C. R. Geoscience 334 (2002) 1071–1077

S1631-0713(02)01853-9/FLA

Géomatériaux / Geomaterials
(Sédimentologie / Sedimentology)

Erosion of particulate inorganic and organic matter in the Gulf of Lion

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Received 16 October 2002; accepted 22 October 2002

Communicated by Lucien Laubier

Abstract – Critical shear stress of erosion and erosion rate of particulate inorganic and organic matter were measured in a flume at three muddy stations. Critical shear stress ranged between 0.022 and 0.038 $\mathrm{N\,m^{-2}}$. At the deepest site, annual erosion of particulate organic nitrogen and phosphorus could exceed net deposition fluxes, showing the importance of erosion processes. Erosion may modify total system mineralisation rates by introducing sedimentary particulate organic matter into the water column and thus this process must be taken into account in studies of biogeochemical cycles. ***To cite this article: E. Schaaff et al., C. R. Geoscience 334 (2002) 1071–1077.***

critical shear stress / particulate organic matter / erosion rate / Gulf of Lion / France

Résumé – Érosion de la matière particulaire inorganique et organique dans le golfe du Lion. Les tensions critiques d'érosion et les flux d'érosion de matière particulaire inorganique et organique ont été mesurés dans un canal à courant pour trois stations vaseuses. Les tensions critiques sont comprises entre 0,022 et 0,038 $\mathrm{N\,m^{-2}}$. Au site le plus profond, l'érosion annuelle d'azote et de phosphore organique particulaire peut dépasser les flux nets de dépôt, montrant l'importance des processus d'érosion. L'érosion est susceptible de modifier le taux de minéralisation total du système par introduction de matière organique particulaire dans la colonne d'eau, d'où la nécessité de prendre en compte ce processus dans les études des cycles biogéochimiques. ***Pour citer cet article : E. Schaaff et al., C. R. Geoscience 334 (2002) 1071–1077.***

tension critique d'érosion / matière organique particulaire / flux d'érosion / golfe du Lion / France

Version abrégée

1. Introduction

L'érosion des sédiments fins cohésifs est un phénomène omniprésent dans le milieu marin [18]. Contrairement aux sédiments non cohésifs, il est actuellement impossible de prévoir leur tension critique d'érosion à partir d'un ou plusieurs paramètres simples [4] et de modéliser de façon fiable la dynamique des sédiments vaseux [23]. Par ailleurs, l'érosion peut se montrer un mécanisme important pour les échanges de matière organique entre les sédiments et la colonne d'eau [3] et donc pour les cycles biogéochimiques. Ce travail propose d'évaluer l'importance de l'érosion de la matière organique.

2. Site d'étude

Le plateau continental du golfe du Lion est caractérisé par un régime microtidal. Il est largement influencé par le Rhône, qui est responsable de 80% des apports terrigènes [14]. Trois stations (Roustan, Rhône et Sofi) y ont été échantillonnées en période printanière. Elles sont situées sur un transect allant de l'embouchure du Rhône vers la rupture du plateau (Fig. 1) à des profondeurs respectives de 40, 98 et 170 m.

L'objectif principal de ce travail est de caractériser l'évolution spatiale de l'érodabilité des sédiments, et plus particulièrement de la matière organique, le long du transect Roustan–Sofi.

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3. Matériel et méthodes

Les sédiments superficiels ont été échantillonnés à l'aide d'un carottier multitubes spécialement conçu pour préserver au mieux l'interface [6]. Des mesures de granulométrie, de CHN et de porosité ont été réalisées. La stabilité des sédiments a été déterminée à l'aide d'un canal à courant (Fig. 2) qui a été décrit par Denis et al. [5] et Redondo et al. [21]. Pour cela, la vitesse du courant a été augmentée progressivement jusqu'à atteindre 32 $cm\,s^{-1}$. Les mesures de courant et de turbidité ont été réalisées à l'aide d'un courantomètre acoustique à effet Doppler (ADV) et d'un turbidimètre. Des prélèvements ponctuels d'eau permettent de déterminer la matière en suspension (fraction inorganique et organique) par filtration. L'azote et le phosphore organique particulaires (NOP et POP) ont été mesurés en utilisant une méthode d'oxydation humide semi-automatique [19]. La vitesse de frottement a été déterminée en utilisant la loi logarithmique (Éq. (1)).

4. Résultats

Les stations les plus vaseuses (Roustan, Rhône) se caractérisent par des porosités de surface comprises entre 0,81 et 0,84. Les sédiments de la station Sofi sont des vases sableuses (teneurs en sables supérieures à 30%). La porosité de surface y est de 0,69 et le gradient vertical marqué montre une consolidation plus importante des sédiments. Le long du transect, les teneurs en carbone organique et en azote décroissent (Tableau 1).

Pour chaque expérience, des graphiques similaires à ceux de la Fig. 3 sont dessinés, afin de déterminer la tension critique d'érosion (Éq. (2)) et les flux d'érosion.

Les tensions critiques (τ_c) et les flux d'érosion de matière totale (F_{ero}) sont résumés dans le Tableau 1. Les tensions critiques sont comprises entre 0,022 et 0,038 $N\,m^{-2}$. La valeur maximum, traduisant une plus grande résistance à l'érosion, est obtenue à la station Sofi. Les flux d'érosion de matière particulaire totale varient entre 54 et 110 $g\,m^{-2}\,h^{-1}$. Les stations Roustan et Rhône présentent les flux les plus élevés.

Les flux d'érosion de matière inorganique particulaire (F_{PIM}), organique particulaire (F_{POM}), de NOP (F_{PON}) et de POP (F_{POP}) sont présentés dans le Tableau 1.

F_{PIM} et F_{POM} varient respectivement le long du transect d'un facteur 2 et 2,8. F_{PON} varie d'un facteur 5,5 et F_{POP} d'un facteur 2,7. Les flux de NOP sont 10 à 20 fois supérieurs à ceux de POP.

5. Discussion

La présence d'un *fluff* aux stations Roustan, Rhône et Sofi, montre qu'il s'agit d'érosion de type I [1]. Nos résultats sont proches des valeurs de la littérature relative à ce type d'érosion [15, 20, 22, 26]. Pour le flux d'érosion, la comparaison n'est permise que lorsque la tension appliquée est de même grandeur et de même durée. Toutefois, il est plus sensible aux variations d'érodabilité que ne l'est la tension critique [11]. Dans notre cas, cela est surtout vérifié pour les flux de matière organique.

Le long du transect, les flux les plus élevés sont mesurés à proximité de l'embouchure du fleuve, où l'apport important de matière organique est assuré par celui-ci et par la production primaire. Bien que l'influence du Rhône soit faible à la station Sofi [21], l'érosion de matière organique reste significative. Les valeurs de N:P de la matière érodée sont proches du rapport de Redfield et attestent donc l'état relativement peu dégradé de la matière organique.

Au site Sofi, des enregistrements in situ de courant ont permis d'évaluer le frottement au fond et d'estimer les flux d'érosion de NOP et de POP. En comparant les flux de dépôt, mesurés à l'aide d'un piège à particules [7], il apparaît que les flux d'érosion sont 13 à 30 fois plus grands. Ceci montre l'intensité des cycles de remise en suspension à proximité du fond.

Par ailleurs, dans l'eau, le taux moyen de dégradation de la matière organique est de 0,96 $g_C\,m^{-3}\,j^{-1}$ [25]. La quantité de carbone organique particulaire (COP) érodé au bout d'une heure est estimée à partir du rapport de Redfield. Le temps de chute des particules situées à 1 m du fond, calculé à partir de la vitesse de chute mesurée dans le canal, est suffisant pour permettre la dégradation de 60% du COP érodé. Nos données étayent donc l'hypothèse selon laquelle la couche benthique de fond pourrait être une zone majeure pour la minéralisation de la matière organique [24].

Les résultats obtenus dans la baie d'Aarhus [13] suggèrent, de plus, que le cycle de remise en suspension est encore plus important pour des sites de plus faible profondeur, comme Roustan ou Rhône.

6. Conclusion

Cette étude a permis d'établir une première gamme de tensions critiques d'érosion pour le golfe du Lion. Les valeurs relativement faibles suggèrent l'omniprésence et la fréquence de l'érosion dans cette région. De plus, nos résultats montrent la capacité de l'érosion à transférer une partie de l'important stock sédimentaire de matière organique particulaire dans la colonne d'eau. Ce processus, susceptible de modifier le taux de minéralisation total du système, devra donc être pris en compte dans les études des cycles biogéochimiques.

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1. Introduction

The erosion of fine-grained cohesive sediment is a ubiquitous phenomenon in marine and estuarine environments [18]. Sediment erosion occurs once a critical value of shear stress exerted by moving fluids is exceeded. The critical erosion shear stress is an important parameter in sediment transport mechanics.

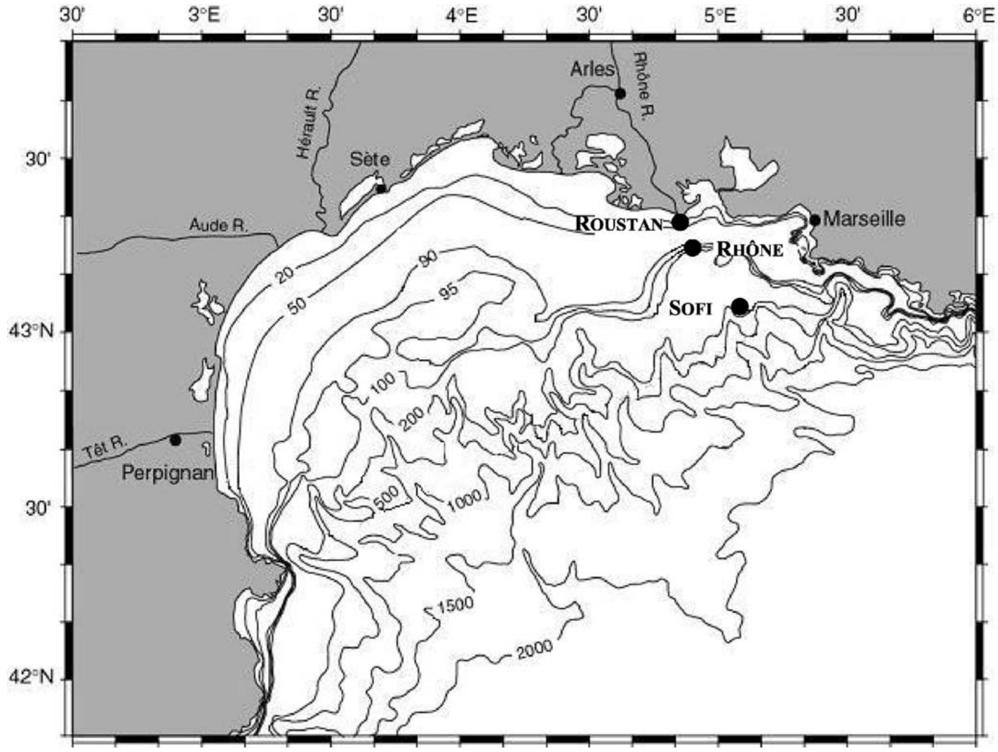

Fig. 1. Location on the continental shelf of the three sampling stations.

Fig. 1. Localisation sur le plateau continental des trois stations d'échantillonnage.

In contrast to non-cohesive sediments, it is presently not possible to generally predict the critical erosion stress of cohesive sediments from one or more easily measurable parameters [4]. Actually, cohesion and erosion resistance in muds are complex functions of a number of interrelated physical, physicochemical and biological properties such as water content, grain size [12], depositional history [8], temperature and salinity [16], and organic composition [26]. The current lack of a detailed understanding of the variability of both erosion critical shear stress and erosion rate is at the centre of our inability to model correctly the dynamics of muddy sediments [23]. Moreover, resuspension can be an important mechanism for the exchange of organic matter between sediments and overlying water [3] and associated biota [5]. Consequently, knowledge of parameters such as critical shear stress and erosion rates are needed for understanding sediment transport and biogeochemical processes.

As a first approach towards investigating the significance of organic matter resuspension, we performed laboratory experiments using a recirculating flume in order to measure critical shear stress of erosion and the associated fluxes of organic and inorganic matter.

2. Study site

The Gulf of Lion continental margin is located in a microtidal sea. The movement of the water masses and of the particulate matter is essentially driven by the cyclonic circulation of the Northern Current [17]. This zone is largely influenced by the Rhone River, which provides more than 80% of total terrigenous inputs [14]. The sedimentology of the area was described by Got and Aloisi [10].

Three stations, named Roustan, Rhône and Sofi (Fig. 1), located on the continental shelf of the Gulf of Lion were selected. They were located respectively at 40, 98 and 170 m deep along a transect going from the Rhone River mouth to the continental shelf break.

The main objective of the present study is to characterise spatial trends in inorganic and organic matter erodibility on a cross-shelf transect displaying an increasing water depth, but decreasing organic matter and fine particle contents.

3. Materials and methods

In order to study spatial variation in sediment erodibility, sediment cores were sampled along the Roustan–Sofi transect once in March and June 2000. At each station, surfacial sediments were sampled with a multicorer specifically designed to obtain 15 cm internal diameter sediment cores with undisturbed sediment–water interface [6].

Several subsamples of sediment were taken using smaller cores (internal diameter 2.6 cm). These cores were sectioned in 4-mm slices, which were analysed for different parameters. Grain size and CHN were measured respectively with a Malvern particle sizer

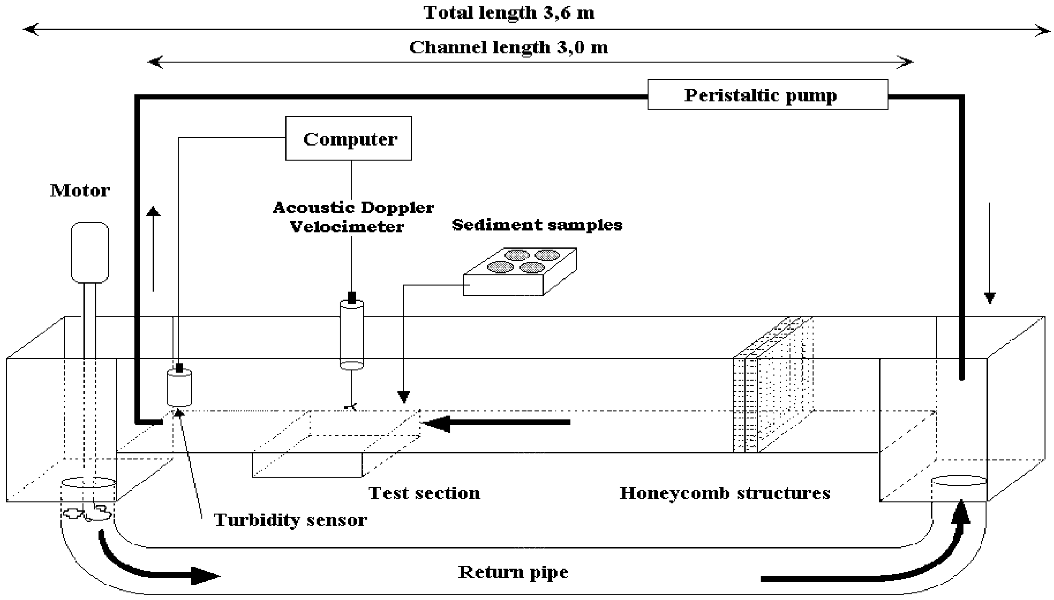

Fig. 2. The recirculating flume used to perform erosion experiments.

Fig. 2. Le canal à recirculation utilisé pour les expériences d'érosion.

and a Shimadzu analyser. The porosity was calculated from water content (weight loss on lyophilisating), assuming particle density equal to 2650 $kg\,m^{-3}$.

Sediment stability was determined in a 3.6 m long PVC recirculating flume (Fig. 2) filled with 300 l of seawater, as described in Denis et al. [5] and Redondo et al. [21]. A new method was developed to transfer the top sediment of four cores in the test section with minimum disturbances. Sediments were slid into a PVC ring by mean of a piston so as to keep 1 cm of the overlying water. The PVC ring was carefully sealed with a cap to exclude air bubbles. The sediment was then sectioned with a thin plate. In the flume, the cap was gently removed and the PVC ring was placed on a wedge, so that the sediment–water interface was levelled with the bottom of the main channel.

Flow measurements were conducted with an Acoustic Doppler Velocimeter (ADV) operating at a sampling frequency of 25 Hz and placed in the middle of the test section at 4 cm above the bottom.

The erosion experiments consisted in a continuous increase in the flow velocity up to 32 $cm\,s^{-1}$. After 20 min, the current was stopped. A turbidity sensor located at 4 cm over the bottom measured the evolution of ambient and resuspended particulate matter. Two water samples were collected every 3 min at approximately mid-depth by mean of a peristaltic pump placed downstream the test section. The first one was used to measure suspended particulate matter (organic and inorganic fraction) by filtration through Whatman GF/F filters. These results were used to calibrate the turbidity sensor. The filter was dried in an oven at 500 °C during 6 h and particulate organic matter (POM) was calculated by loss of ignition. The second filter was used to measure particulate organic nitrogen (PON) and phosphorus (POP) using a semi-automatic wet-oxidation method [19]. Due to the well-mixed conditions, no vertical gradient of suspended matter was observed.

These experiments were used to determine the critical shear stress for incipient erosion (τ_c) and erosion rates for both organic and inorganic particulate matter. Erosion rates were evaluated as the increase with time in the corresponding suspended mass in the flume.

The flow was found to be hydraulically smooth and velocity distribution followed the logarithmic law over the test section. Thus, the critical shear velocity at which particles begin to move was determined using:

$$u_c(z) = \frac{u_c^*}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

with $u(z)$, the velocity at a distance z above the bed; u^*, the shear velocity; κ, the universal Von Karman constant (0.41); z_0, the bottom roughness; $_c$ subscript, the critical condition for onset erosion.

Then the derived critical bottom shear stress was:

$$\tau_c = \rho\, u_c^{*2} \tag{2}$$

in which τ_c is the bottom critical shear stress ($N\,m^{-2}$) and ρ the water density ($kg\,m^{-3}$).

It is questionable whether increasing suspended sediment affects the bottom shear stress. In this study, concentrations in the flume never exceeded 20 $mg\,l^{-1}$. Thus, drag reduction, which is known to occur for concentrations higher than 150 $mg\,l^{-1}$, was neglected.

4. Results

Granulometric distributions within the topmost layer are presented in Table 1. At stations Roustan

Table 1. Granulometric distributions (volume percentage), organic carbon and nitrogen contents (dry weight percentage) of surfacial sediments at the three stations. τ_c is the critical shear stress of erosion, F_{ERO} is the erosion rate of total particulate matter. F_{PIM}, F_{POM}, F_{NOP}, F_{POP} are the erosion rates of particulate inorganic and organic matter and of particulate organic nitrogen and phosphorus.

Tableau 1. Distributions granulométriques (pourcentage du volume), teneurs en carbone organique et en azote (pourcentage de poids sec) des sédiments de surface aux trois stations. τ_c est la tension critique d'érosion et F_{ERO} est le flux total d'érosion de matière particulaire. F_{PIM}, F_{POM}, F_{NOP}, F_{POP} sont les flux d'érosion de matière particulaire inorganique et organique et d'azote et de phosphore organique particulaire.

	Roustan	Rhône	Sofi
Distance from Rhone River mouth (km)	3	12	50
Clay [< 4 µm] (%)	15	15	14
Silts [4 ≪ 63 µm] (%)	68	69	53
Sand [> 63 µm] (%)	17	16	33
C_{org} (%)	2.28–2.36	1.72–2.32	0.36–0.99
N_{org} (%)	0.15–0.18	<0.1–0.14	< 0.1
τ_c ($N\,m^{-2}$)	0.022 ± 0.002	0.023 ± 0.002	0.038 ± 0.003
F_{ERO} ($g\,m^{-2}\,h^{-1}$)	109 ± 38	110 ± 4	54 ± 17
F_{PIM} ($g\,m^{-2}\,h^{-1}$)	96 ± 33	97 ± 0.25	49 ± 12
F_{POM} ($g\,m^{-2}\,h^{-1}$)	13 ± 5	13 ± 4	5 ± 3
F_{NOP} ($mmol\,m^{-2}\,h^{-1}$)	11 ± 5	7 ± 4	2 ± 0.5
F_{POP} ($\mu mol\,m^{-2}\,h^{-1}$)	539 ± 175	357 ± 152	203 ± 97

and Rhône, sediments had similar size distribution. They both contained more than 80% of fine particles (< 63 µm) and around 17% of sand. At station Sofi, less than 70% of fine particles and more than 30% of sand were observed. Thus, sediments at stations Roustan and Rhône were slightly sandy muds and at station Sofi sandy muds [9].

In the surface layer, porosity ranged between 0.69 and 0.84 and decreased exponentially with depth. At stations Roustan and Rhône, surface porosity was respectively equal to 0.81, 0.84, and vertical gradients were very close. At station Rhône, the porosity was slightly higher than at station Roustan. In fact, at this station a lot of burrows due to bioturbating activity, which is known to enhance porosity, were observed. At station Sofi, the porosity was lower (0.69) and vertical gradient was steeper displaying a better consolidation of these sediments. Along the Roustan–Sofi transect, organic carbon and nitrogen contents ranged respectively between 0.36–2.36% and 0.18–⩽0.1% (Table 1). They decreased with the distance from the Rhone River mouth.

In conclusion, at the station Sofi, sediments differed mostly from the others because of lower organic matter and higher contents in coarse particles.

Calibration of the turbidity sensor yielded linear and consistent results for the three stations. Plots similar to Fig. 3 were drawn for all experiments. The critical shear stresses of erosion (Eq. (2)) and erosion rates of particulate inorganic and organic matter were determined from these plots.

Critical shear stresses (τ_c) and erosion rates of total particulate matter (F_{ero}) are summarised in Table 1.

Critical shear stresses of erosion ranged between 0.022 and 0.038 $N\,m^{-2}$. The maximum value was obtained at station Sofi, showing the highest resistance against erosion for these sediments. Erosion rates of total particulate matter varied between 54 and 110 $g\,m^{-2}\,h^{-1}$. The higher erosion rates were found at stations Roustan and Rhône.

Erosion rates of particulate inorganic matter (F_{PIM}), POM (F_{POM}), PON (F_{PON}), and POP (F_{POP}) are presented in Table 1.

Mean erosion rates measured at stations Roustan and Rhône were very close and higher than at station Sofi. This result was in agreement with the higher resistance against erosion showed by critical shear stress at Sofi site.

Erosion rates of particulate inorganic matter varied by a factor of 2 along the transect, while erosion rates of particulate organic matter varied by a factor of 2.8. Erosion rates of PON and POP varied respectively by factors of 5.5 and 2.7. F_{NOP} values were 10–20-fold higher than F_{POP} ones.

5. Discussion

Critical shear stress of muds found in literature varied by a factor of 200. This wide scatter arises from the difficulty encountered in consistently defining critical shear stress and the large number of parameters involved in sediment erodibility.

At stations Roustan and Rhône, visual observations revealed a thin, non-consolidated surficial layer composed of little particles, biogenic and non-biogenic aggregates. At station Sofi, this fluff layer was sparse. Aggregates have lower density than individual particles [2] and so were easily eroded from the sediment. Consequently, critical shear stress was defined by the removal of this fluff layer. So, at these stations erosion can be related to type I erosion, as defined by Amos et al. [1]. Our results are close to common in-situ based estimates of fluff critical shear stresses, which ranged between 0.02–0.05 $N\,m^{-2}$ [15, 20, 22, 26].

Regarding erosion rates comparison with other studies was allowed only if the applied shear stresses were of similar magnitude and duration. Nevertheless, erosion rate is generally a more sensitive indicator of trends in sediment erodibility than is critical shear stress [11]. Here it is especially true for erosion rates of organic matter.

The consistency of our results and these in-situ experiments displays the reliability of our experimental method.

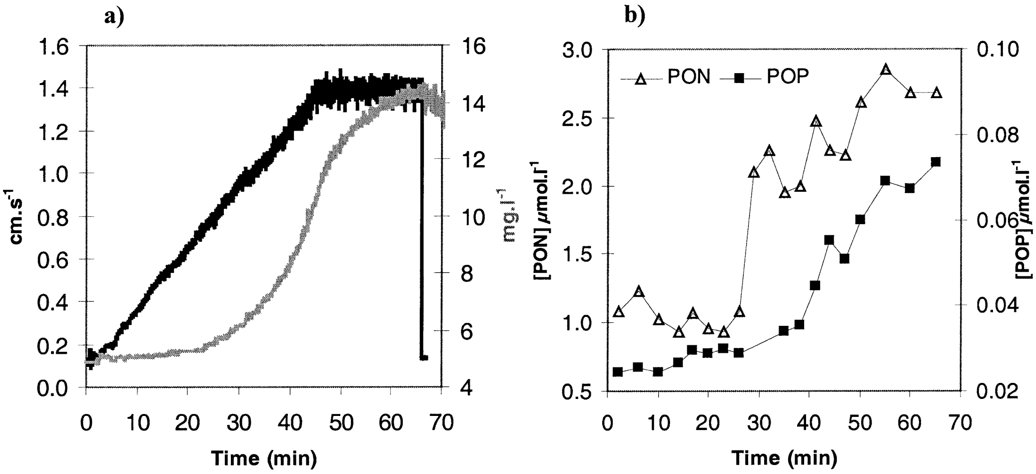

Fig. 3. (**a**) Time evolution of bottom shear velocity (u^*, $cm\,s^{-1}$) and of suspended particulate matter ($mg\,l^{-1}$) in the flume. (**b**) Increase of particulate organic nitrogen (PON, $\mu mol\,l^{-1}$) and phosphorus (POP, $\mu mol\,l^{-1}$) concentrations during erosion.

Fig. 3. (**a**) Évolution temporelle de la vitesse de frottement au fond (u^*, $cm\,s^{-1}$) et de la matière particulaire en suspension ($mg\,l^{-1}$) dans le canal. (**b**) Augmentation des concentrations en azote (PON, $\mu mol\,l^{-1}$) et en phosphore (POP, $\mu mol\,l^{-1}$) organique particulaire pendant l'érosion.

Along the transect, erosion of sediment was always associated to organic matter input in the water column. The highest organic matter erosion rates were measured near the river mouth, where the Rhone River and the local primary production ensured an important organic matter supply. Although the Rhone River influence is limited at station Sofi [6], significant erosion of organic matter occurred. POM represented 9–12% of the eroded particles. The higher percentages were obtained near the river mouth. Surprisingly, the percentage at station Sofi, where organic content was the lower, was of the same order of magnitude. At this site, the decrease in 25% of porosity within the first centimetre displayed the high compaction, which should enhance cohesion of the underlying layer. Particulate organic matter of low density located in the uppermost oxygenated and non-consolidated layer is therefore preferentially eroded.

The molar ratio of N:P of eroded particles varied between 10 and 20. These values are close to the Redfield's ratio and thus are indicative of relatively non-degraded organic matter, especially near the river mouth, during this spring period.

At Sofi site, the primary production is the major source of organic matter to the bottom. Net deposition fluxes of 0.06 $mol_N\,m^{-2}\,yr^{-1}$ and 3×10^{-3} $mol_P\,m^{-2}\,yr^{-1}$ were estimated by means of a sediment trap located 20 m above bottom (mab) [7]. A velocimeter moored during year 1999 and 2000 measured in-situ current velocities at 20 mab. In spite of important depth (170 m), velocity reached 20 $cm\,s^{-1}$ during 8% of the time. Maximum values (> 45 $cm\,s^{-1}$) were associated with a westward direction, suggesting the influence of the Northern Current [17]. Using the log-law (Eq. (1)) with the experimentally determined value of 10^{-6} m for sediment roughness, the bottom shear stress can be estimated. The maximum value of 0.2 $N\,m^{-2}$ reached during flume experiments was exceeded during 5% of the time. Then, estimations of annual input in the water column related to sediment resuspension are 0.8 $mol_N\,m^{-2}\,yr^{-1}$ and 0.09 $mol_P\,m^{-2}\,yr^{-1}$. So estimated erosion fluxes of PON and POP were respectively 13- and 30-fold higher than the primary deposition. It pointed out that the resuspension cycle was intensive near the bottom (< 20 mab).

The Redfield ratio (C:N ≈ 7) provides an estimation of the amount of eroded particulate organic carbon (POC) introduced within the water column after one-hour erosion (i.e. 170 $mg_C\,m^{-2}$). The mean settling velocity measured in the flume is 10^{-5} $m\,s^{-1}$. So particles situated 1 mab could settle during 2 h 30. Considering this residence time and a degradation rate of 0.96 $g_C\,m^{-3}\,d^{-1}$ [25], it appears that 60% of the eroded POC could be degraded. Thus erosion may accelerate the overall degradation of organic matter and may result in lower sedimentary standing stocks of carbon. Therefore, our data support the hypothesis generated in a previous study, i.e. that the near-bed fluid layer of the benthic boundary layer is a major region for organic matter mineralisation [24].

No in-situ measurements of current velocity were available at stations Roustan and Rhône. Nevertheless, Jorgensen [13] reported gross fluxes 60-fold higher than net deposition in Aarhus Bay, which had a mean depth of 15 m. This suggests that, due to higher physical forcing, resuspension loop is even more intensive at sites of lower depth, like Roustan or Rhône. This process should be all the more important because of the lower erodibility and of the higher organic content of sediments. Regarding the continental shelf of the Gulf of Lion, our results display that, due to erosion of the surface, sediment deposited detritus may be recycled through the lower water column many times before burial in deeper layers.

6. Conclusion

This study provides a first data set for critical shear stress of erosion for sediment of the continental shelf of the Gulf of Lions. Their relatively low values compared to other studies suggest that erosion could be a ubiquitous and a frequent occurrence on this area. It should be even more widespread at low depth sites, where interactions between waves and current enhance the bottom shear stress. Moreover, our results highlight that erosion is able to shift a part of the large sedimentary pool of particulate organic matter into the water column. This process may modify total system mineralisation rates and so must be taken into account in studies of biogeochemical cycles.

Acknowledgements. We thank the captain and crew of the RV Tethys II for assistance during field sampling and anonymous reviewers for their detailed comments. Funding for this research was provided by the French 'Programme national Environnement côtier' and the EU (OAERRE: EVK3-CT1999-00002).

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