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Sediment characterization and parameter estimation. ERMS task 3

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Akvaplan-niva Report

Sediment characterization and parameter estimation

ERMS Task 3

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Sammendrag / Summary

This report summarises the work carried out in ERMS Task 3, which aims at characterising undisturbed sediments and developing models for estimating one sediment parameter from other sediment parameters when not all parameters are measured. Most of the data used in this work originates from the MOD database. Equations, including an estimate of the accuracy, are given for the relationships between depth, grain size and organic matter. In addition, the relationships between depth and sedimentation rate and biodegradability of organic matter and organic content of the sediments are discussed.

Key words:

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1 Introduction

As part of the ERMS project Akvaplan-niva AS and MUST AS have carried out a study to describe the properties of undisturbed sediments and how sediment parameters are correlated to each other (ERMS Task 3). The aim of this work is twofold. First, the information will provide important background information regarding the properties of undisturbed sediments, which has a strong influence on the fate of drill cuttings when discharged to sea. Thus, models that aims at predicting the sedimentation of drill cutting on the seafloor should take into account the natural conditions of the sediment and also be developed separately for different sediment categories.

Secondly, the project aims at developing models for estimating one sediment parameter from another sediment parameter when not all parameters are known. Such models can be used to derive baseline data of an area which has not been subject to drilling activities earlier instead of carrying out direct measurements.

The following correlations between sediment parameters are investigated:

- Median grain size (µm) vs. depth
- Pelite vs. depth
- Fraction of organic carbon in the sediment vs. depth and grain size
- Fraction of organic carbon downwards in the sediment
- Natural deposition rate vs. depth and grain size
- Biodegradability of organic matter in relation to organic content of the sediments.

2 Methods

Data available in the MOD (environmental monitoring data base), containing all results from the Norwegian offshore monitoring from 1990, are used in the project. To ensure that the sediments are undisturbed by offshore activities, only the reference and regional stations are included in the analyses. The following sediment parameters are used:

- Grain Size: phi (φ) = -log2d, where d = particle diameter in mm (available in MOD).

- Pelite: % silt and clay = fraction < 63 µm (available in MOD).

- TOM: % Total Organic Matter: mg/kg dried sediment (organic carbon, nitrogen and phosphorus, available in MOD).

- TOC: % Total Organic Carbon: mg/kg dried sediment (not available in MOD).

For an overview of the analytical methods for the various parameters, see Appendix.

With regard to the natural sedimentation rate and biodegradability of organic matter, that are not measured in the offshore monitoring, a literature survey was carried out. In addition, relevant specialists on these topics were contacted.

When investigating the correlation between the various sediment parameters, the model that corresponds with the highest R^2 value is selected as the final model. The R^2 value is the regression coefficient or the fraction of variance explained by the model. Thus it has a maximum value of 1, which would be the case if all points were placed on a straight line, i.e. that the model explained all the variance in the dataset. The various models are investigated in excel, and the outcome may be both a linear and nonlinear relationship between the predictor variable and dependent variable.

3 Results

3.1 Grain size vs. depth

The sediment texture is regarded as one of the most important factors for the structuring of benthic communities, by both direct and indirect mechanisms. Furthermore, the sediment texture has strong influence on the partitioning of contaminants. Thus a measurement of either the pelite content and/or the average grain size in phi or mm is included in most environmental surveys.

A plot of median grain size vs. depth from all stations is given in Figure 1. Both µm and phi is used as the dependent variable in the model. There is a tendency of decreasing grain size with larger depths, but this correlation is not very strong. To improve the correlation, the deep stations (> 500 m) were excluded, see Figure 2. This slightly improves the correlation, but as Figure 2 shows, the grain size varies considerably at depths between 100 m and 200 m. From the R^2 value it is evident that the model will be slightly more reliable when using the grain size in µm compared to phi (φ). Furthermore, the correlation is best described using a non - linear model. For the equation given in Figure 2, the mean error is +/- 100 µm. It is important to be aware of the fact that this equation not applies for locations above 500 m. For such locations it is therefore necessary to carry out a direct measurement of the grain size to obtain a measure of this sediment parameter.

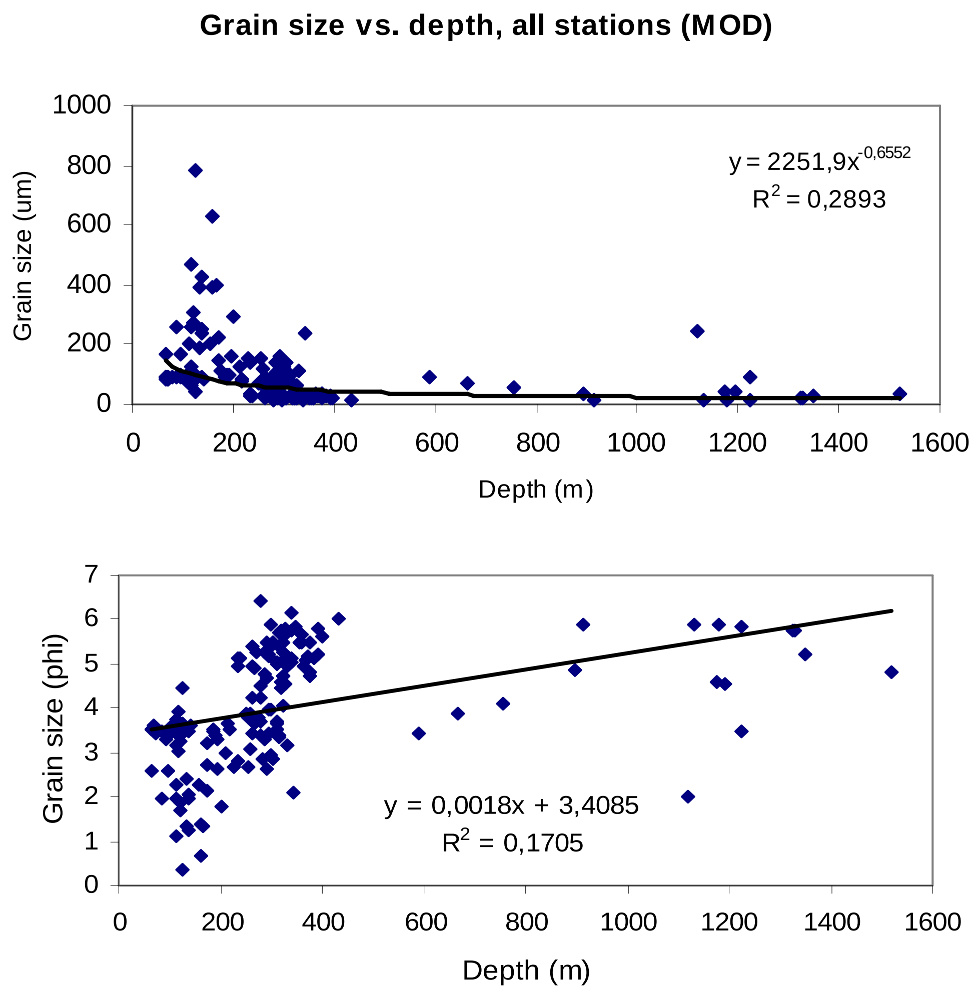
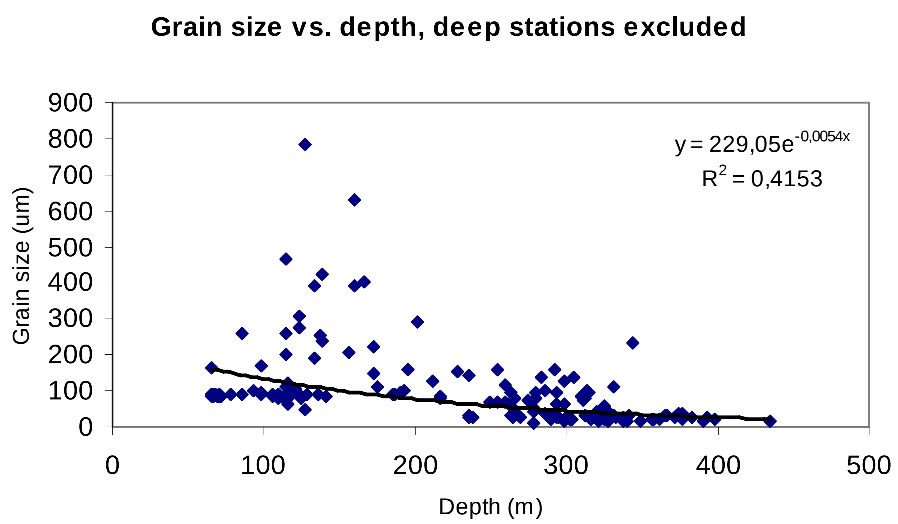


Figure 1. Plot of median grain size vs. depth for all stations (MOD); upper plot for grain size in μm, lower plot for grain size in φ. An equation for the regression model and R^2 value is included.



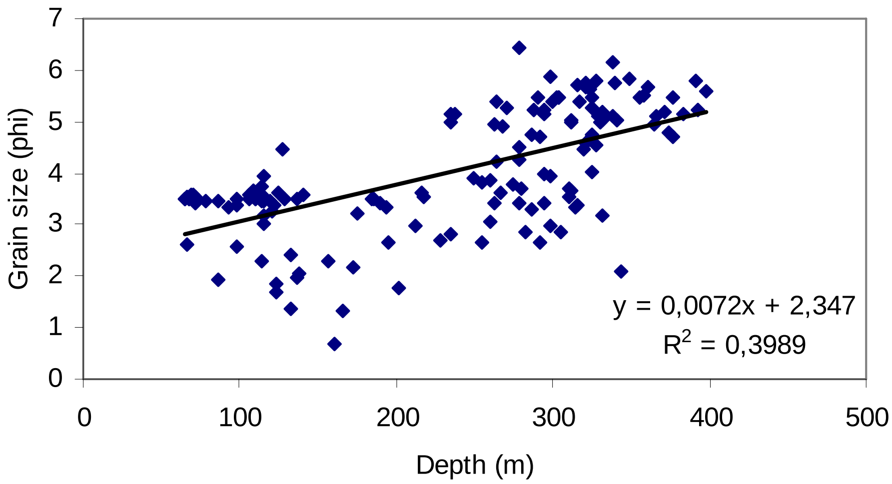


Figure 2. Plot of grain size vs. depth for stations < 500 m (MOD); upper plot for grain size in μm, lower plot for grain size in φ. An equation for the regression model and R^2 value is included.

Pelite vs. depth

A plot of pelite (%) vs. depth is given in
Figure 3. Again it is clear that the deep stations disrupt the regression model. Therefore, a new plot was made for stations < 500 m, see Figure 4. It is now evident that the amount of pelite increases with increasing depth, i.e. that the sediment gets more fine-grained as the depth increases. The final model is given by a nonlinear equation. Again it is important to be aware of the fact that this model only is valid for locations that are shallower than 500 m. As the final fit to data (R^2) for pelite vs. depth is better than for grain size vs. depth, one will obtain a more accurate estimate of the size of the sediment when operating with pelite compared to grain size.

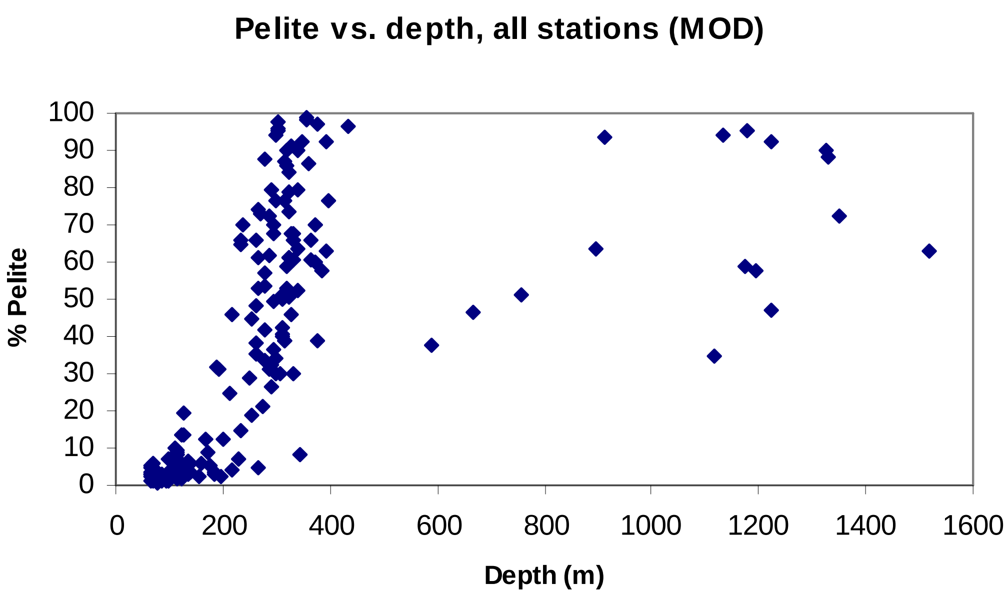


Figure 3. Plot of pelite (%) vs. depth for all stations.

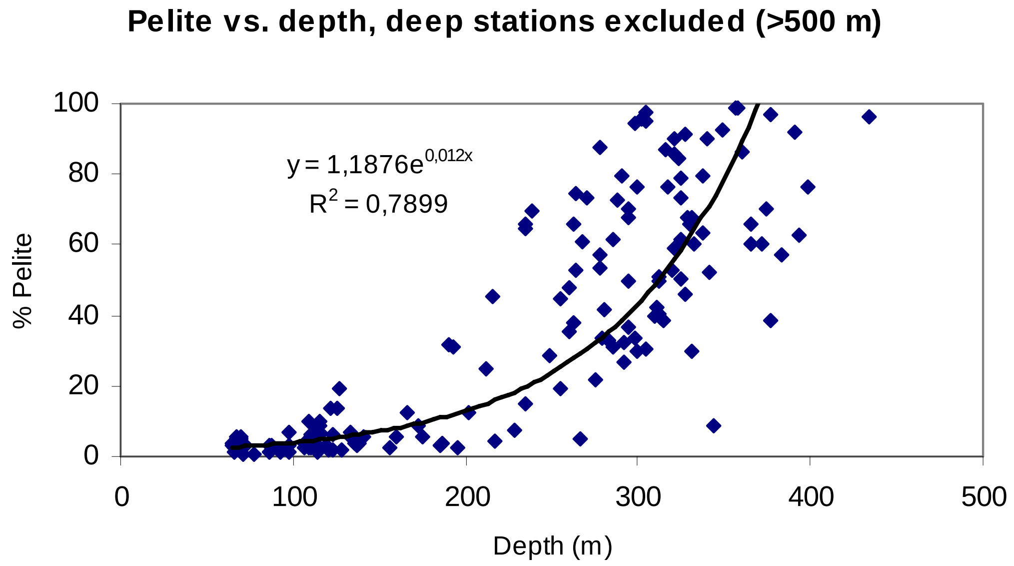


Figure 4. Plot of pelite (%) vs. depth for stations < 500 m. An equation for the regression model and R^2 value is included.

TOM (Total Organic Matter) vs. depth

Total organic matter is another important sediment parameter. Organic matter is a primary source of food for benthic organisms, and is therefore an important structuring factor for the composition of the benthic fauna. Furthermore, the amount of organic matter will influence the partitioning of contaminants in sediments; when the sediments contain a large amount of organic matter a large part of the contaminants will generally be in a particulate form, while sediments containing a small amount of organic matter may have a larger part of the contaminants present in the pore water. The amount of nutrients in the sediment also has a direct role in determining the redox potential in the sediment, which again is a regulating mechanism for the partitioning of contaminants.

Organic matter in the sediments consists of compounds containing carbon, nitrogen and phosphorous compounds. According to the project description the fractional organic carbon (TOC) is a parameter to be used in the model. However, TOM is measured in the offshore surveys and available in MOD, while TOC is only rarely measured in these surveys.

Sources of organic carbon include organic matter from overland runoff and shoreline erosion (mostly marshes), and primary productivity within the bays, all of which eventually settle to the bay bottom and are incorporated into the sediment.

A plot of TOM vs. depth for all reference and regional stations in MOD is given in Figure 5. Here, it appears to be a weak trend with increasing level of TOM with increasing depth. Again, the deep stations disturb the regression and have to be removed from the analysis, see Figure 6. As for the grain size/depth correlation, the highest R^2-value is obtained using a nonlinear model. The mean error of the results shown in Figure 6 is 1.9 TOM units, but as the plot shows the error is larger for deep stations as compared to shallower stations.

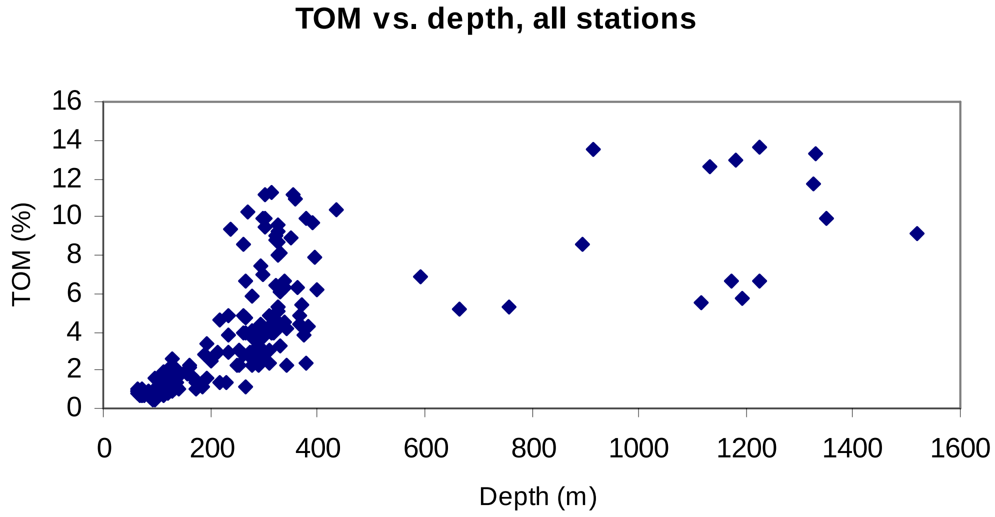


Figure 5. Plot of TOM (% Total Organic Matter) vs. depth for all stations.

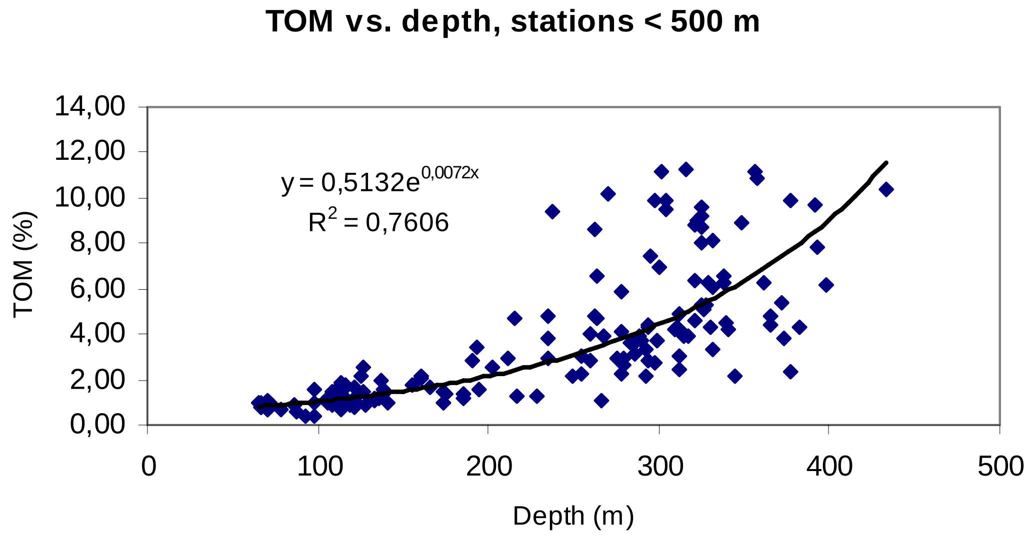


Figure 6. Plot of TOM (% Total Organic Matter) vs. depth for stations < 500 m. An equation for the regression model and R^2 value is included.

TOM (Total Organic Matter) vs. pelite

A plot of TOM vs. pelite for all stations is given in Figure 7, which shows a positive correlation between these parameters. The mean error for the equation is 1.5 TOM units over the whole area, but the error generally increases with increasing pelite content. As the mean error is smaller when estimating TOM from pelite than from grain size (µm), the plot of TOM vs grain size (µm) is not shown. The reason for the correlation between pelite and TOM is that the TOM is adsorbed to sediment particles, and that the surface/volume relationship of the particles increases when the sediments get more fine-grained.

As the R^2-value is slightly higher for the TOM/pelite regression (Figure 7) than the TOM/depth regression (Figure 6), the estimation of TOM will be most accurate when using pelite as the predictor variable. While the TOM/depth regression only is based on stations that are shallower than 500 m, also the deeper stations are included in the TOM/pelite regression. Thus for these deep stations, one needs to measure the pelite content directly instead of predicting this from the depth, but then TOM may modelled from the pelite value.

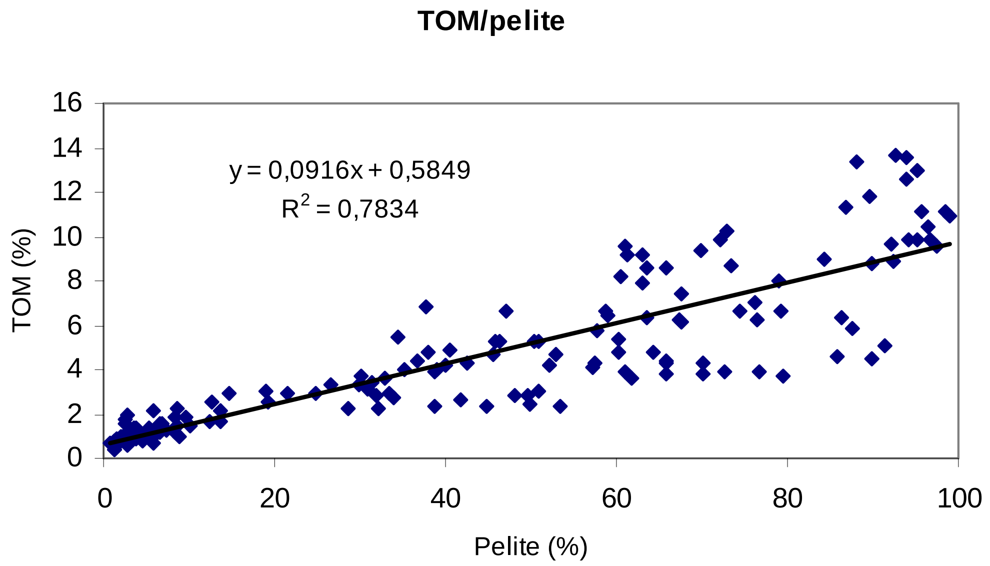


Figure 7. Plot of TOM (% Total Organic Matter) vs. pelite (%) for all stations.

In addition to the data available in MOD, there also exist some measurements of TOM and pelite from the Faroe Islands (Mannvik et al, 2002), which are plotted in Figure 8. The resulting equation is very similar to the equation based on the MOD-stations, although the intercept of the equation is slightly larger for the Faroe Island stations.

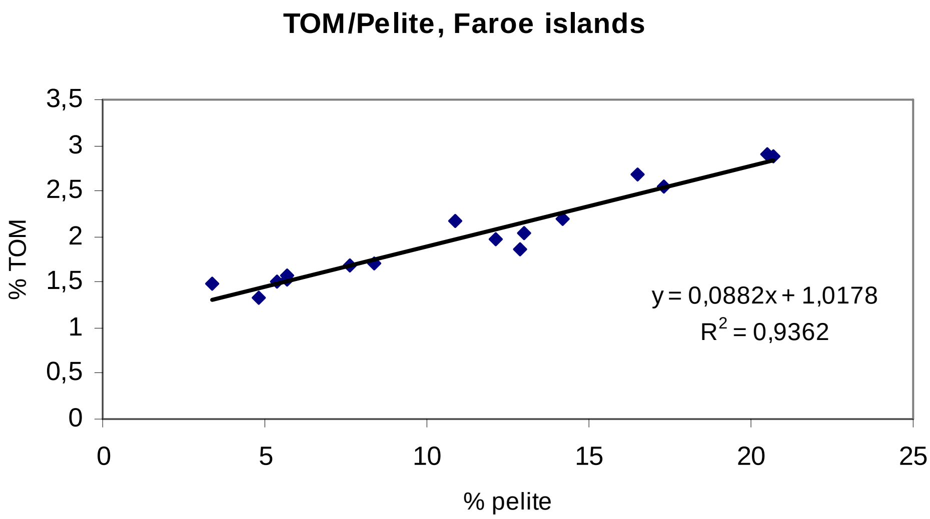


Figure 8. Plot of TOM (% Total Organic Matter) vs. pelite (%) for stations from the Faroe Islands.

Concentration of organic matter downwards in the sediment

In addition to investigating how the content of organic matter at the sediment surface changes with water depth, it was desirable to get knowledge on how this fraction changes downwards in the sediment. Unfortunately, the amount of organic matter is only measured in the upper sediment layer (0-1 cm) in the offshore monitoring, and thus the MOD data base cannot be used to provide this information.

Some information on how the amount organic matter varies with varying sediment depths, is available in de Haas et al. (1997). However, they measured TOC (total organic carbon) rather than TOM, which means that the values given here cannot be compared with the TOM values available in MOD. The stations investigated by de Haas et al. (1997) in the North Sea are shown in Figure 9. In the upper cm of the sediment the organic carbon ranged from 0.02% to 2.6%, see

Table ***1***. A glance at

Table ***1*** indicates that there does not appear to be a trend in the TOC content downwards in the sediment. To investigate this more thoroughly the relative amount of TOC was compared to the upper (0-1 cm) layer, see Figure 10. From this we can conclude that there is no trend with decreasing or increasing TOC downwards in the sediment in the present dataset.

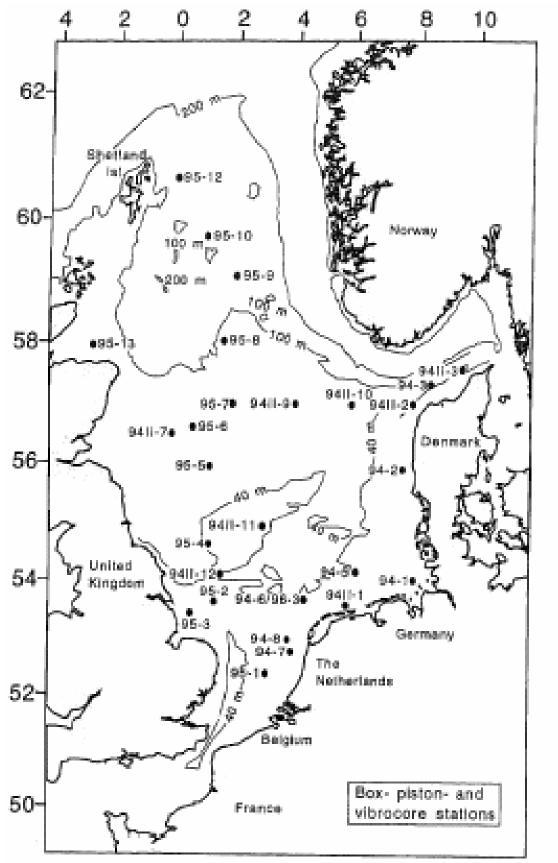


Figure 9. Location map of the stations investigated by de Haas et al, 1997 (figure copied from de Haas et al., 1997).

Table 1. Organic carbon measured at different sediment depths (data from de Haas et al, 1997). The station depth is also given.

Station name	94-1	94-2	94-4	94-5	94-6	94-7	94-8	94II-1	94II-2	94II-3	94II-4	94II-5	94II-6	95-11	95-13
Station depth	20,9	27,7	293	40,5	39,8	21,5	26,6	22	32	31,1	298,5	179,2	306,5	285,7	91
0-1 cm	1,88	0,21	2,6	0,11	0,38	0,02	0,03	0,04	0,02	0,48	1,41	1,64	2,02	0,36	0,78
4-5 cm	0,44	0,2	2,57	0,17	0,42	0,03	0,04	0,02	0,01	0,4	2,14	1,61	1,85	0,35	0,78
9-10 cm	0,32	0,24	2,24	0,16	0,59	0,02	0,04	0,01	0,01	0,5	1,71	1,71	1,72	0,3	0,75
14-15 cm	1,7	0,23	1,96	0,19	0,42	0,03	0,04	0,03	0,01	-	1,86	1,8	1,55	0,25	0,75
19-20 cm	0,6	0,29	3,04	0,23	0,5	-	-	-	0,01	-	2,04	1,89	1,54	0,25	0,74
24-25 cm	1,23	-	2,83	-	0,49	-	-	-	-	-	1,34	1,83	1,31	0,3	0,73
29-30 cm	-	-	2,82	-	0,5	-	-	-	-	-	2,08	1,84	1,53	-	0,69
34-35 cm	-	-	2,81	-	-	-	-	-	-	-	-	1,66	-	-	-

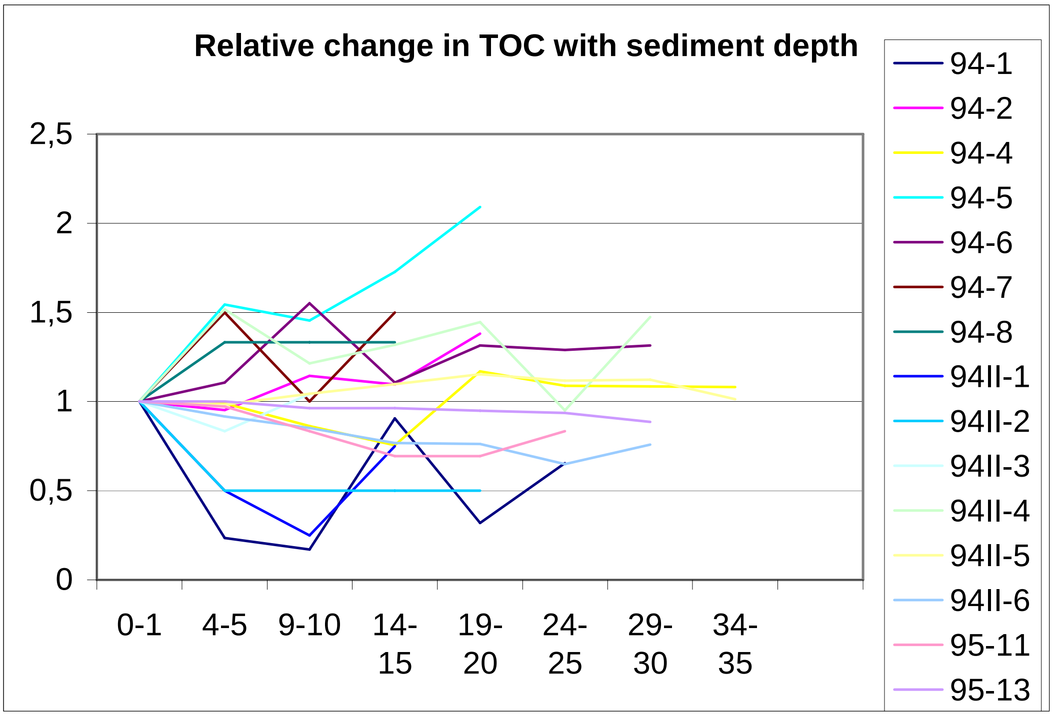


Figure 10. The relative amount of TOC with increasing sediment depth compared to TOC in the upper (0-1 cm) layer (data from de Haas et al, 1997).

Although the amount of organic matter is an important factor for the benthic communities, the concentration of TOM or TOC in the sediment will not necessarily reflect the amount of nutrient that is available. The reason for this is that the amount of biodegradable nutrients that reaches the sediments from the water column above is used very quickly. Generally, when the TOM levels are moderate the TOM content will not show any good correlation with the abundance of benthic fauna (Rygg, pers. comm.). However, extensive supply of organic matter will generally be reflected by a rich fauna, as long as there is sufficient oxygen available. So, in undisturbed sediments, much of the TOM reflects compounds that generally have a low biodegradability. Many of these components have been digested several times, but are inert to degradation in the intestine.

The composition of organic matter in marine sediments is complex. Most of the organic material in strictly marine sediments is derived primarily from marine phytoplankton and sediment microbiota (mainly bacteria and fungi) (Pocklington, 1977), and consists primarily of complex aliphatic assemblages (Jednacak-Biscan and Juracic, 1987). Sediments of enclosed seas, such as the North Sea, may also contain substantial contributions of organic matter from terrestrial sources, mainly plants. The sediment organic matter from terrestrial sources contains lignins, phenols, phenolic acids, cellulose, and xylose (Jednacak-Biscan and Juracic, 1987). The most abundant organic materials in sediments are the humic substances. There are four classes of humic substances, based on molecular weight and solubility behavior (Jonasson, 1977; Aiken et al., 1985):

1. Humins are high molecular weight polymers that are insoluble in water at any pH;
2. Humic acids are extremely complex medium molecular weight organics that are not water-soluble at a pH of 2 or lower, but are soluble at higher pH.
3. Fulvic acids have molecular weights of about 700 to 1000 and are less condensed precursors of humic acids. They are completely soluble at all pHs.
4. Yellow organic acids are low molecular weight soluble acids, probably representing, in part, the final stages of microbial degradation of humic substances in sediments.

The biodegradability of organic matter also varies with the sediment character. Since the level of particle-bound organic carbon generally is higher in fine relative to course sediments, it is likely that the overall TOC value strongly will be influenced by the sediment type. Thus, if silty sediments in a particular area show a high TOC value, this does not necessarily reflect food availability and, as such, cannot meaningfully be used in interpretation of faunal trends.

Similarly, organic carbon levels also are related to sediment particle surface area and pore size, the hypothesis being that organic matter can become protected by its location inside pores too small to allow functioning of the hydrolytic enzymes necessary for organic matter decay (Mayer, 1994a, b). This might go some way towards explaining the marked spatial heterogeneity which often is apparent in TOC content between locations. In many ways, therefore, simple consideration of TOC levels in a given sediment can be extremely misleading. The unreliability of TOC in faunal interpretation is supported by Schaff et al. (1992), who found that trends in macrofaunal abundance did not follow those of sediment TOC, but agreed well with estimates of sediment flux.

The conclusion is that the content of organic matter in sediments, both when it comes to TOM and TOC, is not considered to provide reliable information on the amount of available nutrients or oxygen consumption of the sediments. This is an unexplored research area, which may be looked into if the accuracy of the EIF sediment model in the end should be dependent on knowledge about the amount of degradable organic matter in the sediment.

Natural deposition rate as a function of water depth and grain size

Another important baseline parameter of undisturbed sediments is the natural deposition rate. Knowledge on this is particularly important for the modelling of the extent and effect of burial by drill cuttings. In offshore areas the sedimentation rate is assumed to mainly be a function of depth, and one of the tasks of the present study was therefore to develop a model of the sedimentation rate as a function of depth.

An illustration the sedimentation rate as a function of depth from a large data set obtained from sediments around the world. Figure 11, which is copied from Boudreau (1997), Here it is clear that the sedimentation rate decreases with increasing depth. The fit to the data (R^2) is relatively poor, indicating that the equation is very inaccurate. Furthermore, most of the depths in the figure are too large to be relevant with regard to drilling activities. In order to use these data one should therefore derive an equation only for the data originating from less than 1500-2000 m, but it is important to keep in mind that this equation will not give a very accurate measure of sedimentation rate.

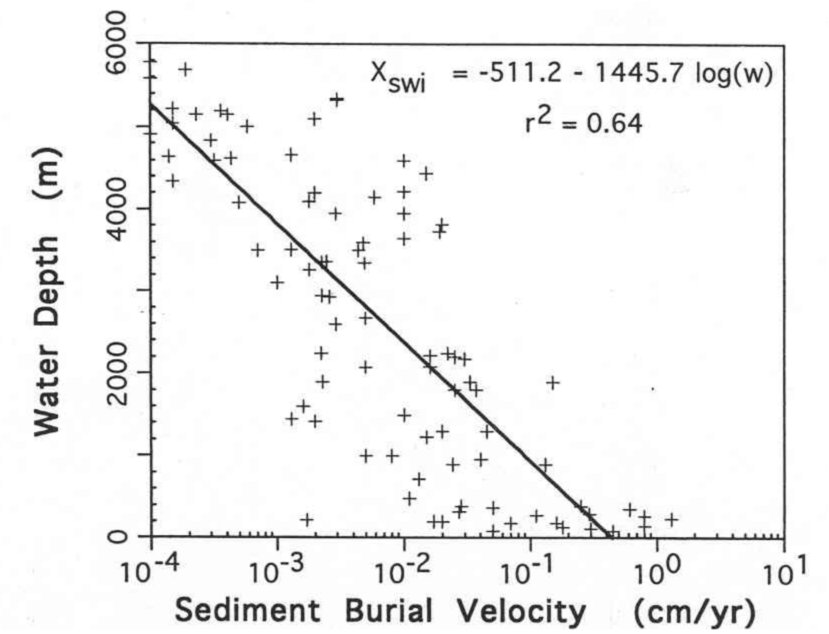


Figure 11. Plot of oceanic water depth (m) versus the burial velocity (log-scale), w, in cm yr^{-1} (from Boudreau, 1997).

In addition to depth, the sedimentation rate will also vary with factors as topography, distance from land and the prevailing current regimes. Thus a more reliable model of sedimentation rate as a function of depth should therefore be developed separately for different areas. Because of a lack of data on the sedimentation rate, a summary of relevant information on this theme is presented, together with the sparse data that was available.

Several studies on sedimentation rate have been conducted in the Skagerrak and Norwegian Channel. However, as there is not any petroleum activity here, these areas are not considered relevant with regard to the present study.

In the North Sea, sediments enter with the inflowing water from the Norwegian Sea, through The Channel, and from the Baltic Sea, in addition to river supplied sediments (Haas et al., 1997). Sea floor erosion, primary production and atmospheric input contribute an unknown amount to the sediment load of the North Sea (Haas et al., 1997). Because of the anti-clockwise residual circulation, sedimentation mainly occurs along the eastern margin of the North Sea (the Wadden Sea, the German bight, the Skagerrak, Kattegat and the Norwegian Channel) (de Haas et al., 1997).

Large storms can cause substantial bed transport to a water depth of more than 200 m, which may cause accumulation of sediments that largely exceeds the natural sedimentation rate. Thus for most locations in the North Sea, which is a shallow sea having a mean depth of 94 m, the accumulation caused by storms will clearly disrupt any model of sedimentation rate as a function of depth. Bioturbation of the benthic fauna and human activities like trawling will also influence sedimentation processes, and fluxes of sediment due to these processes may exceed the natural net sedimentation rates considerably (de Haas et al, 1997).

In the central North Sea, a sparse amount of data is available. de Haas et al. (1997) measured the sedimentation rate at several stations in that area, at depths ranging from 21 to 176 m. For a map of the stations, see Figure 9. A plot of the results is presented in Figure 12, where it is evident that the correlation between depth and sedimentation rate is not very strong. At most stations the results showed no net sedimentation or insignificant sedimentation, while at the other stations the rate ranged from 0.5 to 2 mm/year. Significant net deposition of sediment is restricted to areas in the southern North Sea, while erosion and redeposition and very local sedimentation occurs in the northern North Sea (de Haas et al, 1997).

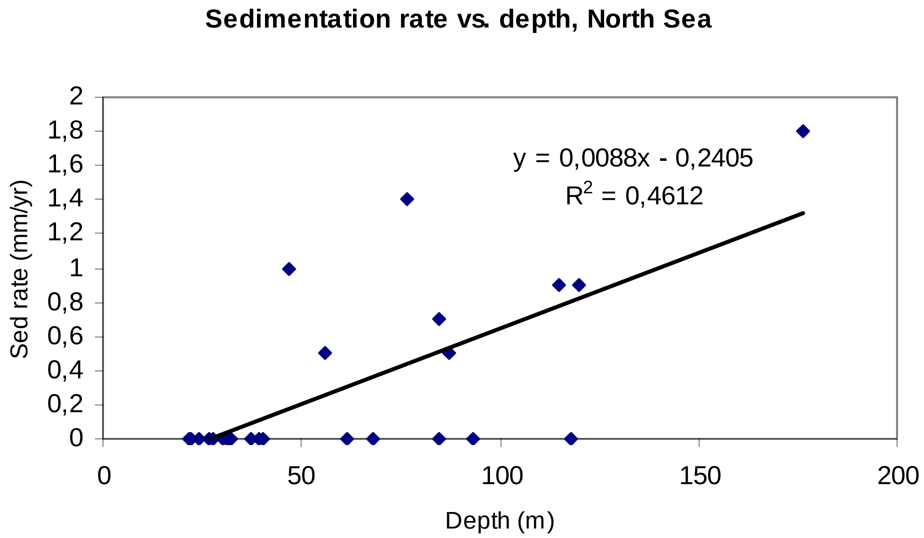


Figure 12. Plot of sedimentation rate vs. depth in the North Sea, from de Haas et al. (1997) (depth data supplied directly from de Haas)

In an environmental baseline study of the Faroese offshore oil exploration in the Faroe-Shetland channel, sedimentation rate was investigated at four stations (Mannvik et al., 2002). The depth of the stations ranged from 970 m to 1148 m. The analysis of the sedimentation rate suggested that the entire area appeared to be non-depositional.

For the Norwegian Sea it was not possible to find data on sedimentation rate. However, some geological studies have been carried out in the Vøring area. This area is characterized by strong bottom currents, causing winnowing or non-deposition down to approximately 1000 m water depth (Dahlgren and Vorren, 2003).

The following information on the Barents Sea is from Wassmann & Elverhøi (1994). The sediments in the central and northern parts of the Barents Sea change character at approximately 200 m depth. This depth corresponds with the boundary between Arctic water and the Atlantic water below. At locations shallower than 200 m, the sediments are mainly composed of sand and gravel, and at deeper locations the sediments are mainly composed of clay. In the western areas that are permanent ice-free, the supply of new sediments mainly arises from erosion of more shallow sediments. In the central northern parts of the Barents

Sea particles that have been incorporated in the ice are the most important source of sediment accumulation. On Svalbardbanken the bottom currents are strong, and the sediments are dominated by shell sand and gravel. The sediments in the slope south of Svalbardbanken and south of Hopen have no accumulation of sediments, and the sediments are composed of depositions from the last glacial period. Generally, in open parts of the Barents Sea the sedimentation rate varies from 0.3 - 2 mm/year (pers. com. J. Carroll).

In conclusion, a trend exists between sedimentation rate and depth, but there is a lack of data to make a meaningful statistical relationship for the region of interest. Regarding most locations in the North Sea, a model that aims at predicting sedimentation rate as a function of depth may be disrupted by the sediment mixing caused by large storms and frequent trawling.

4 Conclusions

This study leads to the following conclusions:

- Grain size, % pelite and TOM may be calculated as a function of depth for moderate depths (< 500 m).
- It is slightly more accurate to calculate TOM from pelite, rather than from grain size or depth.
- No systematic trend in TOC levels downwards in the sediment is evident.
- TOM or TOC are not considered good candidates for a modelling of oxygen consumption of the sediments.
- A weak trend exists between sedimentation rate and depth, but there is a lack of data to make a meaningful statistical relationship for the region of interest.

In the deriving of baseline sediment parameters that should be supplied when a new field will be subject to oil or gas production, there will be three levels of accuracy:

LEVEL 1: Direct measurement of the various parameters.

LEVEL 2: If measured values of pelite are available, TOM may be estimated by the following equation:

$$\text{TOM (\%)} = 0.0916 \times [\text{pelite\%}] + 0.6$$

LEVEL 3: If no measured data are available but depth, TOM and grain size (µm)/pelite (%) may be estimated from depth according to the following equations:

$$\text{Grain size } (\mu m) = 229e^{-0.0054(m)} \qquad \text{(depth < 500 m)}$$

$$\text{Pelite (\%)} = 1.19e^{0.012(m)} \qquad \text{(depth < 500 m)}$$

$$\text{TOM (\%)} = 0.51e^{0.0072(m)} \qquad \text{(depth < 500 m)}$$

As the expressions are based on data from MOD, which encompasses the areas that presently are subject to oil- and gas exploitation, the relationships given above should preferably be validated and verified for new areas.

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JoLynn Carroll, Akvaplan-niva.
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Brage Rygg, NIVA.

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6 APPENDIX

The described methods are based on the methodology used by Geogruppen AS (grain size and TOC) and Unilab Analyse AS (TOM).

6.1 Grain size distribution analyses

The samples are initially split into coarse (> 0.063 mm) and fine (< 0.063 mm) fractions by means of wet sieving. The fine fraction passing through the 0.063 mm screen is dried and weighed. The coarse fraction thus separated is analysed further by dry sieving.
The coarse fraction is oven-dried at 40°C for about 48 hours. The dried sample is weighed and shaken for 15 minutes through a nest of graded sieves at intervals of 2 mm, 1 mm, 0.5 mm, 0.250 mm, 0.125 mm and 0.063 mm. The material on each screen is weighted to the nearest 0.01 g and the weight of each grain size fraction is expressed as a percentage of the total sample weight.

The Udden-Wentworth scale (see Krumbein, 1934) is one of the most frequently used classification systems for grain size analyses and forms the basis of sediment characterisations used here to describe variations in grain size composition across the field. The weight of sediment particles in all grain size fractions is used to calculate cumulative distribution curves and histograms for each sample. These curves are used to calculate summary statistical parameters describing basic sediment characteristics (see Folk and Ward, 1957). The parameters used and the basis for their calculations are presented as follows, where $Ø = -\log_2 d$ (i.e. grain size (d) in mm) and Ø50 represents the Ø value at the 50% percentile and Ø16 its value at the 16% percentile value etc:

Median particle size $Md_Ø$:

$$Md_Ø = Ø50$$

measures the central tendency of the size frequency distribution. The median divides the frequency curve into two equal parts and corresponds to the 50% mark on the cumulative curve.

The range of values and implications for the statistical parameters are presented in A1.

Table A1: The range of values and implications for grain-size distribution parameters (after Folk and Ward, 1957 adapted from Wentworth, 1922)

PARAMETERS	**Range of values**				**Implication**	
	from	**to**	**from**	**to**		
	φ-value		mm		Classification	
Mean particle size (Md□)		-6		62.5	Cobble	
	-6	-2	62.5	4.00	Pebble	Gravel
	-2	-1	4.00	2.00	Granule	
	-1	+1	2.00	0.50	Coarse sand	
	+1	+2	0.50	0.25	Medium sand	Sand
	+2	+4	0.25	0.063	Fine sand	
	+4	+8	0.063	0.0039	Silt	Pelite
	+8		0.0039		Clay	

6.2 Analysis of Total Organic Matter (TOM)

Approximately 20 g of wet sediment is weighed into pre-weighed porcelain dishes. The sediment is oven dried at 105°C to constant weight and thereafter heated at 480°C for 16 hours. The percent weight loss after combustion of the oven dried material is then calculated as described in NS 4764.

6.3 Analysis of Total Organic Carbon (TOC)

The samples are first dried in a drying chamber at 60 °C. Approx. 0.22 g is weighted into porous crucible. The TOC-analysis is done on a Leco IR 212 carbon analyser. The instrument is calculating the carbon content by measuring the CO_2 in the gas that is formed by a burning process.