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Effects of benthic diatoms, fluff layer, and sediment conditions on critical shear stress in a non-tidal coastal environment

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Sixteen sediment samples were collected from a square grid (4×4) with a horizontal distance of about 150 m between positions in Århus Bay in the southwest Kattegat (14 to 15 m water depth). Critical shear stress (τ_c) was measured in all samples and related to sediment parameters: grain-sizes, organic matter, water content, porosity, and chlorophyll-*a* (chl *a*) content, in upper layers. Samples were divided into a low (A) and a high (B) τ_c group in relation to an erosion rate. A significant ($P<0.001$) difference in median τ_c was found between group A ($0.0284\,\mathrm{N\,m^{-2}}$) and B ($0.0380\,\mathrm{N\,m^{-2}}$). Average chl *a* concentrations in group A ($1.4\,\mu g\,g^{-1}$) and B ($1.8\,\mu g\,g^{-1}$) were not significantly different ($P=0.47$) but there was a significant and positive correlation (r^2: 0.7, $P<0.001$) between τ_c and diatom film abundance. Sediment organic matter and water content were significantly higher in group B compared with A, which contradicts that watery and organic rich sediments generally exhibit low τ_c. This was explained by the presence of a diatom film cover on the fluff layer that inhibits the action of erosive forces. A fluff layer is characterized by a high water and organic content. The fluff layer was present in the majority of the samples but the highest average chl *a* content and a significant ($P=0.020$) higher abundance of diatom film was observed in group B (high τ_c). Benthic diatoms were dominated by *Haslea crucigeroides, Pleurosigma strigosum*, and *Bacillaris paxillifer.* Spatial variability of sediment parameters was high and variability of a stability/erodibility parameter even exceeded those recorded for highly heterogeneous tidal flats. The occurrence of benthic diatoms at 14–15 m of water depth in the eutrophic Århus Bay was supposedly related to a measured increase in Secci depth in the bay and thereby increased light penetration depth.

INTRODUCTION

Sediment stability influences processes such as sediment transport, deposition, and resuspension in both tidal and non-tidal coastal environments (e.g. Grant et al., 1986; Grant and Gust, 1987; Vos et al., 1988; Paterson, 1989; Underwood & Paterson, 1993; Yallop et al., 1994; Andersen et al., 2000; Bassoullet et al., 2000). In tidal dominated environments, much research has focused on the role of micro-phytobenthos in relation to sediment stability (e.g. Neumann et al., 1970; de Boer, 1981; Paterson, 1989; Delgado et al., 1991; Madsen et al., 1993; Underwood & Paterson, 1993; Jonge & Beusekom, 1995; Austen et al., 1999; Guarini et al., 2000). See also Heinzelmann & Wallisch (1991), and Paterson (1997) for reviews. These works reported a general positive correlation between critical shear stress for erosion (τ_c) and chlorophyll-*a* (chl *a*) content of surface sediments. Light availability for benthic photosynthesis is not a shortcoming on tidal flats, as benthic algae are exposed to light once or twice everyday. On the other hand, the presence of micro-phytobenthos on the sediment surface has been reported to depths of about 200 m in sub-tropical waters of high down welling irradiance (Cahoon et al., 1990). The present work aims at investigating the relationship between τ_c, micro-phytobenthos biomass/abundance, and sediment parameters such as grain-sizes, organic matter and water content in the coastal eutrophic non-tidal Århus Bay (Denmark). Secci depth in the bay has increased during recent years and a maximum of 16 m was registered during summer 1998 (Århus County, 2000). Average water depth in the bay is about 14 m and recent changes in light conditions may support the presence of benthic diatoms at these depths. Major questions addressed in this study are: 1—Is there a relationship between τ_c and chl *a* concentrations in the sediments? 2—If yes, is such relationship similar to the one found in tidal environments? 3—Is τ_c related to other sediment parameters as grain-size or organic matter in the sediment? 4—Is there a spatial variation of τ_c and sediment parameters, and how large is the variation?

MATERIALS AND METHODS

Århus Bay is a semi-enclosed area in the southwest Kattegat, the transitional zone between the low saline (8–10 psu) Baltic Sea and the high saline (30–34 psu) North Sea (Figure 1). Surface water salinities vary between 14 and 29 psu in the bay and bottom water salinities between 20 and 32 psu (Jørgensen, 1996). Low surface and bottom

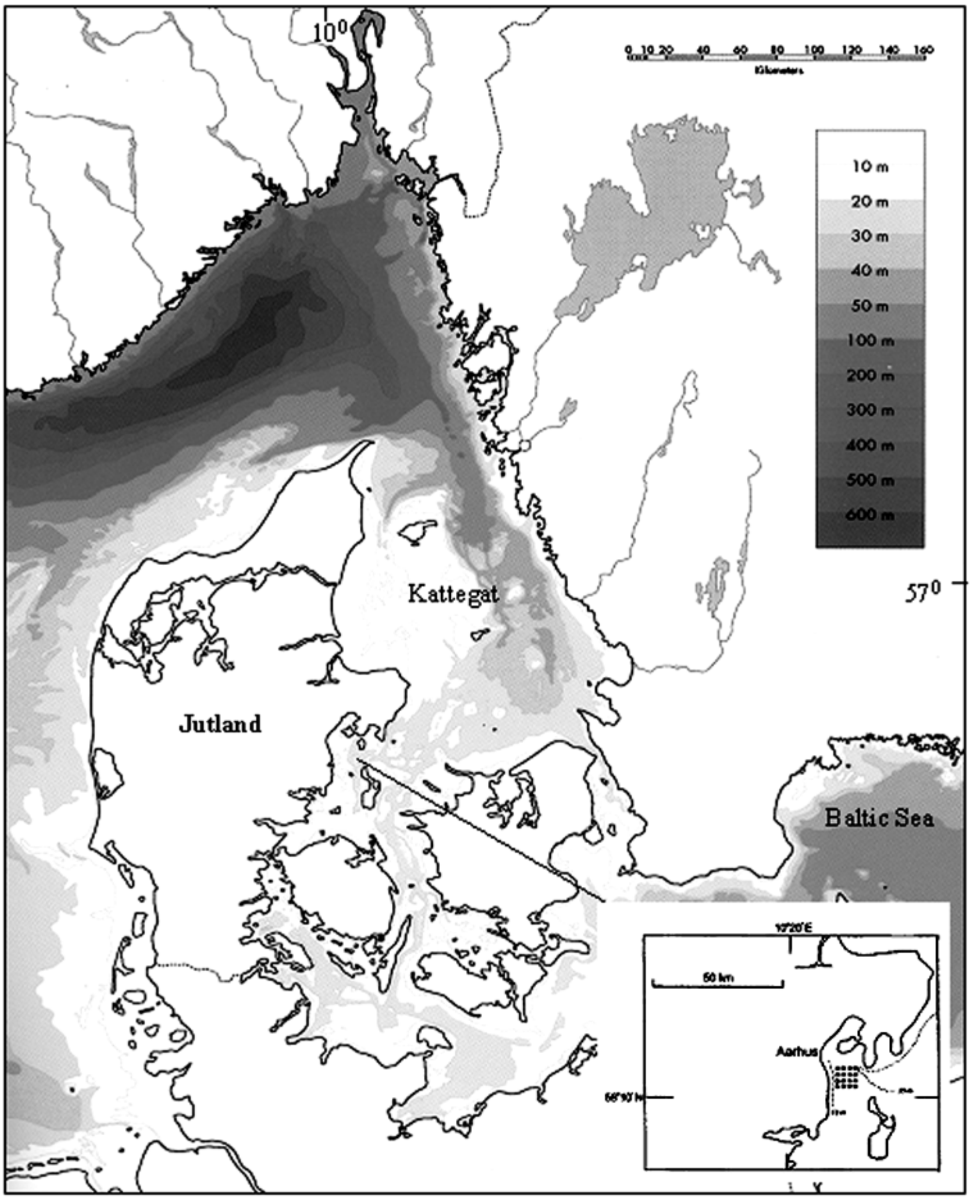

Figure 1. Study area in the south west Kattegat.

water salinities occur during periods of outflow from the Baltic Sea and increased salinities occur in periods of inflow from the Kattegat (Lund-Hansen et al., 1993). Water level variations in the southwest Kattegat are related to wind speeds and directions that by far exceed the tidal range (about 0.4 m). Sixteen positions forming a squared grid (4×4) in the western part of the bay were selected for sediment sampling during calm weather conditions in August 1998 (Figure 1). The distance between the positions was about 150 m (Global Positioning System) and water depths varied between 14 and 15 m (echo sounder). Sediments were collected using a new hydraulic damped and video equipped box-corer (Lund-Hansen et al., 2001) designed for fluff layer sampling and sediment microtopographic studies (Stolzenbach et al., 1992). Sub-samples are taken once the box-corer is withdrawn and placed on deck. One large (diameter=85 mm) and one minor core (diameter=50 mm) were collected at each position. All cores were brought to the laboratory and placed in a dark thermo-regulated room at 5°C where the small cores were immediately processed. The large cores were placed in a stander in a large aerated seawater tank, to keep the sediment in free contact with the circulating water collected during the survey. Before experiments started, sediment cores were kept undisturbed for at least 20 hours to ensure for complete water clearance.

Sediment parameters

The 85 mm diameter cores were used for determination of critical shear stress (τ_c) after digital imaging (Olympus$^{®}$ C-1400L) of sediment surfaces and depth profiles. The 50 mm cores were used for determination of diatom species composition, chl *a*, organic matter and grain size distributions of surface samples (0–2 mm). Sediments were sieved through a 1.5 mm sieve to remove gross detritus and macro-fauna. Water content was determined by weight loss at 60°C for 48 hours. Organic matter content was determined by loss-on-ignition at 550°C for 4 hours. Chl *a* concentrations were measured spectrophotometrically at 664 nm using the method of Lorenzen (1967) being equivalent to algae biomasses (Underwood & Paterson, 1993). Diatom species composition was determined by light microscopy. For each of the sixteen samples, species abundance was expressed as: rare, common or dominant. Grain-size distributions were measured by the laser diffraction method (Agrawal et al., 1991) used in the Malvern® Master Sizer-5 after removal of organic matter through H_2O_2 treatment.

Laberex experiments

Sediment τ_c was determined for each sample using the Laberex chamber, designed to study erosion and sediment stability at low shear stress (Lund-Hansen et al., 1999). The exact relationship between shear stress and impeller motor stirring voltage was determined by laser doppler anemometry in the chamber. It consists of a plexi-glass cylinder with an inner diameter of 85 mm with a four-bladed impeller located in the centre. Light emitter and receiver are placed outside the chamber and measure light attenuation in the water as a function of increased impeller stirring. Changes in light attenuation are related to changes in absorbency and scattering by particles in suspension and were transformed into a light attenuation coefficient (LAC) (m^{-1}) by:

$$LAC = C - C_w = -(\ln F/F_o)/r \qquad (1)$$

where C_w is the LAC of the water itself regarded as a constant in the experiment, F the measured and F_0 the initial light intensity (volt), and r the distance (m) between light emitter and receiver (Wells & Seok-Yun, 1991). Impeller motor, light emitter and receiver are connected to an A/D converter operated through the LABTECH® software for direct monitoring of variables on a computer.

Data analyses

Statistical analysis was carried out using the Statistical Package for the Social Sciences (SPSS).

RESULTS

Critical shear stress and sediment parameters

Results of shear stress measurements are shown in Figure 2 for the samples number 3 (Figure 2a) and 6 (Figure 2b). The τ_c value is reached where the first and pronounced change in LAC occurs in the time-series (Lund-Hansen et al., 1999). These changes occurred at 2.9 hours (sample 3) and at 4.3 hours (sample 6) after start of experiment and relates to τ_c values of 0.023 and 0.034 ($N\,m^{-2}$), respectively. The change in LAC in sample 3 is clearly more gradual compared with sample 6 where LAC exhibits a strong response once τ_c is reached. The concentration of suspended matter in the Laberex chamber at a LAC of about 1 (m^{-1}) is about 3 $mg\,l^{-1}$ according to an *in situ* calibration of a transmissometer operating at the same wave length (630 nm) as the Laberex chamber (Lund-Hansen et al., 2002). A slight increase in LAC is observed during the initial part of the experiments until incipient erosion is reached (Figure 2A–B). The increase is due to resuspension of single flocs and aggregates on the sediment surface and whereby LAC increases but this will not affect the determination of τ_c. Erosion rate was determined as a change in LAC relative to a known time interval following the onset of the erosion, which was about 49 times higher in sample 6 ($9.3\,m^{-1}h^{-1}$) compared with sample 3 ($0.19\,m^{-1}h^{-1}$). Samples were accordingly separated into two groups—A and B—based on whether LAC change with time was more gradual or sudden as in samples 3 and 6, respectively. It turned out that the samples with a gradual LAC change (group A) also exhibited a general low τ_c whereas it was high in group B as shown together with all sediment parameters in Table 1. However, actual τ_c could not be determined in three samples as the upper limit of $0.04\,N\,m^{-2}$ in the Laberex chamber was exceeded. These samples were ranked in relation to the remaining 13 samples and placed in the high τ_c group B. However, a simple comparison of mean values shows that the sand content is higher by 2.2% whereas the clay content is 3.6% lower in the low τ_c group although that these differences are not significant (Table 1). Mean chl *a* concentration was almost 30% higher in group B but the difference was not significant (P=0.47). However, both water content (P=0.048) and organic matter (P=0.011) are significant higher in group B and both the differences in mean (P=0.005) and median ($P<0.001$) τ_c are highly significant. Note that N=8 in group A and N=5

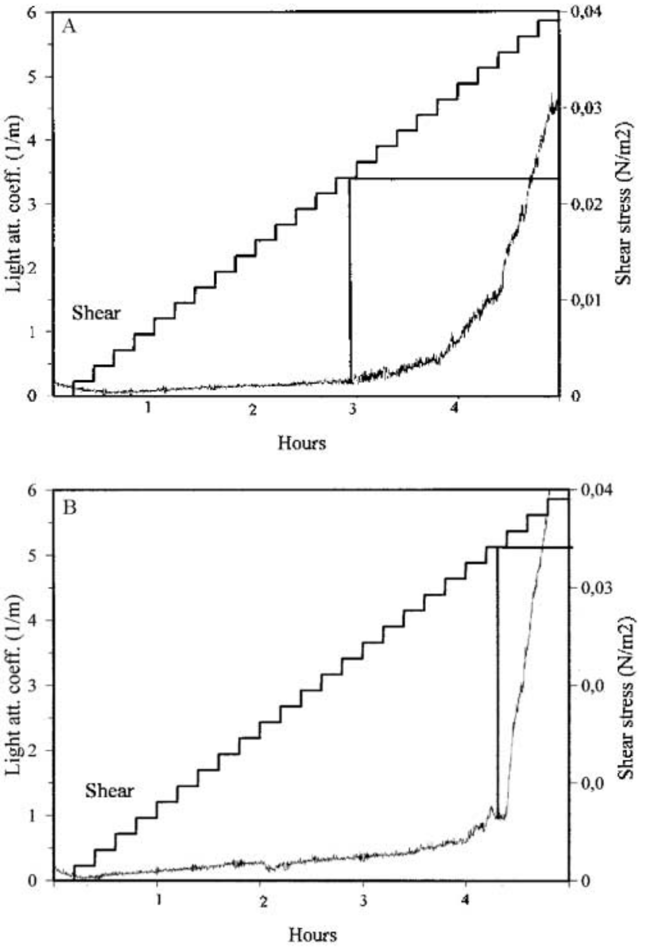

Figure 2a–b. Shear stress and LAC time-series in sample 3 (2a) and sample 6 (2b).

Table 1. *Results of sediment analyses with mean ±SD for each sediment parameter. All cores were separated into group A or B based on τ_c (see text). The* P*-values are based on Student's* t*-test which tests for a significant difference in the average between group A and B. Numbers in parentheses are not real values as maximum limit in the Laberex chamber was exceeded (see text).*

Sample nr.	Sand (%)	Silt (%)	Clay (%)	H_20 (%)	Poro. (%)	Org. (%)	Chl.*a* (myg/g)	τ_c (N m^{-2})	*100
A	13	8.4	62.9	17.5	85	1.1	12.7	1.8	1.9
	3	10	73.7	16.2	74	0.9	10.3	1.2	2.3
	4	25	59.6	15.2	63	0.9	6.5	0.1	2.6
	9	24	59.1	15.8	75	0.9	10.4	1	2.78
	11	16	63.6	28.7	74	1	10.1	2.2	2.9
	5	34	50.3	15.5	66	1	6.6	3	3.25
	8	21	61.6	17.9	69	0.9	7.3	0.4	3.25
	10	18	62.4	17	73	0.8	9.1	1.5	3.25
Mean ±SD		19.6 ±3.0	61.7 ±2.3	18.0 ±1.6	72.5 ±2.3	0.92 ±0.03	9.1 ±0.8	1.4 ±0.3	2.78 ±4.95
B	16	20	62.7	19.9	79	1	11.8	3.2	3.42
	6	14	63.7	22.2	71	0.8	9.4	2	3.42
	14	12	64.4	23.7	81	0.9	12.3	2.6	3.6
	15	14	64.5	21.6	84	0.9	12.7	1.1	3.7
	2	30	55.6	14.2	82	1	11.7	0.5	3.9
	12	12	60.7	27.7	75	0.9	12.5	0.8	(4.0)
	1	13	60.5	26.2	77	1.1	10.4	1	(4.1)
	7	24	58.7	17.3	78	0.9	13.1	3	(4.2)
Mean ±SD		17.4 ±2.4	61.4 ±1.1	21.6 ±1.6	78.5 ±1.5	0.92 ±0.03	11.7 ±0.4	1.8 ±0.4	3.61 ±2.03
P		0.57	0.9	0.13	0.048	0.88	0.011	0.47[1]	<0.001*[1]

[1] Mann–Whitney test and *indicates that this *P* value was for the difference in the median whereas *P* for the mean was 0.005—(n=8 group A, n=5 group B).

in group B as the three high but unknown τ_c values were not include in this test.

Fluff layer and diatoms

Sediment surfaces and down core conditions are shown for samples 12 (Figure 3A–B) and 4 (Figure 4A–B). Images were captured in colour but these were discarded for reproduction purposes. However, these samples were chosen, as they exhibit typical features of group A (sample 4) and B (sample 12) rather than being representatives of the two groups. For instance, τ_c is higher ($\tau_c > 0.04$ N m^{-2}) in sample 12 as compared to sample 4 ($\tau_c = 0.026$ N m^{-2}), organic and water content, and chl *a* are also higher in sample 12 in accordance with general trends (Table 1). A 1–2 mm thick dark grey surface layer is located on top of a lighter grey layer in sample 12 (Figure 3A–B), and a quite similar surface layer occurred in all group B samples. A less distinct but similar dark grey layer was found in six of the eight group A samples albeit the layer was absent in sample 4. There is a tendency that the boundary between the surface layer and the underlying layer was less well defined in group B compared to A as in sample 12 (Figure 3A). However, organic matter and water content increases towards the sediment surface in both group A and B demonstrated by an organic matter increase from 8.4% at 17–22 mm depth in the sediment to 12.5% at the surface (0–2 mm) as in sample 12. Water content increased similarly from 64.9% to 75.0% between 17–22 mm and 2–7 mm. This emphasizes the presence of an organic and water rich surface layer. In fact, the dark grey surface layer in sample 12 is recognized as a fluff layer, characterized by a loosely compacted, organic and water content rich layer on top of a more consolidated sediment (Stolzenbach et al., 1992). The high organic content of a fluff layer follows that such layer consists of recently deposited material, which is then degraded through biogeochemical processes and incorporated into the sediment over time. The fluff accumulates on the sediment surface during calm weather periods from where it is frequently resuspended in shallow water regions (Lund-Hansen et al., 1999; Edelvang et al., 2002) as fluff layer critical shear stress is generally low (Stolzenbach et al., 1992). However, both median τ_c, organic and water content are significantly higher in group B (high τ_c) compared with A (Table 1) which opposes the above characteristics of a fluff layer. Now, a major part of the surface in sample 12 is covered by benthic diatoms (Figure 3B) shown by the darker grey colours at the periphery of the core as well as in the central part (Figure 3B). The sample 4 sediment surface was not covered by benthic diatoms but these were present in varying degrees in seven of the eight group A samples. The dark grey colours at the rim in the northwest and southeast part of the sample 4 sediment surface are due to shadow effects (Figure 4B). On the other hand, the data set showed no correlation between τ_c and chl *a* concentrations as observed in other studies (see Introduction). The absence of such correlation might, however, be related to the fact that chl *a* analyses were performed on samples from the small cores and not on the cores that were used for determination of τ_c as this would have destroyed the samples. Instead, a visual inspection of digital images and three separate rankings of the samples were carried out in order to detect any relations between: 1) τ_c, 2) diatom film abundance, 3) polychaet abundance, and 4) surface topographic homogeneity. There is well known positive relation between τ_c and diatom

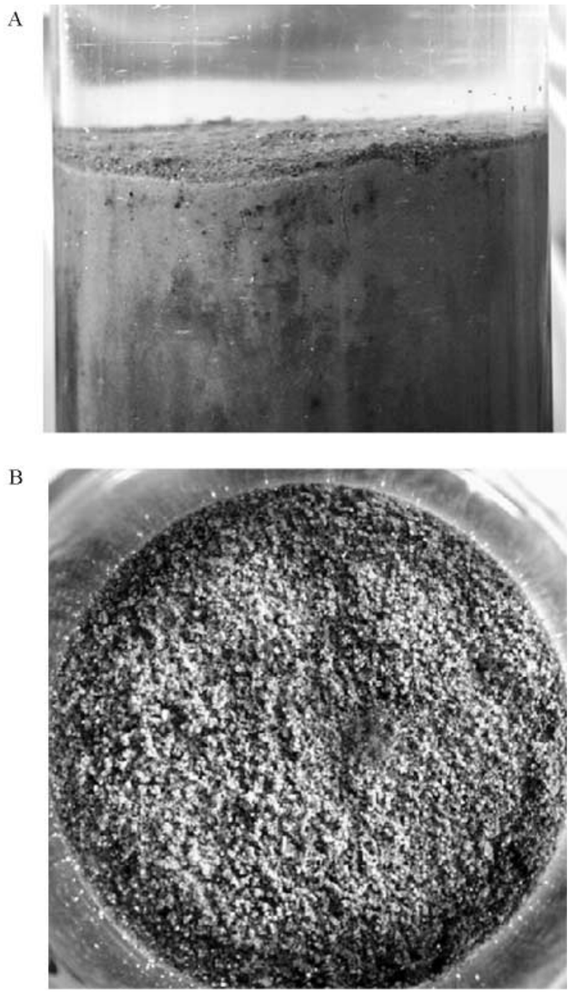

Figure 3a–b. Sample 12: Photographs of profile (3a) and surface (3b). Colours were discarded for reproduction purposes.

film abundance expressed as chl *a* (see Introduction). Bioturbation and sediment ingestion by polychaetes has been shown to reduce critical shear stress (Aller & Yingst, 1985), and polychaete burrows are observed in sample 4 (Figure 4A) but not in 12 (Figure 3A). Surface roughness, here expressed as topographic homogeneity, also affects critical shear stress as a smooth sediment surface, in general, raises critical shear stress (McCave, 1984). For instance, the sample 12 sediment surface is topographically more homogeneous and smooth with less borrows and hollows as in sample 4 (Figure 3B–4B). The sediment surface in sample 4 is the less homogeneous in group A where the surface of the other samples more resemble sample 12. Now, each of the surface and depth profile images were assigned a score value between 1 (low) and 16 (high) in relation to diatom film abundance, i.e. how much of the sediment surface was covered by benthic diatoms, polychaete abundance at the rim, and surface topographic homogeneity. Median τ_c was calculated for the low (1–8) and high (9–16) score groups as this parameter showed a significant difference between group A and B (Table 1). A two-tailed Mann–Whitney test was applied to test for differences between the two groups. Results show that surface topographic homogeneity seemed to be associated with a high median τ_c value but the relation appeared only marginally significant ($P=0.058$).

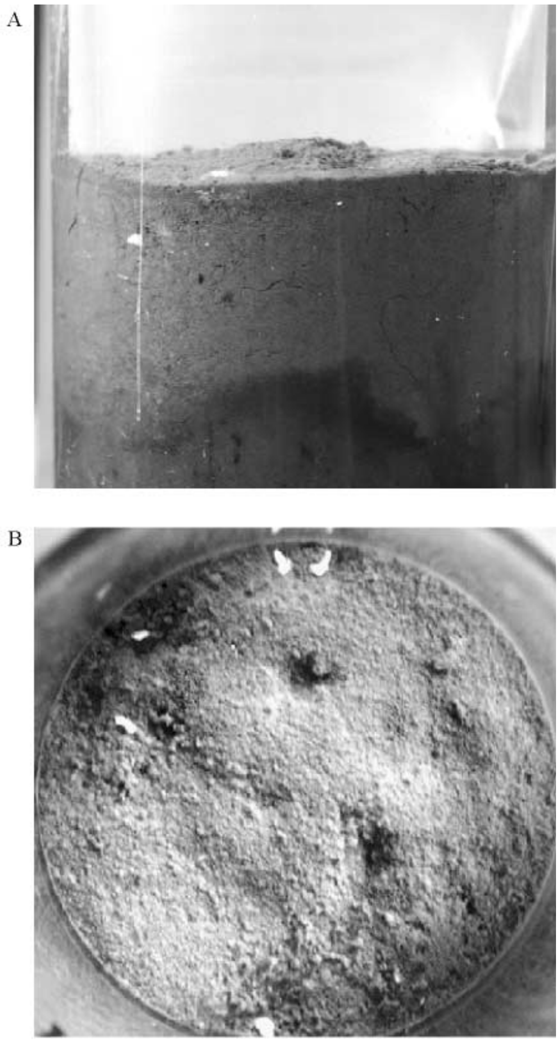

Figure 4a–b. Sample 4: Photographs of profile (4a) and surface (4b). Colours were discarded for reproduction purposes.

Diatom film abundance was significantly ($P=0.02$) related to median τ_c which was not the case regarding polychaete abundance ($P=0.126$). However, organic matter and water content were positively related to τ_c likely explaining principal part of the variance in τ_c (Table 1). A partial correlation analysis was hence carried through correlating τ_c with surface topographic homogeneity, organic matter and water content, each time controlling for the effects of diatom abundance. Results show that none of these three parameters alone influences significantly the τ_c value. Furthermore, the correlation between τ_c and diatom abundance, controlling for topographic homogeneity, water, and organic mater content, showed that diatom abundance was the most important parameter explaining the largest variability of τ_c (r^2: 0.70, $P<0.001$) (Table 2). These results strongly suggest that topographic homogeneity, water, and organic matter content are related to the presence of diatoms rather than being determinants of τ_c. Results show that the homogenous surface was covered by a diatom film which exhibited a high τ_c and that organic and water content were high in the diatom covered surface fluff layer (Table 2). It was observed during the Laberex experiments that the sediment surface broke apart in flakes (0.5–1 cm) and were brought into suspension once τ_c was reached in the major part of the group B samples. This phenomenon attributes

Table 2. *Correlation matrix showing the association between critical shear stress and potentially related parameters. r^2 and p-values (bold) are given.* P*-values are one-tailed probabilities regarding shear stress and two-tailed otherwise. Df=14 for all tests.*

	Diatom film	Surface homogeneity	Organic material	Water content
Shear stress	0.70 **<0.001**	0.20 **0.042**	0.12 **0.10**	0.17 **0.058**
Diatom film		0.33 **0.021**	0.30 **0.028**	0.28 **0.034**
Surface homogeneity			0.02 **0.60**	0.015 **0.65**
Organic material				0.81 **<0.001**

to the presence of the diatoms as flocs and aggregates are still kept together by diatom film. This is in agreement with other studies, which showed a correlation between the brake up in flakes and the presence of diatom films (Madsen et al., 1993; Laima et al., 1998). About 30 species of benthic diatoms were identified but three species of epipelic benthic diatoms dominated all 16 samples: *Haslea crucigeroides, Pleurosigma strigosum*, and *Bacillaria paxillifer.* There were no clear differences between group A and B in relation to the occurrence of both dominant and less dominant species, and there were no clear differences in species composition or abundances between positions. A few pelagic algae species were found in all samples.

DISCUSSION

Critical shear stress

The *in vitro* measured τ_c values lie within the range reported for *in situ* studies in areas with similar sedimentological conditions as Århus Bay. For example, erosional studies at a water depth of 16 m in Buzzards Bay showed an average τ_c of 0.023 N m^{-2} (N=9) (Young & Southard, 1978). This value lies within the range of the median τ_c (0.0278 N m^{-2}) measured for group A sediments (Table 1). Other authors reported a τ_c of about 0.05 N m^{-2} obtained at *in situ* in water depths from 5 to 6 m (Maa et al., 1998). However, average current shear stress in Århus Bay, measured during a 1.3 year long period at a position close (~2 km) to the present sampling positions, is about 0.01 N m^{-2} but may reach 0.1 N m^{-2} in periods of wind wave generated shear stress (Lund-Hansen et al., 1997). Shear stresses of 0.01 and 0.1 N m^{-2} relates to current speeds of about 10 cm s^{-1} and 30 cm s^{-1} at 1.0 m above the seabed, respectively, depending on drag coefficient (C_d) and water density (ρ_w) as: $\tau=C_d\rho_w u^2$ (Soulsby, 1997). In comparison to minimum measured τ_c of 0.019 N m^{-2} (Table 1), these results show that erosion only occurs very infrequently at the sampling positions. On the other hand, it must be anticipated that the sediment surface is only covered by diatoms during spring, summer and part of the autumn where light intensity is high enough but whereby the observed entrapment of the fluff layer by the benthic diatoms only acts on a yearly scale.

Fluff layer

Studies of fluff layer critical shear stress along a river mouth-depositional area gradient at different water depths (16–47 m) showed an average of 0.018 N m^{-2} (N=8) with a range between 0.021 and 0.013 N m^{-2} (Jähmlich et al., 2002). This average is comparable to the minimum τ_c of 0.019 N m^{-2} of group A whereas the averages reached 0.0278 and 0.0361 N m^{-2} in groups A and B, respectively (Table 1). Apart from any differences in floc and aggregate sizes between the Jähmlich et al. (2002) study and the present, these results clearly show that the presence of benthic diatoms strongly increases critical shear stress and even in samples with a low diatom film score value as in group A (Table 1). This detailed comparison is justified as the hydraulic damped box-corer and the Laberex chamber were used in both studies. The development, maintenance, and general dynamics of fluff layers are less studied although it is known that fine-grained organic rich material enriched in clay minerals (fluff layer/material) is responsible for the transportation of particulate bound pollutants, for instance heavy metals (Sadiq, 1992). It has recently been shown that the fluff layer acted as conveyer belt in the transportation of organic pollutants on a river-depositional area gradient in the southern Baltic Sea (Witt et al., 2001). Heavy metal concentrations were not measured in the present study but that the benthic diatoms strongly raise the critical shear stress of the fluff layer has some implications. For instance, the transport of associated heavy metals and other particle bound pollutants will remain deposited for a longer period in the shallow water region where down welling irradiance is high enough to sustain populations of benthic diatoms. This is especially the case in the non-tidal Århus Bay where τ_c only infrequently is higher than 0.01 N m^{-2}, although that the earlier supposed yearly variation in benthic diatom abundance has to be considered.

Chlorophyll-a

Recent studies in tidal environments have shown a positive correlation between τ_c and chl *a* concentration (Vos et al., 1988; Delgado et al., 1991; Paterson, 1989; Heinzelmann and Wallisch, 1991; Yallop et al., 1994). A similar relation was also found in the present study shown by the significant correlation (r^2: 0.7, $P<0.001$) between shear stress and abundance of diatom film (Table 2). The correlation was, however, based on quantative image analyses rather than direct measurement of chl *a* in the sediment which showed no correlation (Table 1). Chl *a* analyses were carried out on samples collected from the small cores and not from the cores that were actually used for τ_c the determination as such sampling would have disturbed the samples. Average sediment surface chl *a* concentrations in Århus Bay are 1.6 μg g^{-1} (Table 1), or two times higher as those measured in a tropical embayment between 20 and 60 meter of water depths (Burford et al., 1994). And also higher compared with the mean of 0.6 μg g^{-1} on the subtropical (34°N) south-east coast of the US at water depths between 10 and 19 m (Cahoon et al., 1990). Chl *a* concentrations in Århus Bay are low compared with the Danish Wadden Sea area where concentrations of about 20 μg g^{-1} were reported for intertidal sand flats

(Mouritsen et al., 1998) and 219.1 $\mu g\, g^{-1}$ in mudflats (Austen et al., 1999). The diatom *Bacillaria paxillifer* was assigned a low stability coefficient in a study comparing the effects of different diatom species on sediment stability (Holland et al., 1974). *Bacillaria paxillifer* was one of the three dominant species in Århus Bay. However, the low stability coefficient is difficult to evaluate in the present study as Holland et al. (1974) compared *Bacillaria paxillifer* to species that were not found in the Århus Bay.

Sediment parameters and variability

Organic matter and water contents were both significantly higher in group B (high τ_c) whereas there were no significant differences in grain-sizes between the two groups (Table 1). The statistical analyses comprised only three main groups of grain-sizes: sand, silt and clay, which is, however, a very coarse scale regarding grain-size distributions. Nevertheless, the sediment samples are typical cohesive sediments shown by the high proportions of silt and clay (60–70%), high organic matter (~10%), and water (~75%) contents (Table 1). The physical characteristics of the cohesive sediments, in relation to an applied shear stress, are then generally governed by variations in organic matter and water contents, compared to the small variations in grain-sizes (McCave, 1984). However, the present study shows that benthic diatoms occur at relatively deep water (14–15 m) even in an eutrophic bay where down welling irradiance is generally controlled by phytoplankton and dissolved organic matter (Jørgensen, 1996). However, no obvious patterns regarding any of the sediment parameters were recognized in Århus Bay, i.e. high τ_c values or samples with a high organic content were clustered in a separate part of the grid, for instance. The variability of τ_c in Århus Bay is high with a coefficient of variation (CV) of 18.6% which is a high value compared the CV of 12.8% reported for areas recognized as highly heterogeneous, for instance along an intertidal gradient. Paterson et al. (1990) carried out replicate measurements of critical pulse velocity (CPV, m s^{-1}) on a range of stations covering several different tidal flats (9 to 25 km apart) and different tidal levels (high, medium, and low). Concentrating on two hours of exposure, a CPV value (chosen at random among the mean, mean +SD, and mean −SD) was deduced directly from graphs shown by Paterson et al. (1990). In this way, 13 CPV readings were obtained, embracing 5 different tidal flats and 2–3 different tidal levels, and the calculated CV was 12.8%. It was expected that the exposure of heterogeneous tidal flats to strong current and wave shear stress variations would result in a higher CV compared with the seemingly homogeneous sampling positions in Århus Bay. High spatial variability in benthic diatom patchiness in a tidal flat has also been recognized by Jonge and Beusekom (1995) and Delgado et al. (1991) noted a clear spatial variation in that concentrations of benthic diatom were increased at less exposed stations to waves and currents.

DOM definition OK?

Benthic diatoms in Århus Bay

The Secci depth has increased from 6 m in 1987 to about 8.5 m in 1998 at a central position in the bay as shown by weekly measurements, and a maximum Secci depth of 16 m was reached in July 1998 (Århus County, 2000). It is unlikely that benthic diatoms in any way have been transported from shallow water as June, July, and August 1998 were governed by calm wind conditions. The increased Secci depth and thus increased light penetration depth observed in 1998 was most likely the background for development of benthic diatom films at these water depths. The increased light penetration depth might be related to the reduction in nutrient loads into the Århus Bay and surrounding waters that has been observed in recent years, especially regarding phosphorus (Århus County, 2000).

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