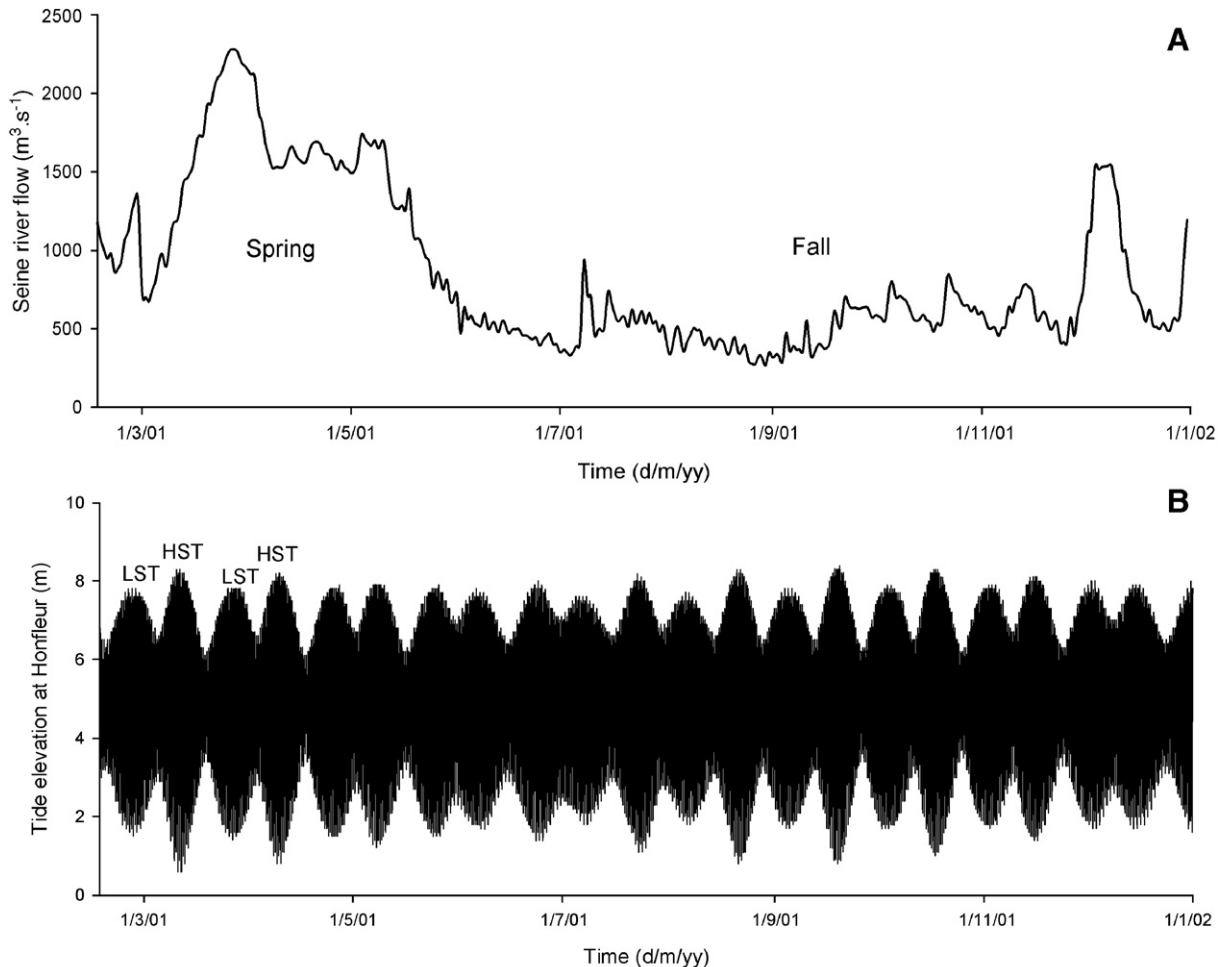


Fig. 4. Graphs showing (A) the Seine river flow near Honfleur (Seine estuary mouth, France) and (B) showing a nearly 1 yr record (2002) of tide elevation. Note the seasonal increase in fluvial discharge from March–May. Also note the unequal amplitudes of spring tides associated with the anomalistic month and the minimal diurnal inequality of the semidiurnal tides. HST: high-spring tide; LST: low-spring tide.

by random events may disturb the semidiurnal cycle. For example, the ebb tide T_n , perhaps enhanced by an increase in rain fed fluvial discharge, might disturb the flood tide T_{n+1} and not allow its entry into the site. If the next ebb tide T_{n+2} is a more normal tide, then the following flood tide T_{n+3} would normally enter into the site and so on. Thus even some semidiurnal tides of the highest spring tide period may also not be recorded.

As a result of changes in the earth–moon distance during the anomalistic month there is a difference in water height between high-spring tides and low-spring tides (Fig. 4) at the Seine estuary mouth. As a consequence, Deloffre et al. (2004) described a higher bed elevation during high-spring tides and a lower bed elevation during low-spring tides in the northern mudflat located at the mouth of the Seine estuary. Thus thicker lamina couplets are potentially deposited during high-spring tides than during low-spring tides (Fig. 5).

In the case of a neap–spring cycle and anomalistic month, the time spans represented by the studied deposit and the entire laminated sequence are 96 days and 1.5 yr, respectively (Table 1). The deposition occurred in a short-term period and as a result the sedimentation rate is

211 cm/yr. The linear trend removed from the signal before the Fourier processing would thus reflect part of the semi-annual (2Y) cycle. The neap–spring cycle and the anomalistic month may thus be a good explanation to the lamina succession observed in the intertidal environment described by Huault and Lefebvre (1983). The presence of root trace indicating the development of plants involves either the final stage of the infilling or a lower sedimentation rate than the one calculated here. In the second case, longer term cycles involving a lower sedimentation rate will thus be considered.

5.2. Semiannual and annual cycles

The expressed periods may also be the result of semi-annual and annual cycles. This interpretation depends, in part, on the position of the sediment on the tidal flat. Tessier (1998) showed that deposition is likely to occur only on the upper intertidal to supratidal zone during the highest equinoxial tides. The diatom content of the rhythmites, includes some species that tolerate temporary emersions (Huault, 1985), thus suggesting an intertidal environment. Moreover, the lithological succession after

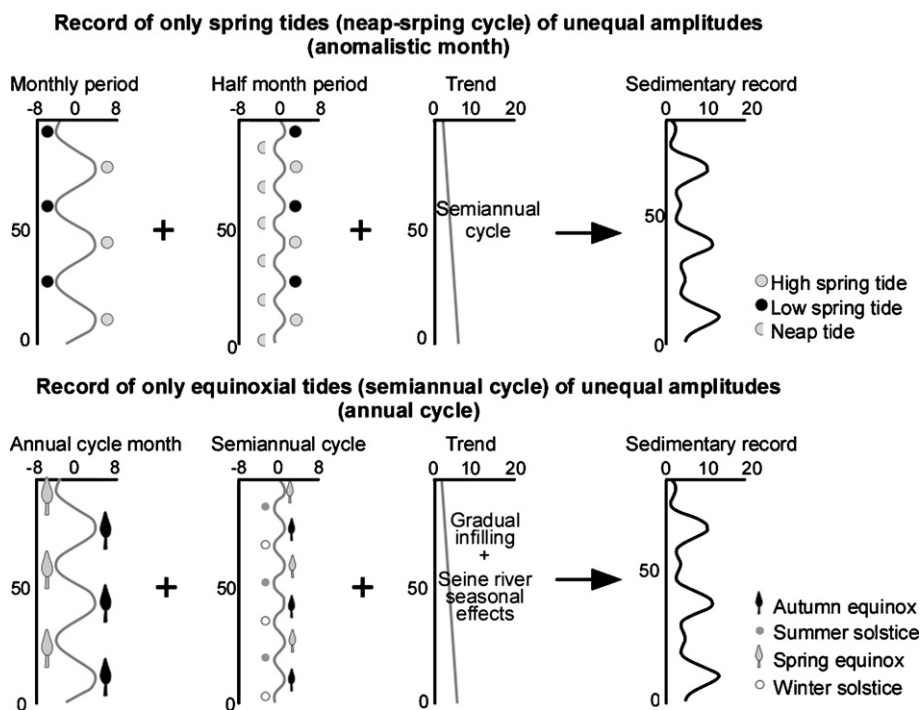


Fig. 5. Representation of each different spectral cycle observed in our deposit and the trend in regards to our hypotheses. In each graph, the x-axis indicates the expected variation in the lamina thickness (in mm) with respect to the considered processes and the y-axis represents the studied lamina number. In the first case, the rebuilt signal represents the spring tides of the synodic neap–spring cycle and the anomalistic month and probably reflects a part of the semiannual cycle. In the second case, the rebuilt signal represents the equinoxial tides and a gradual infilling, and perhaps contains a seasonal contribution of the Seine River.

the peat dated 5500 ± 150 yr ^{14}C BP indicates a shallowing upward succession as indicated by the progressive upward increase in the number of the rootlets preserved in the core followed by the formation of a peat. The presence of root traces in the studied deposit (Fig. 2) suggests an upper intertidal position. This further suggests that the lamina couplets were deposited only during the equinox tides (spring and fall), when the tidal forces reached a maximum in the Seine estuary (Fig. 5).

In the case of semiannual and annual cycles, the time spans represented by the studied deposit and the entire laminated sequence are 3.7 yr and 21.3 yr, respectively (Table 1). The deposition results in a sedimentation rate close to 15 cm/yr, comparable to the one observed today in the sheltered Authie Bay (Deloffre et al., 2004). The linear trend may thus reflect a gradual infilling of the area basin as observed today in Authie Bay.

The unequal amplitude between spring and fall equinoxes may be related to the seasonal changes in Seine river discharge (e.g. flood and low water periods). During spring, the turbidity maximum zone remains in the Seine Bay because of the high Seine river flow (Fig. 4), reducing sedimentation rates within the Seine River and producing potentially thin couplets (Fig. 5). During fall, the turbidity maximum zone lies in the Seine estuary mouth as the Seine river flow is low (Fig. 4), thus enabling the sedimentation to occur normally during fall equinox tides (thick couplet; Fig. 5). This pattern reflects the current situation in the Seine estuary. Sedimentation phases mainly occur during low water periods downstream of the lower Seine Valley (i.e. where the Marais Vernier lies) in the northern mudflat of the Seine estuary mouth (Deloffre et al., 2004).

5.3. Record of marine material income

According to both above-mentioned hypotheses, the depositional time span is less than 22 yr for the entire laminated deposit. This time span represents only a tenth of the time span between the last two peats (based on AMS dating of the peats). In the deposit studied, the diatom record indicates two marine influxes interpreted by the authors as transgressive onlaps (Huault, 1985). Considering the time span for deposition based on the rhythmite analysis, the transgressive hypothesis appears unlikely, as it would imply very short timescales for each relative sea-level fluctuation. In fact, Roth and Reijmer (2005) concluded that the timescale of Holocene sea-level fluctuations is of several millennia (i.e. 3000 to 3500 yr), based on data coming from both sides of the Atlantic Ocean. Thus both marine influxes indicated by diatoms within the studied deposit likely reflect the result of the breaking of the coastal barrier at least twice.

6. Conclusion

To conclude, the variation in the lamina thicknesses enables the study of a sedimentary signal recorded in a part of the Subboreal laminated deposit. Spectral analysis suggests that short-term tidal cycles controlled sedimentation. The sedimentation cycles can be favourably compared to the current tidal pattern of the Seine estuary. This comparison indicates that tidal cycles (neap–spring and anomalistic month or semiannual and annual cycles) are a plausible explanation for the processes that controlled lamina deposition.

Future studies should include an investigation to determine if the deposition of the entire Subboreal clastic sequence has been continuous or not and if the tidal cycles identified in our small sequence have been constant through time or if there has been any change in the tidal dynamics. They should also include a study of the diatom content at the lamina scale to discriminate the neap–spring cycle and anomalistic month from the semiannual and annual cycles. In the case of a quick filling (1st hypothesis), the diatom content should remain almost the same in the entire sequence. In the case of a longer period of time (2nd hypothesis), the diatom content should indicate seasonal variations.

Finally, the study of this laminated deposit puts into question the likelihood of the transgressive events previously described, as the time span involved in the lamina deposition indicates too short of a period to account for two eustatic sea-level rises.

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