Geostatistical Mapping and Spatial Variability of Surficial Sediment Types on the Beaufort Sea Shelf Based on Grain Size Data

K. Jerosch[1], V.E. Kostylev[2], S.E. Blasco[2]

[1] Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, (kerstin.jerosch@awi.de +49-471-4831 1518)
[2]Bedford Institute for Oceanography, Natural Resources Canada (Atlantic), Geological Survey of Canada

Figure 1 Location map of the Canadian Beaufort Shelf showing the distribution and fill material of artificial islands (textural dots).

Year of Sampling	Reference	Number of Samples
1969-2008	Expedition Database (ED), 2010.	1114
1976	EBA Engineering Consultants and LTD Beaufort-Delta Oil Project limited, 1976.	42
1976	samples located using offsets from transponder; locations found in a field notebook provided by Dr. H. Kerfoot.	22
1987	Kauppaymuthoo, V., 1997.	13
1970	Dewis, F.J., 1971.	49
1969-2008		**1240**

Table 1 Sediment grain size data (1969-2008) used for geostatistical interpolation.

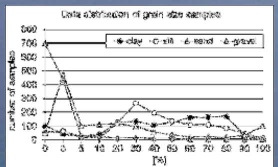


Figure 2 Data distribution of the clay, silt, sand and gravel components of grain size samples, classified after Wentworth (1922), plotted against the total number of samples (1240) used in this study.

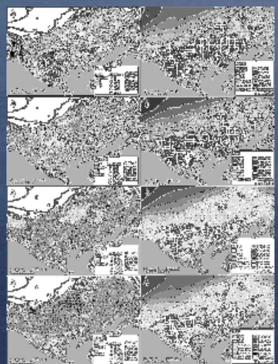


Figure 3 Grain size maps classified according to Wentworth (1922) and predicted standard errors.Cokriging was used for clay, silt and sand; ordinary kriging for gravel.

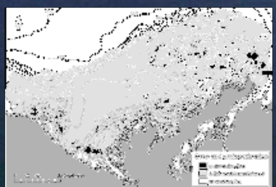


Figure 4 Areas of over- (white) and underestimation (black) as the result of adding together the silt, clay, sand and gravel grids. Gray areas meet the standard of a 95% confidence interval.

ABSTRACT

A new sediment texture map, based on the grain size maps, is provided according to commonly used grain size and sediment type classification systems. We describe an approach for a quality controlled mapping of grain sizes and sediment types for the Beaufort Shelf in the Canadian Arctic. The approach is based on grain size data collected during 1969-2008. A replenishment of grain size data since the 1980's, as well as the consideration of correlating parameters (bathymetry, slope and sediment input) to a cokriging algorithm, amends the former way of mapping the surficial sediments of the Beaufort Shelf. The cokriging analysis showed that the simulation of a sediment input by the Mackenzie River, modeled as a cost-distance function, was the key variable in reducing the errors of the output estimate. The predicted mean standard errors showed that in this study cokriging was the superior interpolation method for clay, silt and sand while ordinary kriging was more suitable for gravel.

INTRODUCTION - Beaufort Sea Sediments

The nearshore Beaufort Shelf (Figure 1) is a sensitive marine environment that is the focus of oil and gas exploration. Offshore, the Beaufort Sea contains large potential reserves of hydrocarbons. Any future exploitation of these resources will present unique engineering challenges and will require an understanding of the processes that govern sediment behavior. Knowledge of the surficial sediment distribution is, therefore, necessary to understand sediment stability, sediment transport and nearshore morphology. Sediment distribution is also needed balance engineering challenges with environmental concerns, resource development and precautionary sustainable management. We describe an approach for a quality controlled mapping of grain sizes and sediment types for the Beaufort Shelf in the Canadian Arctic. The approach is based on grain size data sampled during the period 1969-2008 (Figure 2 and Table 1). A replenishment of grain size data since the 1980's, as well as the consideration of correlating parameters (bathymetry, slope and sediment input) to a cokriging algorithm, amends the former way of mapping the surficial sediments of the Beaufort Sea Shelf.

METHODS - Kriging and Standardization

Subsequent to data exploration, processing and analyzing autocorrelation, four single grids (clay, silt, sand and gravel) were generated from grain size data by ordinary kriging and cokriging Figure 3). Cokriging also considered parameters that influence sediment texture such as bathymetry, slope, cost distance from the Mackenzie River and data anisotropy (directional dependency). The cokriging algorithm expressed as variograms was quality controlled by cross-validation. For a detailed description please refer to Pesch et al., 2008). By subtracting each measured value from its estimated value an estimation or cross-validation error can be calculated resulting in an error estimation for the whole dataset:

- mean standardized error (MSE) – the standardized average value of the cross-validation errors which at best should be 0
- root mean square standardized error (RMSSE) – ratio of mean squared cross-validation errors and the kriging variances which at best should equal 1
- correlation coefficient after Spearman (C_S) – in case of an ideal correlation the C_S-value should equal 1, if no such correlation exists Cs tends towards 0
- predicted standard errors (PSEs) express a maximum deviation of modeled from the real values and therefore help to estimate the quality in these regions regarding the interpolation results for each grain size range.

PSEs were used to define the extent of a reliable interpolation area.

Due to the kriging algorithm over- or an underestimation for the predicted values can appear. Therefore, each grain size grid was standardized using a "100%-grid" (cell values = 100) as follows: grain size $\text{grid}_{\text{standardized}}$ = grain size grid / over-underestimation grid x 100%-grid (Figure 4).

The mono-parametric grids of sand, silt and clay were reclassified into four percentage classes: 0-25%, 25-50%, 50-75% and 75-100% and the gravel grid reclassified into two classes: 0-10%, 10-50% (no values higher than 50% occurred in the dataset).

RESULTS & CONCLUSIONS - Comparing ordinary kriging and cokriging

A new sediment texture map of the Beaufort Shelf was developed applying quality controlled ordinary and cokriging. Each cell shown in the map in Figure 5 contains the percentage of *clay*, *silt* and *sand* according to Wentworth (1922) and was applied to Shephard's (1954) classification system. The grains size *gravel* consists of a separate GIS layer and is overlaid as a grey hatched polygon.

Cokriging provided superior interpolation results for silt, clay and sand compared to ordinary kriging by using secondary variables (bathymetry, slope and sediment input of the Mackenzie River). Cokriging delivered improved statistical mean values for clay and sand as given in Table 2. Ordinary kriging achieved better prediction probabilities for gravel and was, therefore, used for generation of the final distribution. Cokriging was able to capture most of the small variations in the sediment type distribution. Further, a reduced nugget-effects confirmed that the cost distance grid was a better indicator for sediment types when compared to bathymetry and slope.

Two main issues concerning the grain size datasets used in this study are obvious: the variability of the sampling method (grab samples and topmost layer of piston cores) and the variability in the resolution of information. Especially in the shallow areas, as in the Mackenzie Bay, the sampling is not very dense. Local events could have been missed. Nevertheless, the procedure of cokriging and ordinary kriging greatly enhanced interpolation estimates without additional sampling. Especially in nearshore regions, like the Beaufort Shelf, these geostatistical interpolation techniques are needed because sampling is often difficult or impossible due to ice conditions or even prohibited near oil platforms.

The described methodology along with the inclusion of recent data, provided an improved mapping of the surficial sediments of the Beaufort Sea Shelf.

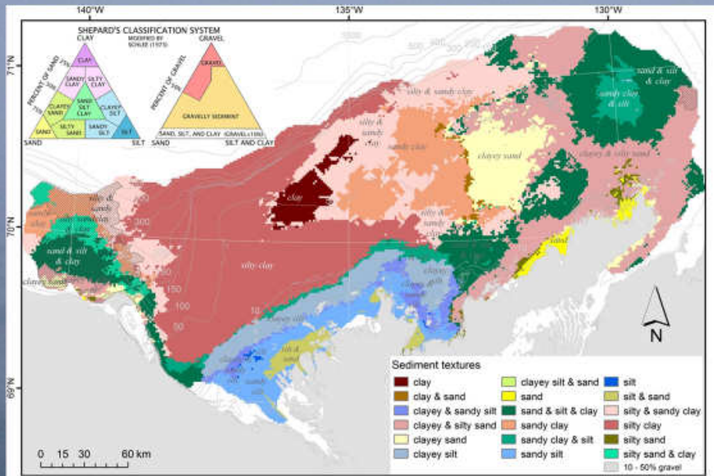


Figure 5 Sediment type map of the Beaufort Shelf. Colors generally are chosen as follows: silt in blue, clay in red, sand in yellow and mixed sediments in green See Table 3 for the grain size percentage composition for each sediment type.

QUALITY ASSESSMENT - I

To assess the quality of the surface estimations key parameters were calculated from the results of cross-validation. The MSE, RMSSE, C_s as well as the nugget-sill ratio values are listed in Table 2. MSE shows that the average cross-validation errors equal almost zero in all cases. RMSSE equals almost 1 for all parameters indicating that variances calculated from the cross-validation errors by average equal the theoretical kriging variances. In all other cases, except sand, the C_s lies above 0.8 indicating high degrees of associations between the measured and estimated values. With the exception of sand and the cokriging result for gravel, the nugget–sill ratios lie below 0.5 which is indicative for low small-scale variances and strong autocorrelations of the measurement values. For all grain sizes beside gravel, the MSE and the RMSSE can be observed to be improved by applying cokriging.

	MSE		RMSSE		C_s		N-S ratio	
	OK	CK	OK	CK	OK	CK	OK	CK
gravel	0,00	-0,01	0,99	0,96	0.88	0.74	0.13	0.25
sand	-0,16	-0,01	1,05	1,02	0.67	0.78	0.59	0.52
silt	0,02	0,01	0,94	0,99	0.87	0.93	0.24	0.09
clay	0,02	0,02	0,97	1,01	0.93	0.97	0.20	0.12

Table 2 A comparison of ordinary kriging (OK) and cokriging (CK). Mean standardized errors (MSE), ratio of mean squared cross-validation errors and kriging variances (RMSSE), correlation coefficient after Spearman (C_S) and nugget–sill ratios (N-S ratio).

Sediment type	Clay [%]	Silt [%]	Sand [%]	Area [km2]
clay	75-100	0-25	0-25	1246.34
silty clay	50-75	25-50	0-25	15257.75
sandy clay	50-75	0-25	25-50	5377.55
silty and sandy clay	50-75	0-25	0-25	8575.41
clay and sand	50-75	0-25	50-75	203.64
sand	0-25	0-25	75-100	1012.53
clayey sand	25-50	0-25	50-75	4133.09
silty sand	0-25	25-50	50-75	548.69
clayey and silty sand	0-25	0-25	50-75	9859.46
silt and sand	0-25	50-75	50-75	1157.72
silt	0-25	75-100	0-25	54.68
sandy silt	0-25	50-75	25-50	3708.85
clayey silt	25-50	50-75	0-25	2815.10
clayey and sandy silt	0-25	50-75	0-25	1114.35
sandy clay and silt	25-50	25-50	0-25	1800.69
silty sand and clay	25-50	0-25	25-50	940.88
clayey silt and sand	0-25	25-50	25-50	3.77
sand and silt and clay	25-50	25-50	25-50	9374.88

Table 3 Areas of sediment types (km²) and their grain size composition in percentages as they are presented in the sediment type map of the Beaufort Shelf in Figure 8. The largest contiguous area is covered by silty clay which is 22.7 % of the total area (67,185.38 km²).

ACKNOWLEDGEMENTS

We thank the Natural Sciences and Engineering Research Council Canada (NSERC) for granting a Visiting Fellowship in Canadian Government Laboratories as a part of the International Polar Year (IPY). We also appreciate Natural Resources Canada (NRCan) for providing the sediment grain size data (Expedition Database NRCan). Thanks to my colleague K.A. Jenner at the Geological Survey of Canada, Atlantic for fruitful discussions. We would like to send special thanks and thoughts to S.M. Solomon who tragically passed away during this study.

QUALITY ASSESSMENT - II

The charts in Figure 5 show the frequency of samples falling into the 10-percent-intervals of each grain size and their corresponding averaged errors of the predictions. The errors bars describe the deviation from the measured and the predicted values resulting from the cross-validation for each interval. They provide the sediment texture map with a comprehensible quality assessment showing, for instance, that best predictions were achieved for low sand and gravel contents (0-50%) and intermediate silt and clay values (30-80%). In contrast, there are considerable deviations in predicting high percentage values (> 80%) for all grain sizes.

COMPARISON WITH EXISTING MAPS

Both Pelletier's (1984) study and this study have used almost the same data base for the time period 1969-1983. This study also includes recent data (1969-2008) which extends the data set, particularly in shallow areas close to the coast. To enable a direct comparison of the single grain size maps, the intervals for the grain size maps were classified according to those of Pelletier (1984) (Figure 7). The grain size maps show similar patterns, however, regional differences can be recognized from the map pairs. Pelletier (1984) highlights single measurements with considerable gradients by drawing circles around them, while kriging algorithms tend to smooth measured gradients. The variogram values for gravel are suboptimal. This is caused by the relatively sparse occurrence of gravel in the data set as well as a reduced correlation of gravel to the cokriging parameters. Pelletier's (1984) method might, therefore, present superior results for gravel. When comparing the silt and clay map pairs, the variogram analyses were more reliable and this corroborates the methodology of this study (Figure 2).

OUTLOOK

Sediment type distribution is closely linked with the discipline of benthic habitat mapping but also with geochemical properties of the sediments since increased methane contents e.g. are correlated with muddy sediments. Since textural or morphological classes are relevant to seabed ecology, the new sediment type map could be used for benthic ecosystem mapping and for predictive occurrence of gassy sediments in the Beaufort Sea. Additionally, the interpolated grain size distribution maps can be used to supplement our understanding of sediment deposition on the Beaufort Shelf.

REFERENCES

Jerosch, K. (in press): Geostatistical mapping and spatial variability of surficial sediment types on the Beaufort Shelf based on grain size data. Journal of Marine Systems.

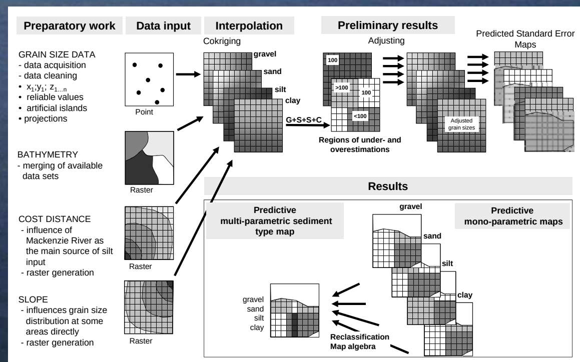
Pelletier, B.R., 1984. Marine science atlas of the Beaufort Sea sediments, Geological Survey of Canada, Miscellaneous Report 38.

Pesch, R., Pehlke, H., Jerosch, K., Schröder, W., Schlüter, M., 2008. Using Decision Trees to Predict Benthic Communities within and near the German Exclusive Economic Zone (EEZ) of the North Sea. Environmental Monitoring and Assessment, 136, 313–325.

Shephard, F.P., 1954. Nomenclature Based on Sand-silt-clay Ratios. J. Sediment. Res. 24(3), 15–58.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. Journal of Geology, 30: 377–392.

THE PROCESS OF GENERATING A SEDIMENT TYPE MAP FOR THE BEAUFORT SHELF APPLYING COKRIGING



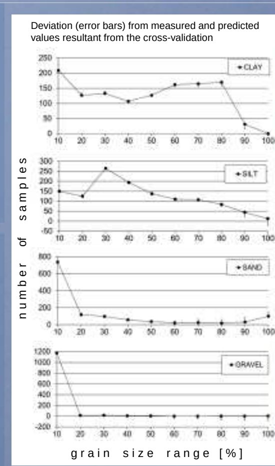


Figure 6 Deviations between measured and predicted values expressed as PSE for each grain size are presented on the left. Cokriging was used for clay, silt and sand; ordinary kriging for gravel.

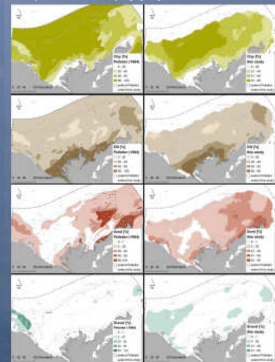


Figure 7 Grain size distributions are given according to Pelletier (1984) on the left side and according to this study on the right side. The dashed lines highlight the border of reliability of the interpolated areas based on the interpolated results. Class ranges are consistent with those of Pelletier (1984) to enable a comparison between the two studies.

Natural Resources Canada
Ressources naturelles Canada

Geological Survey of Canada (Atlantic)

Foundation Alfred Wegener Institute for Polar and Marine Research Helmholtz-Association Germany