Nutrients and Organic Matter in Southern Kattegat - Western Baltic Sea Sediments : Effects of Resuspension

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Organic matter and nutrient concentrations in sediments are studied in three areas representing a depth profile from shallow to deep water in the transition zone between the Kattegat and the Baltic proper. Considerable differences between the three areas exist in surface water concentrations of nutrients reflecting increasing distance from terrestrial sources of nutrients. In spite of this, there are great interareal similarities in the average concentrations of organic matter (1.8-1.9%) as well as nutrients (0.04-0.06% total-N and 0.02-0.03% total-P) in the sediments which are subjected to frequent wave induced resuspension. Concentrations in deep water sediments (8-15% organic matter, 0.19-0.62% total-N, and 0.05-0.14% total-P) with no or infrequent resuspension are up to 10 times higher and lowest in Kattegat, where the fetch allows resuspension in the deepest parts. The data suggests that the sediments have a preferential loss of their N content compared to the C content during resuspension and transport from erosional bottoms to accumulation bottoms. This indicates that the C/N ratio may be used as an indicator of bottom type, provided that the sediments are sampled in the same season.

Keywords: *Resuspension, deposition, nutrients, Kattegat, Baltic Sea.*

Sedimentation and resuspension of fine particulates are not only important as physical/sedimentological processes, they also constitute a cycling of nutrients and energy and provide a coupling between the pelagic and benthic remineralizing system. Further, resuspension changes light extinction coefficients (Pejrup, 1983) and affects nutrient exchange between the water column and the sediments (Bates & Nearfus, 1980) and thus also the phytoplankton productivity (Gabrielson & Lukatelich, 1985).

In shallow waters gross sedimentation will be much larger than net sedimentation due to resuspension (Floderus, 1989; Christiansen et al., 1991; Valeur et al., 1992). Resuspension may be induced by either currents or waves or a combination of both. Wave induced resuspension appears to dominate in exposed littoral zones in the absence of strong tidal currents (Lund-Hansen et al., 1993). Even on shelves at depths as great as 150-200 m sediments may be reworked by waves during storms. Such storm events are reported to influence shelf sedimentation processes out of all proportion to their infrequent occurrences (Open University, 1989).

The purpose of the present paper is to examine the fate of organic matter and nutrients as a function of as well increased distance from terrestrial sources as increased water depth. The mechanisms behind alteration of C:N:P ratios during early diagenesis are very complex. However, Koop et al. (1990) found a preferential loss of nitrogen relative to carbon along a depth gradient in the Baltic proper. This could indicate that material, originally deposited in shallow water, is frequently resuspended and that a more rapid loss of nitrogen occurs during its transport to final settling in deep water.

Study Areas

Vejle Fjord is a micro-tidal estuary (tidal range 0.4 m) located on the east coast of Jutland, Denmark (Fig. 1). The area is 62 km^2 and the depth ranges from 0-4 m in the shallow inner part of the estuary to 16-18 m in the deeper outer part. Because of the small tidal range, current velocities 1 m above the bottom average 4 cm s^{-1} and only exceed 20 cm s^{-1} for 0.4% of the time (Christiansen et al., 1992). Such small velocities do not result in current-induced resuspension. Terrestrial discharge of nutrients (in 1990) to the estuary is about 2000 10^3 kg y^{-1} of nitrogen (tot-N) and about 160 10^3 kg y^{-1} of phosphorus (tot-P). The freshwater discharge in Vejle Å (Å = river) averages 4 m^3 s^{-1} with maximum discharges up to 29 m^3 s^{-1} in the early spring. Therefore, and also because of its near-coast position, the concentrations of inorganic nutrients in Vejle Fjord are high (0,7 mg l^{-1} of inorganic N and 0.055 mg l^{-1} of inorganic P) in early spring (Fig. 2 A,B).

Because of its shallowness the waters in the main part of Vejle Fjord are generally well mixed. During strong westerly winds the pycnocline in the Kattegat (normally situated at a depth of 15-20 m) will penetrate into Vejle Fjord (Christiansen et al., 1992).

The Kattegat study area is situated in the southern part of the Kattegat (Fig. 1) in the transition zone between inflowing water from the North Sea with high density and out-

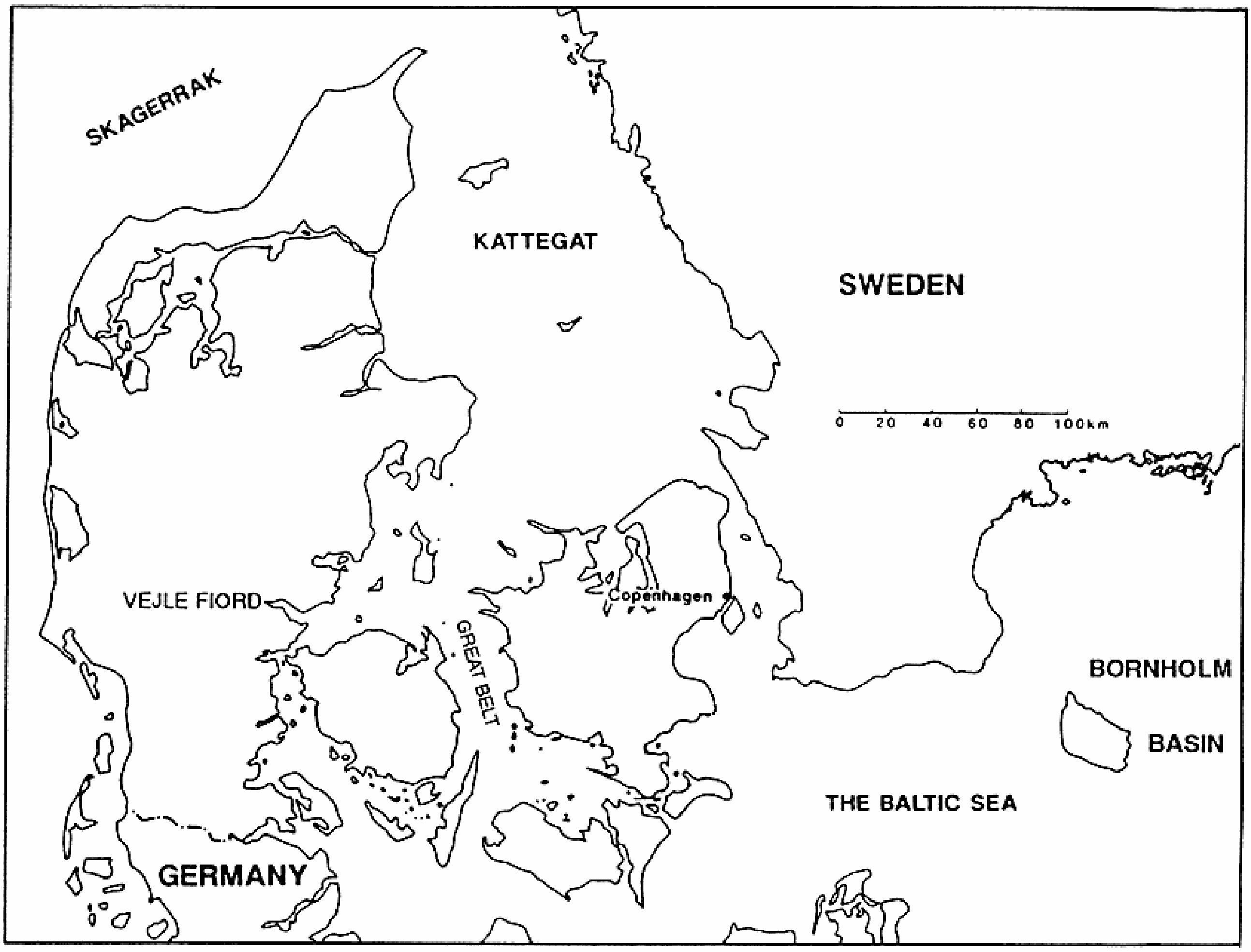

Figure 1: Map showing positions of the 3 study areas. A more detailed map of the Bornholm Basin is included in Figure 7.

flowing water from the Baltic with low density. Because of the circulation, this study area has a strong pycnocline in the spring and summer periods, whereas the water column is generally less stratified during autumn and winter when the outflow is smaller and wind-induced mixing of the water column is more frequent. The tidal range is in the same order as in Vejle Fjord (~ 0.4 m). The depths are 20-30 m in the western part of this study area and 30-45 m in the eastern part. Because of the depth distribution wave induced resuspension is more frequent in the western part than in the eastern part (Floderus, 1989). As this study area is situated further away from land, maximum concentrations of nutrients in the spring are smaller than in Vejle Fjord (Fig. 2 A,B). It is clear from Fig. 2 A, B that the surface water nutrient concentrations in the Kattegat are, in general, intermediate between Vejle Fjord and the Bornholm Basin.

The Bornholm Basin (Fig. 1) occupies an area of 38990 km^2 of which about 40% have depths greater than 50 m. From April to September a thermocline is present at a depth of about 15 m. At a depth of roughly 60 m there is a permanent halocline. The area is situated relatively far from terrestrial sources of nutrients. The concentration of inorganic N and P is therefore low in the surface water (Fig. 2). Inflow to the Bornholm Basin occurs as a dense bottom current which enters through the Bornholm Strait and then, due to the Coriolis force, the current flows anticlock wise towards the south along the depth contour as a subsurface current (Jacobsen, 1991).

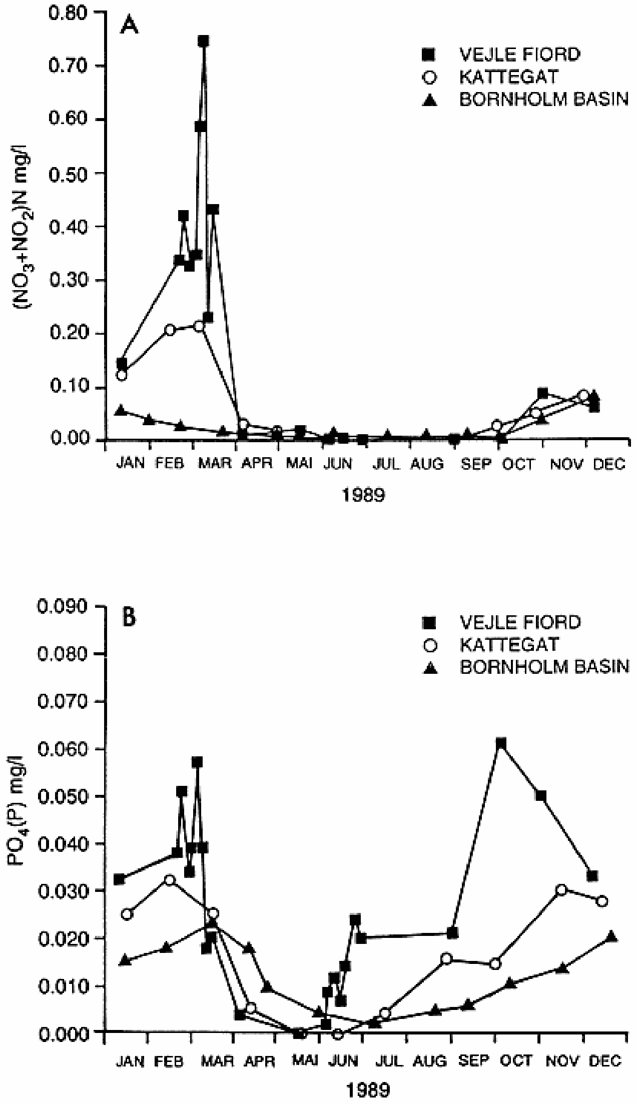

***Figure 2:** Seasonal variations in the concentrations of nutrients in surface waters of the three study areas. A) $NO_3 + NO_2$. B) PO_4 (P).*

Methods

The sediments were sampled with van Veen type grabs. As a grab sampler may disturb the sediment surface (Holme, 1964), great care was taken to ensure that only the top 0.5 cm of the sediment from the central part of the grab was used for further laboratory examination. In addition two 4.5 m gravity corers were taken in the Kattegat and the Bornholm Basin.

The loss on ignition (IG) was determined after heating the dried sediments at 500°C for 6 hours. The organic carbon content was calculated by multiplying the IG by 0.5 (Håkansson & Jansson, 1983). The total phosphorus content, after wet-acid oxidation, was measured spectrophotometrically at 880 nm using the molybdenum blue method (Murphy & Riley, 1962). Total nitrogen was determined as Kjeldahl-nitrogen (Jönsson, 1966). All wet chemical determinations were made in duplicate.

Grain-size distributions were determined using standard sieving (ASTM sieves with certificate) and pipette techniques.

The rate of resuspension in deep water was estimated from current velocities using the method outlined by Miller et al. (1977). Wave resuspension was calculated in three steps: 1) Wave height and period was estimated using the formulas in Beach Erosion Board (1975). 2) Maximum orbital velocity (U_m) at the bottom was found using the Airy wave theory (Beach Erosion Board, 1975).

$$U_m = \pi\, H/T \sinh(2\pi h/L) \qquad (1)$$

where H is wave height, T is wave period, L is wave length and h is water depth. 3) Threshold grain-size for the calculated velocities was found by

$$\rho_w U_m^2 / (\rho_s-\rho_w)gD = 0{,}30\,[H/\sinh(2\pi h/L)D]^{1/2} \qquad (2)$$

where ρ_w is the density of sea water, ρ_s is the density of sediment, g is acceleration due to gravity, and D is grain diameter (Komar & Miller, 1973). Such calculations can only give estimates of waves and wave-induced resuspension. However, a comparison of measured wave- height and period with predicted values in the Kattegat (Floderus, 1989) showed that such predictions were correct within an uncertainty of 10%.

Results

Vejle Fjord

For known grain-size distributions in the Vejle Fjord sediments in each grid of Fig. 3, Fig.3 shows (using formula (2)) calculated percentages of the grains on the bottom that can be resuspended by waves with a wind from the W of 10 m/s (Fig. 3A) and a wind from the E of 10 m/s (Fig. 3B). Such wind velocities occur 15% of the year (Christiansen et al., 1993a). It can be seen that, in both cases, there is resuspension in shallow near shore waters although the average grain-size in shallow water is 0.250

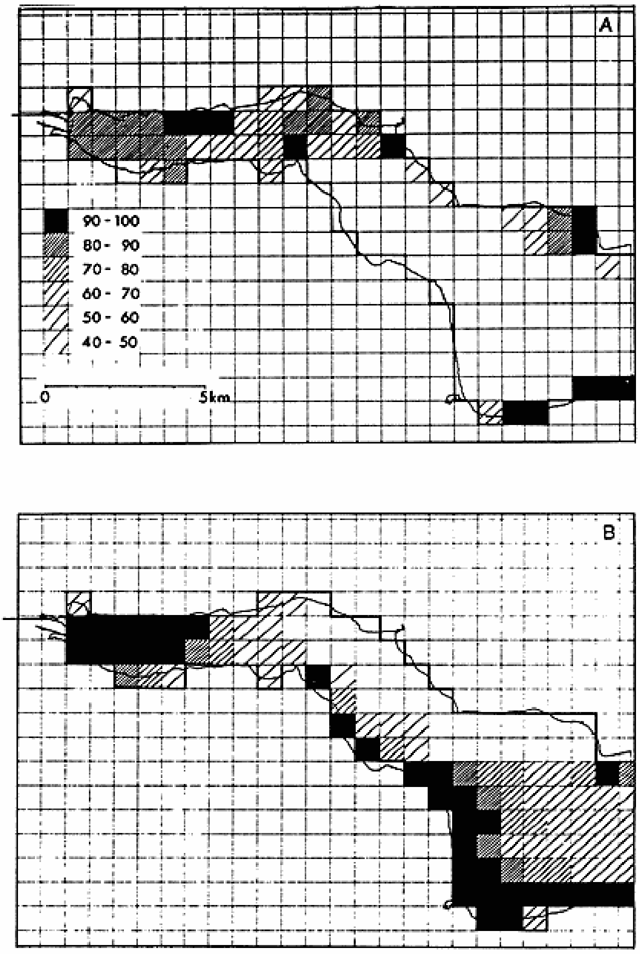

Figure 3: Outlines of Vejle Fjord showing estimates (in grids) of percentages of resuspendable grains in Vejle Fjord sediments due to waves for a wind velocity of 10 m/s. A) wind from the west. B) wind from the east.

mm. Christiansen et al. (1992) showed that the shallow areas were subjected to frequent resuspension and therefore had a net nitrogen sedimentation of only 19 T/y compared to a gross nitrogen sedimentation of 850 T/y. These numbers mean that, because of frequent resuspension, net sedimentation in the shallow water areas, making up 10% of the total area, is less than 1% of the supply of nitrogen to Vejle Fjord.

In the deeper central part of Vejle Fjord there are areas without resuspension both with 10 m/s winds from the W and the E (Fig. 3, A,B). This does not take place despite the average grain-size in deep water being only 0.008 mm. These central parts coincide with the areas of highest nutrient concentration in the sediment. As there is an almost perfect linear relationship between percentages of organic matter in the sediment and concentrations of nutrients (see section on comparison), Fig. 4 shows that sediments in shallow water areas with frequent resuspension have a low content of organic matter and nutrients, whereas such contents are high in deep water sediments with no or infrequent resuspension.

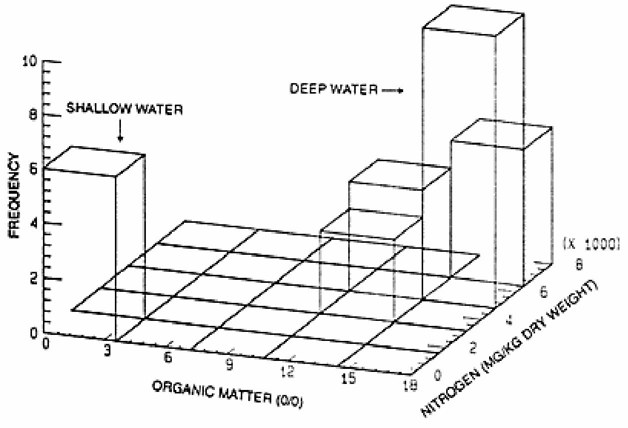

Figure 4: 3-D histogram showing the contrast between Vejle Fjord shallow water and deep water sediments in their content of organic matter and nitrogen.

The Kattegat

Based on a similar, but more crude approach than the present using L/4 as wave base for resuspension, Floderus (1989) compiled a map (Fig. 5) showing the spatial distribution of calculated recurrence of wave-induced resuspension in the Kattegat. When comparing Fig. 5 with hydrographical charts it becomes clear that areas of infrequent resuspension coincide with the deeper eastern parts of the Kattegat. Fig. 6 A shows a SW-NE depth profile together with the content of organic matter and concentrations of nutrients. It is clear, from Fig. 6 A, that the content of organic matter (2-3%) and concentrations of nutrients (0.03-0.08% N and 0.018-0.021% P) are low in the SW part of the profile with relatively frequent wave-induced resuspension. The concentrations are highest in the deepest situated stations in the NE part of the profile (10% org. matter, 0.3% N and 0.075% P).

Fig. 6 B shows for each station the calculated wave-orbital velocities at the bottom together with the maximum grain-size that can be resuspended with these velocities. The calculations are based on a NW wind with a velocity

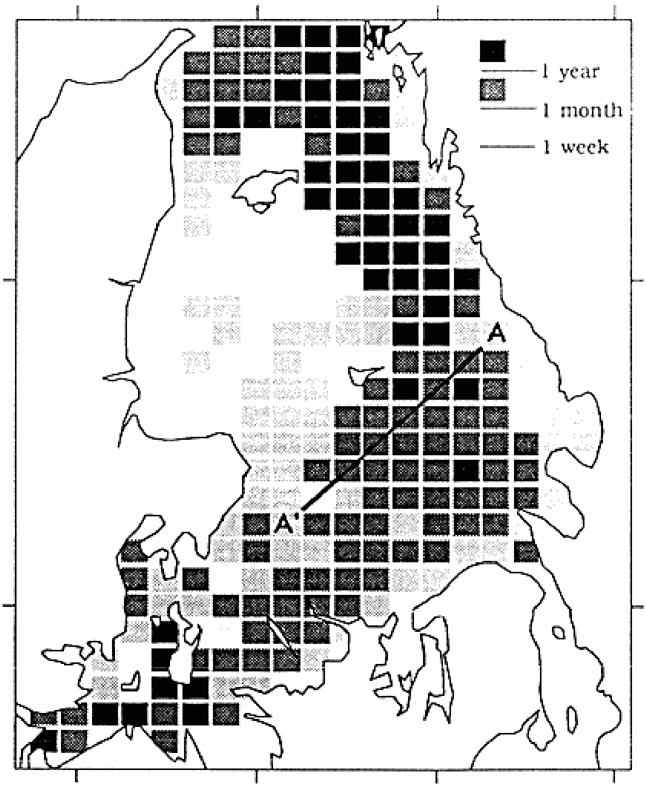

Figure 5: Spatial distribution of calculated recurrence of wave-induced resuspension. A-A' gives the position of the profile in Fig. 6. (Modified after Floderus (1989)).

of 15 m/s. Such winds occur 0.2% of the year (Kristensen & Frydendahl, 1991). In the more shallow western part of the profile such wind velocities can resuspend grains up to 0.250 mm. In the deeper eastern part of the profile resuspension only occurs at stations 36 and 39, where grains as large as 0.080-0.100 mm can be resuspended. A comparison of Fig. 6 A and Fig. 6 B shows a good correlation between possible resuspension and a low content of organic matter as well as of nutrients. The fine and organic material on stations with possible resuspension will ultimately be swept away and transported to deeper positions with less chance of resuspension. This means that sediment organic matter and nutrient concentrations are positively correlated to depth (r=0.67 for organic matter, 0.64 for total-N, and 0.54 for total-P; p>99.9% as n=80).

The Bornholm Basin

Fig. 7 A,B shows the areal distribution of P and $C_{org.}$ in the recent sediments of the Bornholm Basin. Areas of high concentrations coincide to a high degree with depths greater than 50 m (Fig. 7 C). Also in the Bornholm Basin, there are strong indications that the areal distribution of organic matter and nutrients to a high degree depends on the potential for resuspension.

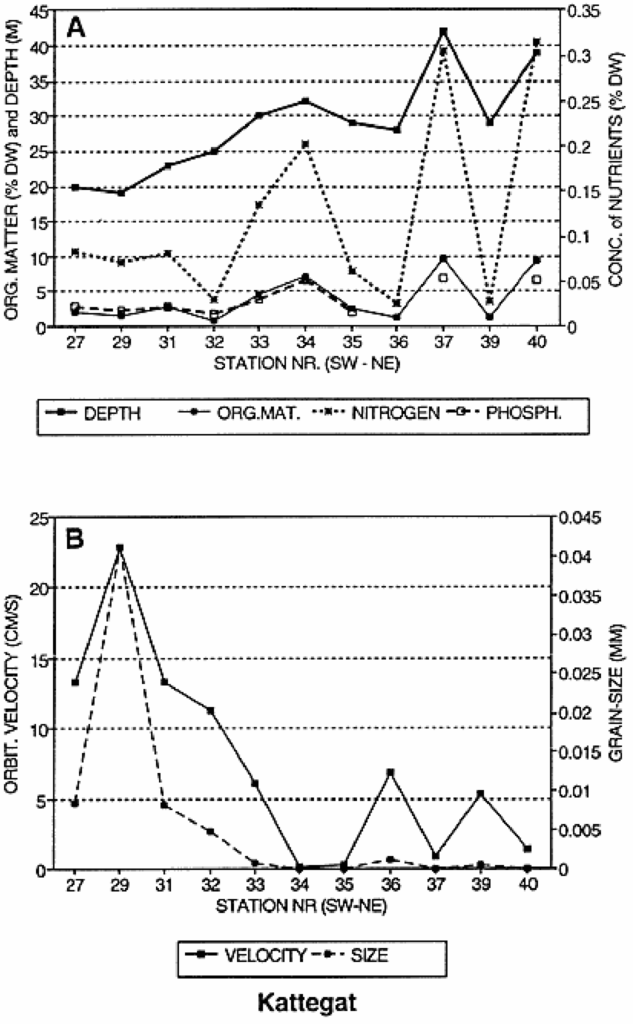

Figure 6: A) SW-NE depth profile (note the inverted depth scale) of line A-A' in Fig. 5 together with content of organic matter and concentrations of nutrients (percentages of dry weight).
B) Calculated near-bottom maximum orbital velocity and resuspendable grain-size at a 15 m s^{-1} NW-wind in line A-A'.

Thus, Fig. 8 shows that with strong winds (25 m/s) from the longest fetch (E) there are possibilities for wave-induced resuspension down to a depth of about 50 m. In the Bornholm Basin there are two exceptions to this rule. Two samples from the depths of 75 and 83 m have a low concentration of organic matter and nutrients. These two

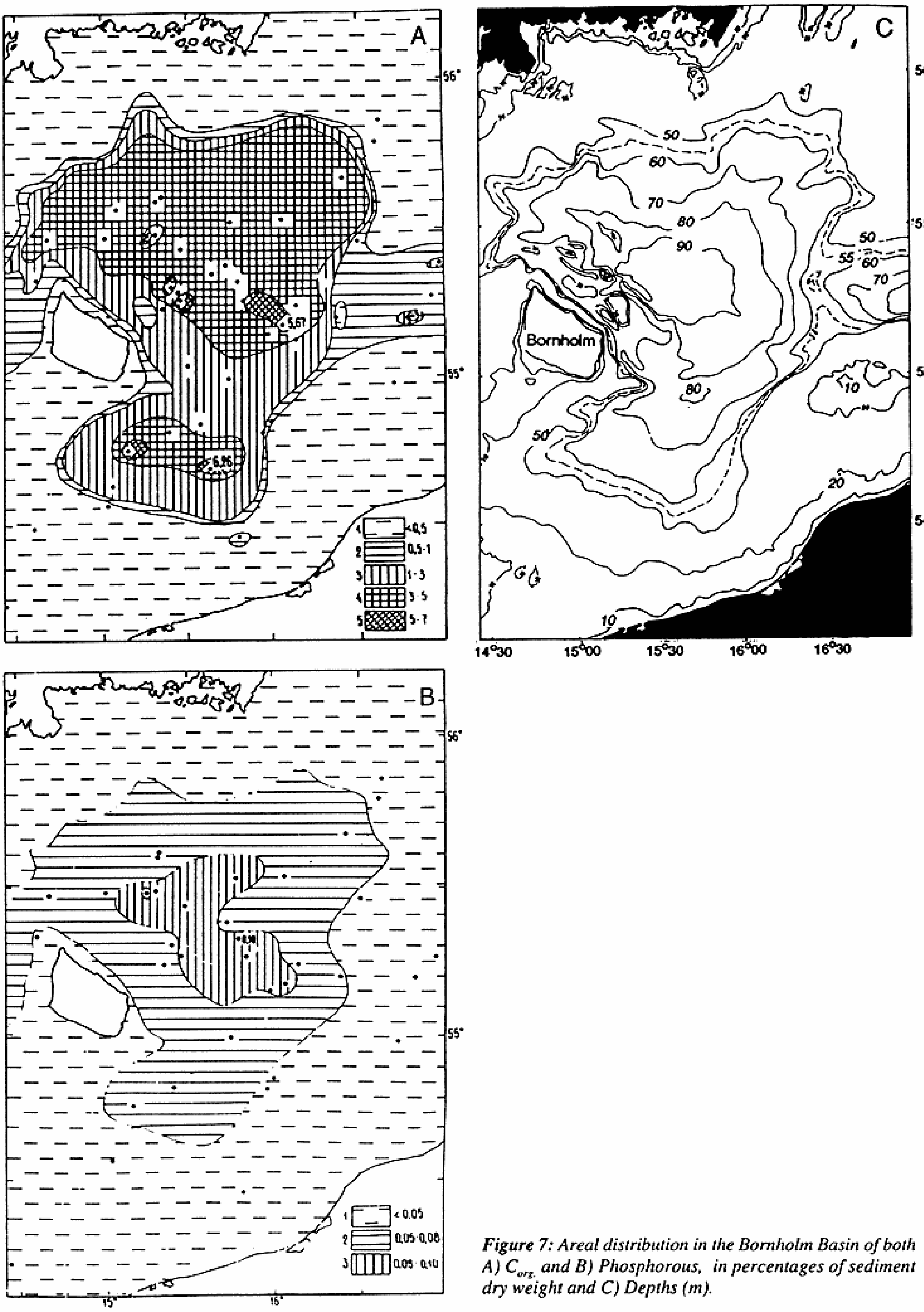

Figure 7: Areal distribution in the Bornholm Basin of both A) $C_{org.}$ and B) Phosphorous, in percentages of sediment dry weight and C) Depths (m).

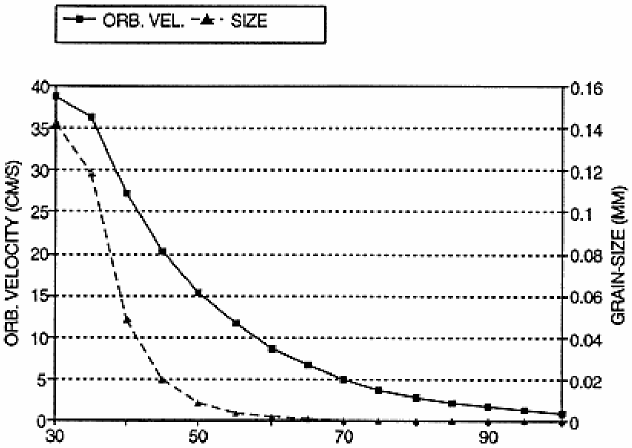

***Figure 8:** Calculated near-bottom maximum orbital velocity and resuspendable grain-size in the Bornholm Basin for a wind velocity of 25 m/s from the E.*

samples were both taken on relatively steep slopes, so it might be that these two locations are influenced by current-induced resuspension. Jacobsen (1991) describes currents of high velocity following the depth contours in the basin.

Comparisons

Although there are great differences in the concentrations of nutrients in the surface waters, Table 1 shows that there are great interareal similarities in the concentrations of nutrients in the shallow water sediments. In shallow water with frequent resuspension the average concentration of organic matter is low (1.8-1.9%). This is also the case for both Tot-N (0.04-0.06%) and Tot-P (0.02-0.03%). In deep water with no or infrequent resuspension, concentrations of N are up to 10-15 times higher and concentrations of P are up to 5-6 times higher. Table 1 also shows that in the southern part of Kattegat, where resuspension also takes place in deep water, there are much lower concentrations of organic matter and nutrients in the deep water sediments when compared to the deep water sediments of Vejle Fjord and the Bornholm Basin.

An increase in the concentration of P is observed from a level of 15-20 cm below the surface in both the Kattegat and the Bornholm core samples. We have no exact datings of this level, however, using a sedimentation rate of 3-4 mm/y from nearby stations (Christiansen et al., 1993b) which can be considered typical for the Kattegat (Madsen & Larsen, 1986;). This indicates that the present eutrophication started to influence the sediment 40-50 years ago. Such an estimate is difficult to give for the Bornholm Basin because of a limited number of datings of recent sediments.

There is a strong (r=0.96-0.98, p>99.9%), linear correlation between the content of organic matter and both N and P in Vejle Fjord and the Bornholm Basin. In the Kattegat, with frequent resuspension-episodes, there is also a strong correlation (r=0.96, p>99.9%). In this case, however, lesser N concentrations are observed relative to C (Fig. 9). As our Kattegat sediments are generally subjected to more frequent resuspension than the sediments from the two other areas, this could indicate that there is a preferential loss of N compared to C during transport and resuspension. In all three areas organic content and nutrients are positively correlated to the sediment content of clay and silt and negatively correlated to resuspension possibilities expressed as the maximum resuspendable grain-size for

***Table 1:** Comparison of the content of nutrients and organic matter (IG) in water and sediments in the three study areas. The sediments were sampled during three subsequent October months: the Bornholm Basin 1989, Vejle Fjord 1990, and the Kattegat 1990.*

	Water		*Sediment*							
			Shallow water				Deep water			
	NO_2+NO_2 (mg/l)	*PO_4(P) (mg/l)*	*Depth (m)*	*IG (%)*	*Tot-N (%)*	*Tot-P (%)*	*Depth (m)*	*IG (%)*	*Tot-N (%)*	*Tot-P (%)*
Vejle	0.70	0.055	0-2	1.8	0.04	0.02	4-18	15.0	0.62	0.12
Kattegat	0.20	0.032	15-25	1.9	0.04	0.02	24-40	8.1	0.19	0.05
Bornholm	0.05	0.022	35-50	1.9	0.06	0.03	50-95	12.1	0.56	0.14

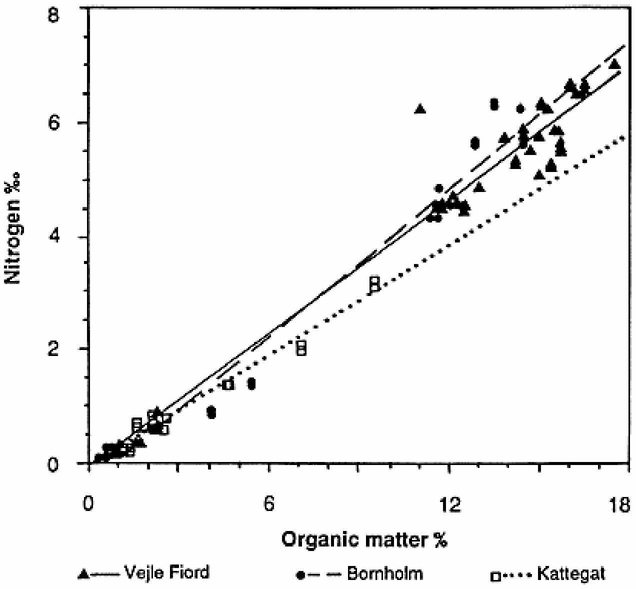

Figure 9: Correlations between N and $C_{org.}$ for the three study areas.

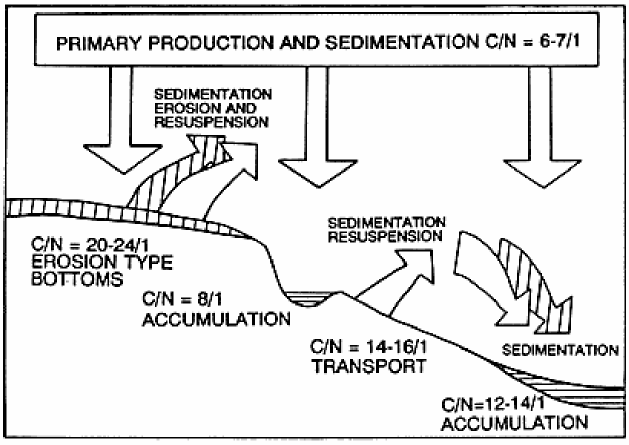

***Figure 10:** Model to explain observed effects of resuspension on the C/N ratio.*

wind speeds of 10 m s^{-1} over shallow waters and 20 m s^{-1} over deep waters.

Fig. 10 shows a model which may explain the observed C/N ratios in the sediments. The C/N ratio in the surface water is 6-7/1 or very near to the Redfield ratio (Redfield, 1934). On primary accumulation bottoms as the central part of Vejle Fjord the C/N ratio (8/1) is very near to the Redfield ratio. On transport bottoms, as in the Kattegat and the shallow water of Bornholm Basin, the C/N ratio is higher (14-16/1) due to the preferential loss of N during transport. In secondary accumulation areas, as in the deep parts of the Bornholm Basin, with sedimentation of both the primary production and transported material, the C/N ratio takes intermediate (12-14/1) values. On erosive bottoms with no marine accumulation the C/N ratio is high (20-24/1).

Discussion

The C/N ratio is often used to characterize the organic matter with respect to origin and degree of decomposition. However, most sediments consist of a mixture of more or less refractory organic matter with completely different C/N ratios. To some extent this baffles the interpretation of registered ratios. Microbial decomposition of the organic matter during settling in the water column also increases the C/N ratio. This means that bottom sediment organic matter and nutrient concentrations may change through the year. However, with these complexities in mind, and because the sediments were sampled in the same month of the year, the C/N ratio turned out to be a useful tool to discriminate between transport/erosion bottoms and accumulation bottoms. Such observations corroborate the findings from trap studies in Valeur et al. (1992), and Olesen & Lundsgaard (1995) that there is a preferential loss of N relative to C when organic matter is repeatedly brought back to the water column during resuspension. Kolp et al. (1990) also observed a preferential loss of N compared to C in the sediments from a depth profile in the Baltic proper. Resuspension is thus an important factor in the redistribution of sediments and their content of organic matter and nutrients.

It is noteworthy that the concentrations of nutrients in the sediments in the Bornholm Basin are just as high as in Vejle Fjord although the concentrations of nutrients in the surface water are much smaller (14 times for nitrate and nitrite and 2-3 times for phosphate). This could imply that there may be an additional source for the nutrients in the Bornholm Basin sediments. Based on budgets for the nutrients in the Baltic Sea and taking into account both primary production and external sources Jonsson et al. (1990) also needed an additional source to explain the concentration of nutrients in the Baltic deep basins. They suggested that erosion and resuspension of post-glacial deposits could contribute more than 85% of organic matter and nutrients found in deep basin sediments. Richardson & Christoffersen (1990) showed that the primary production in the southern part of Kattegat was higher than could be explained by the external sources of nutrients. There was evidence that the nutrients were recycled at least 4 times.

All of the above points to the importance of resuspension in the recycling and redistribution of nutrients.

Acknowledgements

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