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1 Introduction

Spatial data analysis is not a new discipline. Beginning with the initial need to dig in order to find water, coal or petroleum, methods of spatial analysis were developed to minimize the effort to succeed. However, it is only in the last century the a statistical framework appeared, which tried to explain mathematically, what was mainly empirical before this time. Geostatistics was expanding from the specific domain of mining and geological science to reach Environmental sciences, Geography, and more generally, all fields where the notion of spatial correlation had a meaning. The application of geostatistics in Marine Sciences arose due to the dynamic development of advanced technology designed for marine scientific applications and offshore industry within the last 20 years. This has led to a significant increase of geodata derived by chemical, optical, and acoustic sensors.

The recent event in the Gulf of Mexico demonstrates an urgent need to determine the risk to the coastal and marine environment in the event of blowouts and accidental oil spills due to engineering or navigational hazards. The risk exists but the impact is still unidentified. Not enough is known about the framework of the region including the biological and physical relationships and the possible damage to this association by an oil spill.

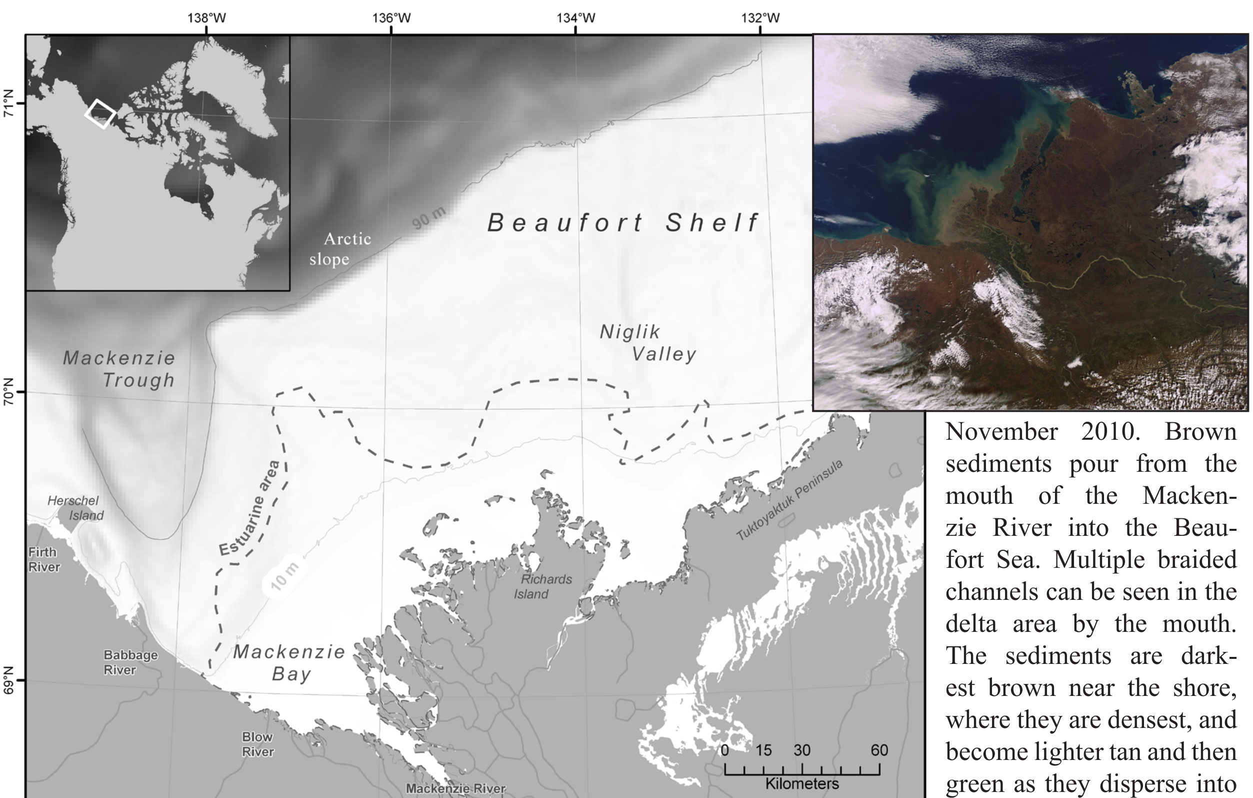
The offshore area beneath the Beaufort Sea contain enormous potential reserves of hydrocarbons, which are extensively petroleum basins explored by oil companies. However, in addition the Beaufort Shelf is also an immense supporter of diverse biology comprised of millions of staging and nesting birds, huge fish-spawning streams as well as larger marine and land animals such as seals, whales and polar bears. Pelletier (1984) published a marine science atlas of the sediments directed towards the combined aim of resource development and environmental protection of the Beaufort Sea. More specifically, sediment types, bathymetry and other environmental influences are strongly correlated with species distribution and diversity in a marine environment.

The goal of this project is to reproduce Pelletier's collection of sediment maps using basically the same data in addition to data sets available at NRCan since 1984. Today, 27 years later, the focus of attention is to apply geostatistical methods and to provide improved versions of grain size maps of the Beaufort Sea. The results are intended for exploration companies, scientific communities, government agencies and the interested Canadian public. Instead of proceeding deterministically using a method such as Inverse Distance Weighted (IDW), one way to statistically model the sea floor geometry is through the use of geostatistical interpolation techniques. The most common one is generally known as kriging. kriging takes the degree of spatial autocorrelation into account when it is predicting measurements. Applying cross-validations geostatistics supply the users with quality assessment information of the maps which is one of its biggest advantages.

The generation of geological models always goes along with the geotechnical engineers' wish to keep the models as accurate as possible. Care must be given to the statistics associated with the geometric parameters of the grain size layers. However, the most commonly used ordinary kriging techniques produce strongly smoothed model results that lead to an inaccurate regionalization of geological layers.

The Open File describes an approach for a quality controlled mapping of grain sizes and sediment textures for the Beaufort Shelf in the Canadian Arctic. The approach is based on grain size data collected during the The *Nahidik* Program (2005-2009) and earlier. 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 considerably.

Furthermore, the approach compares the geostatistical interpolation methods of ordinary kriging and of cokriging and recommends the use of a combination of both. 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.



November 2010. Brown sediments pour from the mouth of the Mackenzie River into the Beaufort Sea. Multiple braided channels can be seen in the delta area by the mouth. The sediments are darkest brown near the shore, where they are densest, and become lighter tan and then green as they disperse into the sea.

Figure 1 Location map: The Canadian Beaufort Shelf and the Mackenzie estuary. Chelys Earth Snapshot | Copyright © 2008-2011 Chelys srl | All Rights Reserved.

A new sediment texture map, based on the grain size maps, is provided according to commonly used grain size and sediment type classification systems.

2 Sediments of the Beaufort Shelf

The nearshore Beaufort Sea is a sensitive marine environment that is also 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 stability, nearshore morphology and sediment properties in the extensive shallow coastal zone of the Beaufort Shelf. Knowledge of the surficial sediment distribution is, therefore, necessary to provide a framework for understanding sediment stability, sediment transport, platform foundation conditions and to balance engineering challenges with environmental concerns, resource development and precautionary sustainable management. Management of offshore resources has always been constrained by a lack of high-quality information on the marine ecosystem. However, additional surficial grain size data coupled with precise positioning using Global Positioning System technology, and the utilization of new and contextual analysis methods provides an innovative method of gaining information over wide areas of the Beaufort seafloor.

The Canadian Beaufort Sea (Figure 1) is an extremely dynamic environment susceptible to reworking by both arctic marine and periglacial processes. Its sediments are subjected to many of the normal processes affecting temperate latitude sediments, such as wave action, tides and storm surges as well as many uniquely arctic processes, such as ice push, thermo-erosion and thaw subsidence. In addition, normal offshore processes may be strongly modified by the uniquely arctic nature of the system; for example, the presence of offshore sea ice limits wave activity and even during the short open-water season, offshore ice affects the fetch window available for wind-wave generation (Harper, 1990).

The erosional nature of the Mackenzie delta front and the drowned morphology indicate that the delta is undergoing transgression, resulting in minimal water depths for sediment accumulation (Hill et al., 2001). However, bar accretion still occurs within large embayments at the mouths of some distributary channels (Jenner and Hill, 1998). In general, the nearshore area (seaward of the Holocene delta) is very shallow. Water depths are less than 2 m at distances in excess of 15 km from the shore. Mean tides are 0.3 m and large tides are up to 0.5 m, whereas winds may raise water levels as much as 2.4 m (Hill et al., 2001) or lower them by up to 1 m (Henry, 1975).

According to Pelletier (1984) fine-grained sediments occupy most of the seabed, particularly in the central part of the southern Beaufort Shelf and seaward of the 10 m isobath (Figure 1). This is the area of clay deposition and indicates relatively low hydrodynamic conditions. Silt is found chiefly from the 10 m isobaths landward into the nearshore, from Mackenzie Bay to Kugmallit Bay in the east. Sand is common along the eastern edge of Mackenzie Trough, in the coastal zone, seaward of the 2 m isobath, and on bars, spits and offshore islands, due to increased sorting action by waves and currents which remove finer sediments. A considerable amount of sand deposition occurs on the eastern portion of the shelf where some erosion by bottom currents exposes older beach deposits (Pelletier, 1984). Gravel is also common in this area, but is found in much higher quantities along bars, beaches and at the base of coastal cliffs undergoing erosion. The offshore sand and gravel deposits west of Herschel Island are due mainly to ice-rafting. Here, sediments are deposited from ice impeded by the winter freeze-up and impinged against western Herschel Island. Isolated occurrences of sand and gravel on the outer shelf, to the east, may also be due to ice-rafting (Pelletier, 1984).

Most of the sediment is deposited from the Mackenzie, Firth, Babbage and Blow Rivers. A sediment plume defining an estuarine zone (Figure 1) extends about 55 to 70 km north of the coastline. The Mackenzie River is the largest river on the North American side of the Arctic with an annual freshwater discharge of 330 km^3 and an annual sediment load of 127 Mt. to the Canadian Beaufort Shelf (Macdonald et al., 1998). Massive quantities of predominantly fine-grained sediment and associated organic carbon are transported into the Arctic Ocean during the freshet from May to September (Forest et al., 2007, Hill et al., 1991, Walker et al., 2008). Under the influence of the Coriolis force, this plume moves easterly, and sediments derived from coastal erosion on the seaward fringes of the estuary and Tuktoyaktuk Peninsula may be entrained in this system. West of Shallow Bay, sediment movement in the nearshore is also controlled by coastal currents (Pelletier, 1984). O'Brien et al. (2006) note that the Mackenzie River is the largest source of sediment to the arctic region; therefore the discharge of the Mackenzie River is the major component for the geostatistical modeling of Beaufort Shelf sediments.

The goals of this study are to use and describe an appropriate interpolation method achieved by comparing ordinary kriging and cokriging, to deliver quality controlled results by predicted standard errors of each sediment class, and to provide a series of new georeferenced grain size maps and sediment texture map of the Beaufort Shelf.

3. Methods

Realistically, it is impossible to get exhaustive values of data at every location because of practical constraints. Thus, interpolation is fundamental to the graphing, analysis and understanding of 2D data. Different possibilities exist to describe the relationships (autocorrelations) of spatial data. They are based on the assumption that the autocorrelation of the data is not dependent on the absolute (geometrical) location of the sites, but on the spatial distribution of the sites relative to each other in distance and direction (Isaaks and Srivastava, 1992). Geostatistical methods like kriging (Krige, 1951; Matheron, 1963) include the degree of spatial autocorrelation and the directional dependency (anisotropy) when predicting measurements. cokriging is based on the kriging algorithm and provides a superior estimation of map values, if a secondary variable as (e.g. currents) is sampled more intensely than the primary variable that is in this case grain size data (Davis, 2002; Goovaerts, 1997). The availability of grain size data is limited and cokriging could improve its interpolation estimates. For more detailed information about kriging and cokriging refer to section 3.2.

The majority of the grain size data used in this study are stored in the Expedition Database (ED) of Natural Resources of Canada (NRCan), Geological Survey of Canada, Atlantic (GSCA) and include data from box cores and the upper parts of piston cores. More than 100 samples were collected during the Nahidik program. A compilation of grain size data sampled during the period 1969-2008 is presented in Table 1.

Table 1 Sediment grain size data - compilation 1969-2008

Data set	Year	Reference	Number of Samples
ED	1969-2008	Expedition Database NRCan	1114
Oil project 1976	1976	EBA Engineering Consultants and LTD Beaufort-Delta Oil Project limited, 1976: Report on Offshore Pipeline Activities 1975-1976. Part 2. Volumes I and II of III	42
Radium express	1976	RadiumExpress76 samples were located using offsets from transponder locations found in a field notebook provided by Dr. H. Kerfoot.	22
GS compile2 NAH87	1987	GScompile2NAH87 1987. Kauppaymuthoo, V. 1997. Etude de la Dynamique Sedimentaire Hivernale du Delta du Mackenzie au Niveau de Kugmallit Bay. M.Sc. Thesis, Universite du Quebec a Rimouski, Canada.	13
Levinson_70	1970	levinson_70 1970 LEVINSON70 samples were located by digitizing sample locations from a map in Dewis (1971). Dewis, F.J. 1971. Relationship Between Mineralogy and Trace Element Chemistry in Sediments from Two Fresh Water Deltas and One Marine Delta within the Mackenzie River Drainage Basin. M. Sc. Thesis, University of Calgary, Alberta.	49
Grain size data	**1969-2008**	**Sum of all data above**	**1240**

Three cokriging parameter maps were utilized: 1. a bathymetry map was merged based on unpublished data provided by NRCan and the Canadian Hydrographic Service (1986), 2. a slope map was derived from the bathymetry raster assuming that slope influences grain size distribution directly, and 3. a cost distance grid was created to simulate the influence of the Mackenzie River as a significant source of silt.

Cost distance tools in ArcGIS (ESRI) calculate the lowest accumulative cost (or in this application - distance) for each cell in order to reach the source (black triangle - the Mackenzie River mouth). Using the cost raster, the source of sediment input (Mackenzie Delta) and the sediment transport is simulated. The cost distance function produces an output raster (see Figure 2). Each cell is assigned a value that represents the lowest accumulative distance of getting back to the source (note the higher cost at point A than at point B).

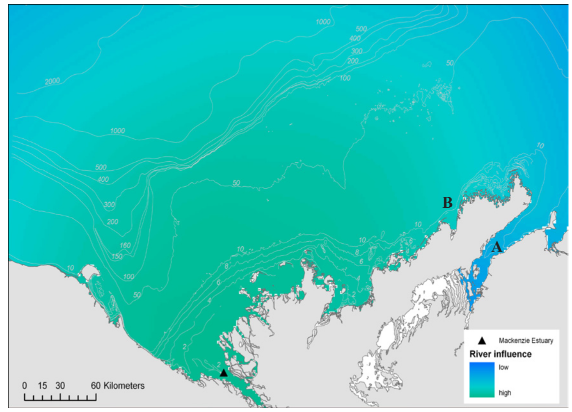


Figure 2 Cost-distance grid Mackenzie Estuary.

3.1 KRIGING

Kriging is an interpolation method for the computation of surfaces from regional distributed point data which is based on the concept of regionalized variables. A variable is called regionalized if it's values are dependent on a location. Different possibilities exist to describe the relationships (autocorrelations) of spatial data. They all are based on the assumption that the autocorrelation of the data is not dependent on the absolute (geometrical) location of the sites, but on the spatial situation of the sites relative to each other in distance and direction (Isaaks and Srivastava, 1992). Thus, a regionalized variable is called autocorrelated if the characteristics of close points are more similar than those from distant points. Kriging considers the spatial distribution of natural characteristics as a combination of a calculable deterministic (e.g. with a mathematical function) and a coincidental component (recordable with statistic methods). The spatial limit of autocorrelation can be quantified based on the computation of a variogram which identifies statistically the correlations of independence between the measured points (Schlüter, 1996). The variogram is a crucial basis for the execution of the kriging interpolation.

Variogram analysis can be performed following two principals, the first is based on determining semivariances for defined distance intervals and radial angle sectors (Figure 3a), and the second on computation and visualization of the semivariogram as so-called variogram maps.

Variogram maps give hints about anisotropies in the data set and assign where spatial dependence not only changes with both distance and direction. Such processes can be found in marine systems where ecological patterns strongly depend upon topography or water currents. The four work steps as described by Pesch et al. (2008) are distinguished when used in modeling the spatial autocorrelation structure with the aid of variogram maps. They are:

1. performing direction vectors (also referred to as lag vectors) from all point pairs of the considered point distribution (Figure 3b);
2. connecting the origins of all lag vectors (Figure 3c);
3. overlaying the result of 2. with a grid of a defined mesh size, assigning the semivariogram values for each cell, respectively (Figure 3d), which results in a variogram map (Figure 3e). The semivariogram values are weighted according to a Kernel-function depending on the distance of the ending of each lag vector to the centre of each cell (Johnston et al. 2001, pp. 25 therein). Variogram maps are point-symmetrical relative to their origin, because all lag vectors have a counterpart in the opposite direction;
4. assigning the calculated semivariances to a coordinate system defined by separation distance (x-axis) and semivariance (y-axis) resulting in the experimental variogram (Figure 3e).

It is necessary to fit a defined variogram model to the experimental data. In order to perform kriging, three key parameters (range, sill and nugget effect) can be defined that allow describing the variogram model (Figure 3a). The range equals the maximum separation distance within which a distinct increase of semivariogram values can be observed. This indicates spatial autocorrelation. The sill corresponds to the

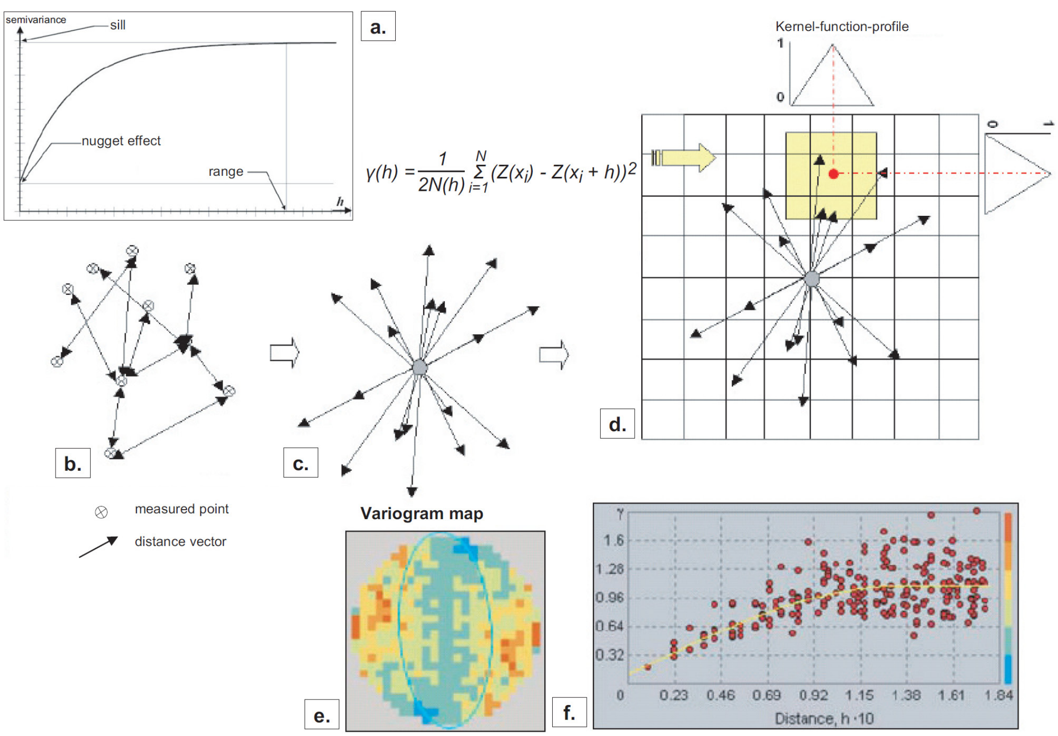


Figure 3 Operating sequence of variogram analyses by means of variogram maps (modified after Pesch et al., 2008). a. semivariogram, b. lag vectors from point pairs, c. lag vectors connected by their origins, d. overlay with a grid assigning the semivariogram values, e. variogram map, f. experimental variogram.

semivariance assigned to the range. If anisotropies can be detected, both sill and range will vary with respect to direction. Small-scale variability or measurement errors may lead to high semivariances at nearby locations.

The variogram model refers to this in terms of the nugget effect, where the variogram model cuts the ordinate above the origin. A pure nugget effect indicates a complete lack of spatial autocorrelation. The adaption of the variogram to the experimental data can be achieved by means of mathematical models fitted to the experimental variogram in terms of a least-squares regression line. ArcGIS Geostatistical Analyst distinguishes eleven models (Johnston et al., 2001), from which the spherical and the exponential models are used most frequently. For a detailed mathematical descriptions, refer to Webster and Oliver (2000) or Johnston et al. (2001).

Crossvalidation can be used to choose the optimal variogram model. For this purpose, each measurement value is extracted from the dataset and estimated by means of the selected variogram model and the kriging method to be applied. By subtracting the measured value from the estimated value, an estimation or kriging error can be calculated resulting in an error distribution for the whole dataset. Various key parameters can be calculated from the distribution to characterize the global quality of the chosen variogram model and the resulting surface estimation.

Cokriging is an interpolation technique that provides a superior estimation of map values by kriging, if the distribution of a secondary variable sampled more intensely than the primary variable is known. If the primary variable is difficult or expensive to measure, then cokriging can greatly improve interpolation estimates without having to more intensely sample the primary variable. The kriging estimate is based not only on the distance to nearby sample locations for the target variable to be interpolated Z_{tar} and the variogram for Z_{tar}, but also the distance to nearby sample locations for the co-variable Z_{co}, the variogram for Z_{co}, and the cross-variogram for Z_{tar} x Z_{co}. This can provide a more robust estimate of Z_{tar} at unsampled locations if Z_{tar} and Z_{co} are sufficiently correlated. Preliminary work has shown that the cokriging technique produced better results than the ordinary kriging, since it was able to more accurately capture small variations in sediment type distribution.

3.2 Mapping Procedure

The data input was built by extensive pre-processing of the sediment data set. The process consisted of data acquisition, data cleaning and projecting (Universal Transverse Mercator (UTM) zone 8N and North American Datum of 1927 (NAD27)). Data without confirmed references, data proximal to artificial islands according to Klohn-Crippen (1998) and outliers were deleted. Furthermore, this study required data sets with a minimum data resolution comprised of gravel, sand, silt and clay percentages. Finally, a data set of 1240 sample sites fulfilled all requirements (see Figure 4).

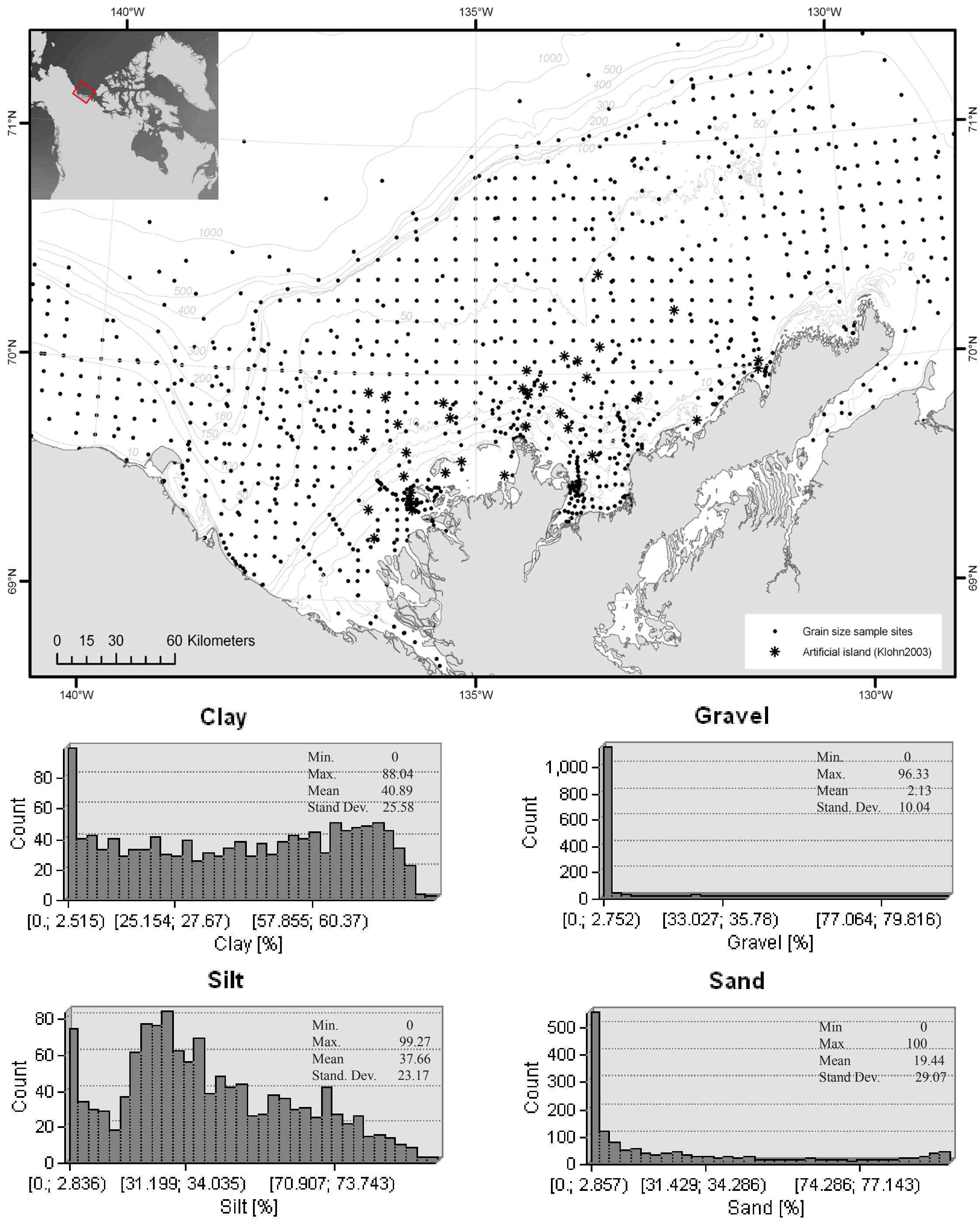


Figure 4 Spatial distribution of grain size data which provides the database for the sediment type map of the Beaufort Shelf. Data density plots (histograms) show an improved distribution of clay and silt (even if they are not normal distributed). The distribution of the sand and gravel data will supposedly produce inaccuracies with regard to interpolation purpose.

The process of cokriging generated predictive mono-parametric maps for the surficial grain size ranges gravel, sand, silt and clay. For interpolation purposes, the samples were classified on the basis of Wentworth's (1922) grain size classification where gravel is > 2000 µm; sand is 2000 µm to 62.5 µm; silt is 62.5 to 3.91 µm, and clay is < 3.91 µm. Figure 4 presents the frequency distribution of the grain size classes.

Shephard's sediment classification system (1954) shown in Figure 5 was then applied to the mono-parametric maps by using reclassification and raster calculations to generate a multi-parametric sediment type map. This classification system is simple, practical, has a wide application and groups sediments into useful categories that make the presentation of textural data effective.

For graphing the Shephard's (1954) system, a total of 100 % is required when adding the cell values (percentages) of the four mono-parametric grain size grids gravel, sand, silt and clay. But this is not always the case (Figure 6). Regions of slight over- and underestimation can appear due to the cokriging algorithm (see Figure 7). The cokriging algorithm does not stop interpolating when it reaches values of 0 or 100 percent. Again, it implicates autocorrelation, which is the spatial distribution of the sites relative to each other in distance and direction (Isaaks and Srivastava, 1992). Thus, it is possible for cokriging to calculate an over- or an underestimation for the predicted value, when using a row of values close to 100 or 0 and assuming no data point is close enough to influence the algorithm. If these values are close to each other and to be estimated the pixel is located either at the same distance or further away, the predicted value can reach values above 100 or below 0. Therefore, each grain size grid was recalculated using a "100 %-grid" (cell values = 100) as follows: grain size $\text{grid}_{\text{recalculated}}$ = grain size grid / over-underestimation grid x 100 %-grid.

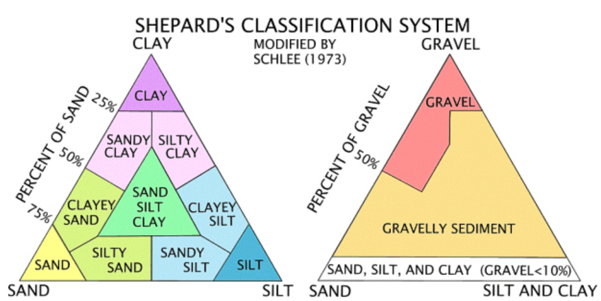


Figure 5 Shephard's (1954) sediment classification system modified after Schlee (1973) with sand, silt, and clay-size fractions based on the Wentworth (1922) grade scale: sand, silt, and clay-size particles having respective diameters of 2000 to 62.5 µm, 62.5 to 3.91 µm, and less than 3.91 µm. Shepard's (1954) sediment classification is a function of sand, silt, and clay-size percentages.

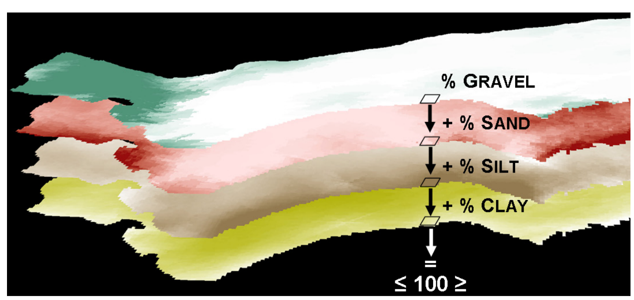


Figure 6 Overlay of the grain size maps. The sum of the four grain size values (percentages) at the associated pixels of the maps should equal 100 %, as provided in the sampling data setBut this is not always the case. Over and underestimations may appear due to the procedure of kriging algorithm.

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).

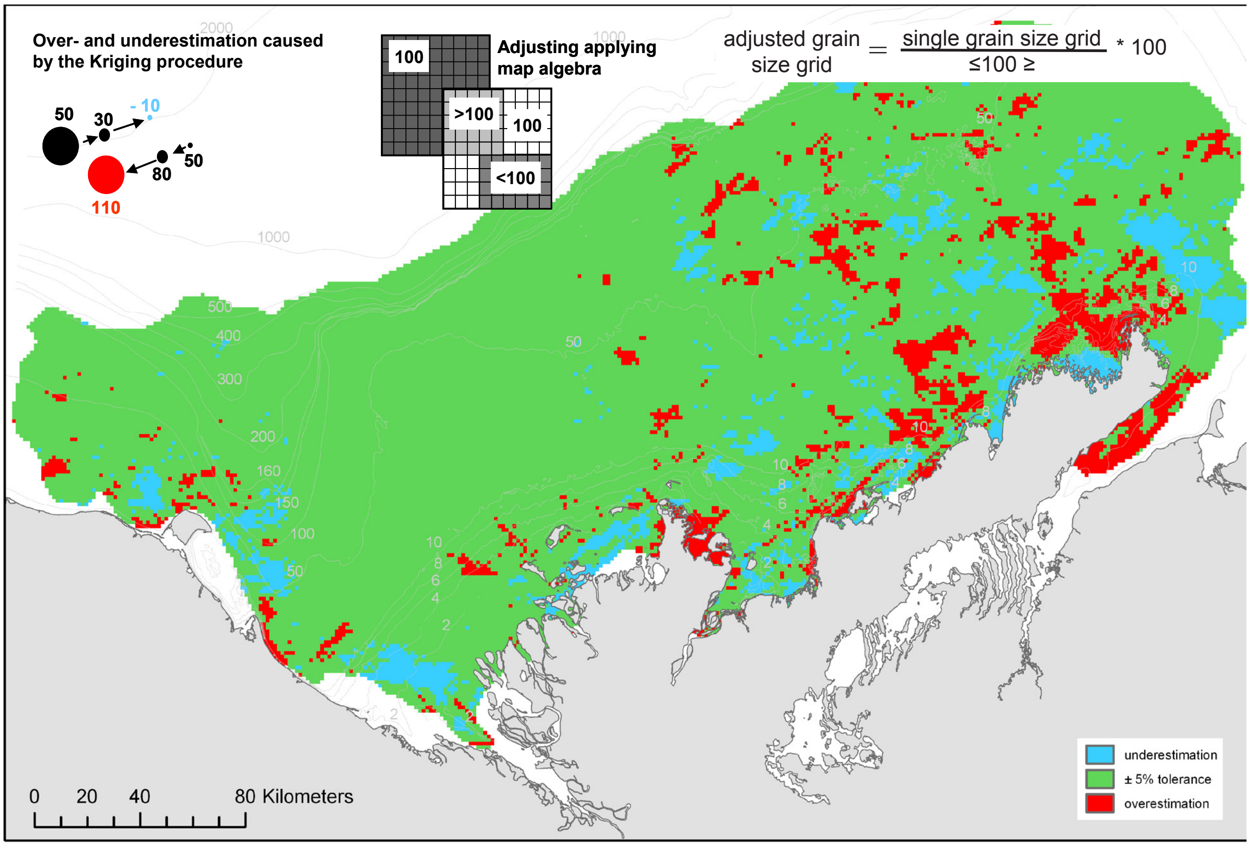


Figure 7 Areas of over- (in red) and underestimation (in blue) after. Green areas meet the standard of a 95% confidence interval.

The final product of a multi-parametric sediment type map, providing the percentages of three grain sizes in each cell according to Shephard (1954) required the combination of the mono-parametric maps of sand silt and clay. The gravel layer is provided separately according to Shephard's second ternary diagram that classifies the composition of gravel, sand and mud. The full process to generate the sediment texture map of the Beaufort Shelf is summarized in Figure 8.

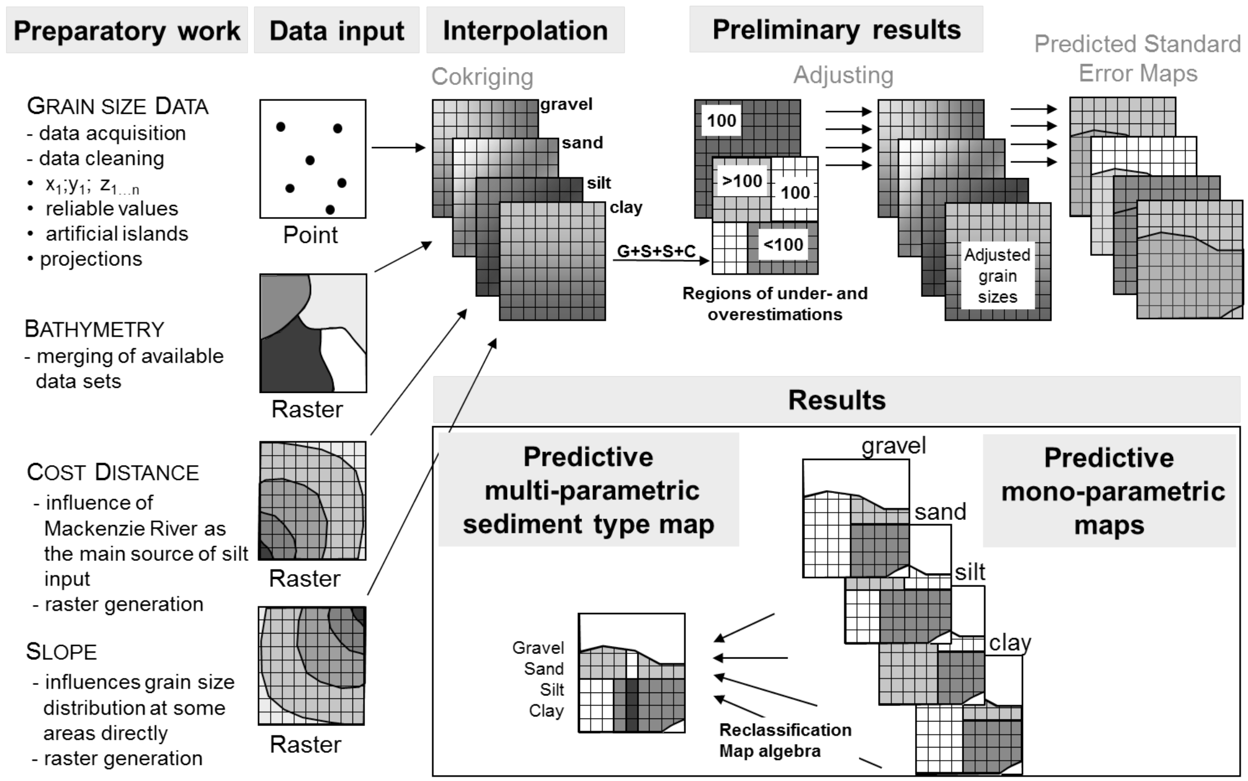


Figure 8 Operating flow for the generation of a sediment texture map applying cokriging.

4 Results - Sediment Texture Map and Single Grain Size Maps of the Beaufort Shelf

This section presents the following:

- four grain size range maps: gravel, sand, silt and clay applying cokriging which considers bathymetry, slope and cost-distance from Mackenzie Delta,
- a sediment texture map using the grain size range maps according to Shephard‘s Classification System (1954) and
- a mean grain size map which was generated according to the same method as for the grain size range maps.

Figure 9 shows preliminary results for sand, silt and clay raster calculations and displays the distrribution of sample sites and the predicted standard errors (PSEs) for each grain size. The PSE values express a maximum deviation of the real values and therefore help to estimate the quality in these regions regarding the interpolation results for each grain size range. The PSEs were also used to define the extent of a reliable interpolation area (Figure 10).

Final adjusted cokriging results which consider bathymetry, slope, cost-distance from Mackenzie Delta and anisotropy for clay, silt, sand and gravel (Figure 11) provide grain size maps of the Beaufort Shelf as continouus grids. These four predictive mono-parametric grids (grain size range maps) were reclassified according to Shephard’s (1954) classes (Figure 12). Finally, the multi-parametric sediment texture map (Figure 13) resulted by raster calculations.

Each cell of the sediment texture map of the Beaufort Shelf in Figure 13 contains the percentage of the three grain sizes clay, silt and sand. Gravel consists of a separate GIS layer and is overlaid as a grey hatched polygon. The percentage values of the grain size composition and aerial coverage of each of the eighteen classes seen in Figure 13 are given in Table 2. Colors generally are chosen as follows: silt in blue, clay in red, sand in yellow and mixed sediments in green. The charts in Figure 13 show the PSEs for every class of every grain size used in the sediment texture map. Best predictions could be achieved for low sand and gravel contents (0-50 %) and intermediate silt and clay values (30-80 %).

ED was the source of 1208 reliable mean grain size measurements which were used for a mean grain size map of the Beaufort Shelf (see Figure 14). The map was created following the same cokriging procedure as the grain size maps considering bathymetry, slope, cost-distance from Mackenzie Delta and anisotropy. A standard error range of 0.080 - 0.083 % defines the reliability boundary of the map.

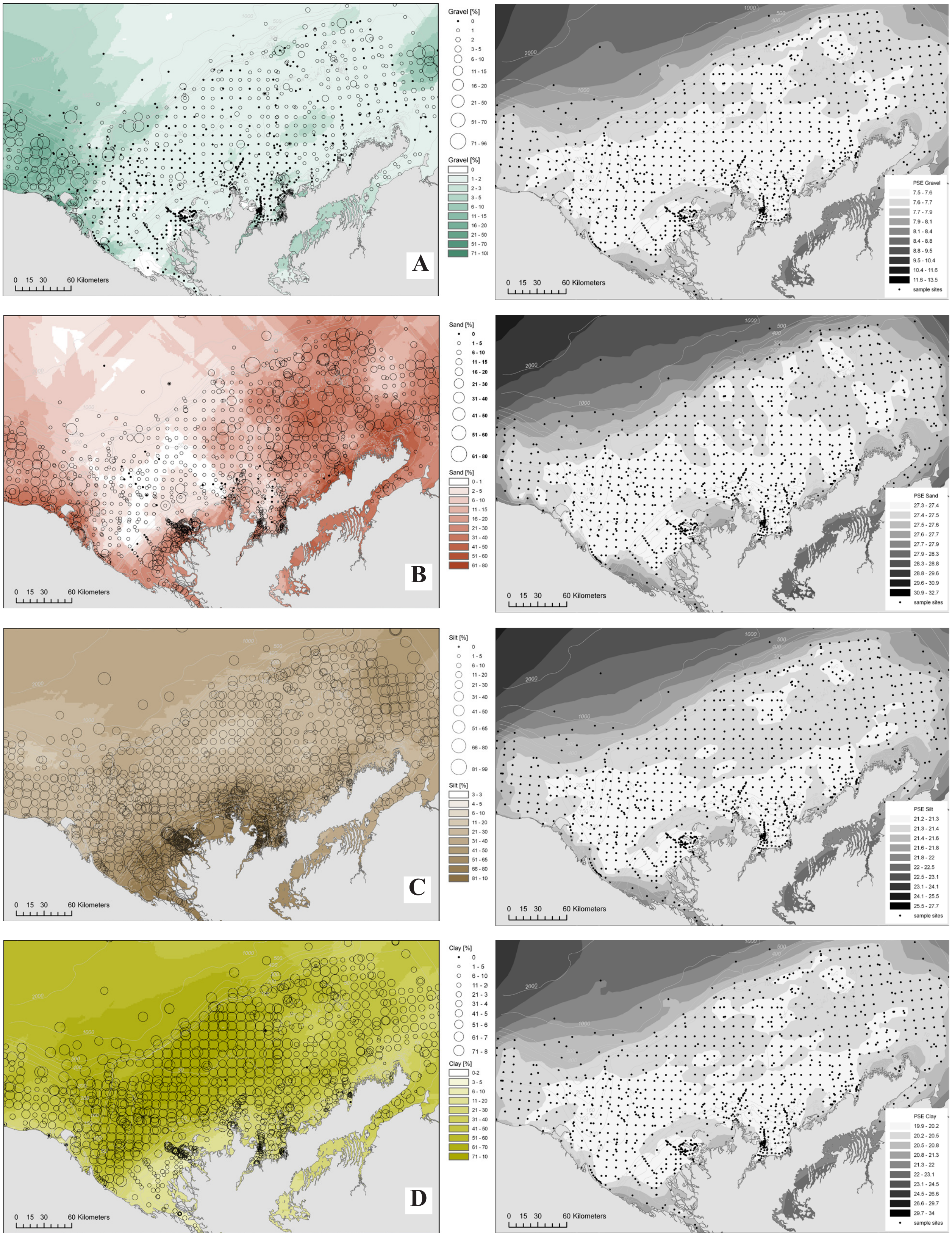


Figure 9 Preliminary interpolation results of cokriging (considering bathymetry, slope and cost-distance from Mackenzie Delta and anisotropy) and Prediction Standard Error maps for gravel (A), sand (B), silt (C) and clay (D).

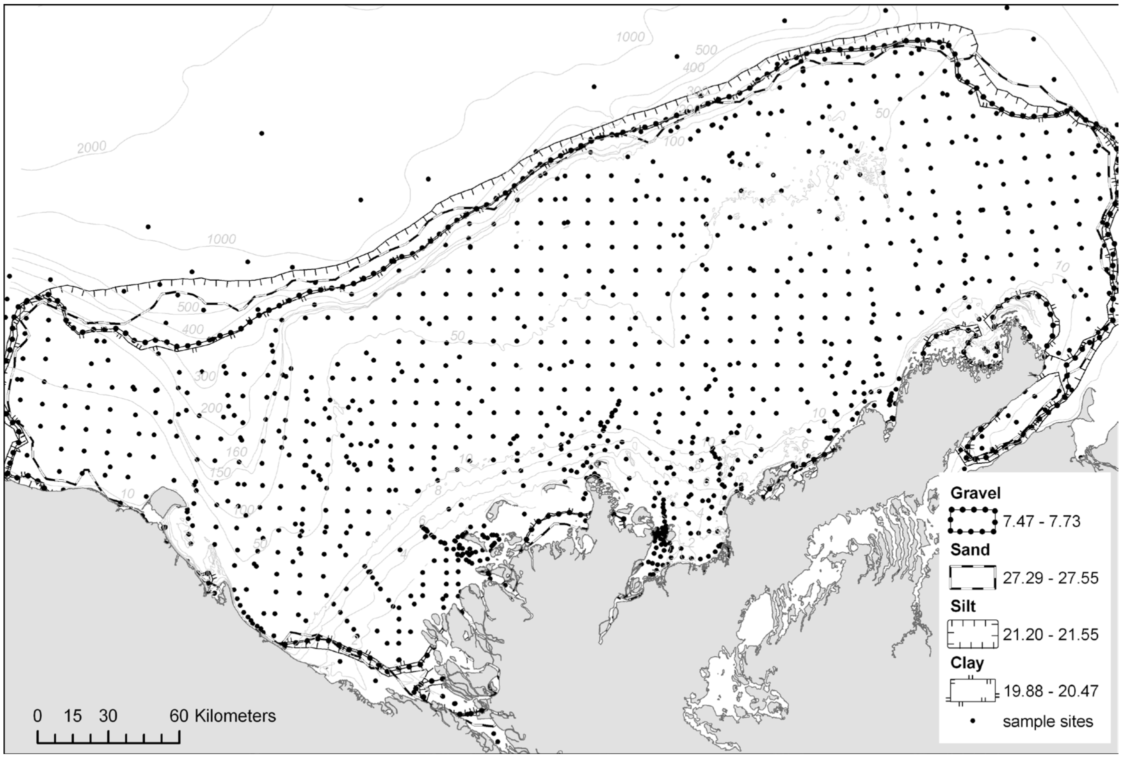


Figure 10 Overlaying the predicted standard errors of all four sediment grain size ranges (gravel, sand, silt and clay) was used to define the boundary of a reliable interpolation area. The values express a probability of the prediction and therefore help to estimate the quality in these regions regarding the interpolation results for each grain size range.

Table 2 Areas of sediment types (km^2) and their grain size composition in percentages as they are presented in the sediment type map of the Beaufort Shelf in Figure 13. The largest adjunctive area is covered by silty clay which is 22.7% of the total area (67,185.38 km^2).

Sediment type	Clay [%]	Silt [%]	Sand [%]	Area [km^2]
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

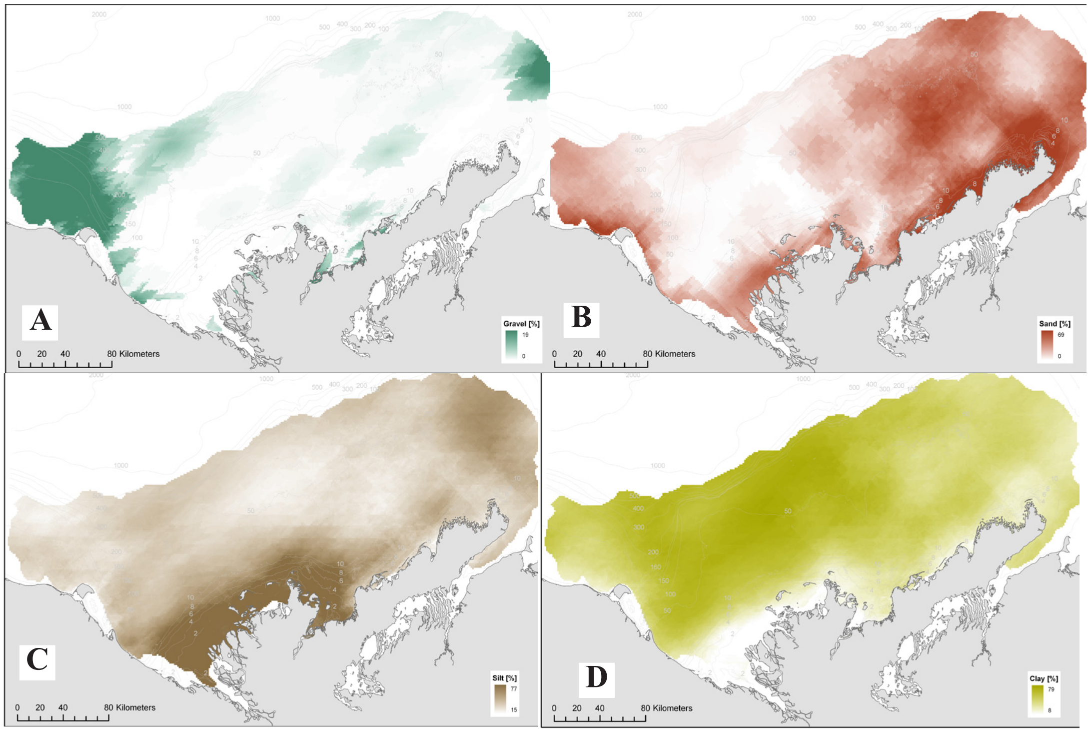


Figure 11 Final adjusted cokriging results (considering bathymetry, slope and cost-distance from Mackenzie Delta and anisotropy) for gravel (A), sand (B), silt (C) and clay (D).

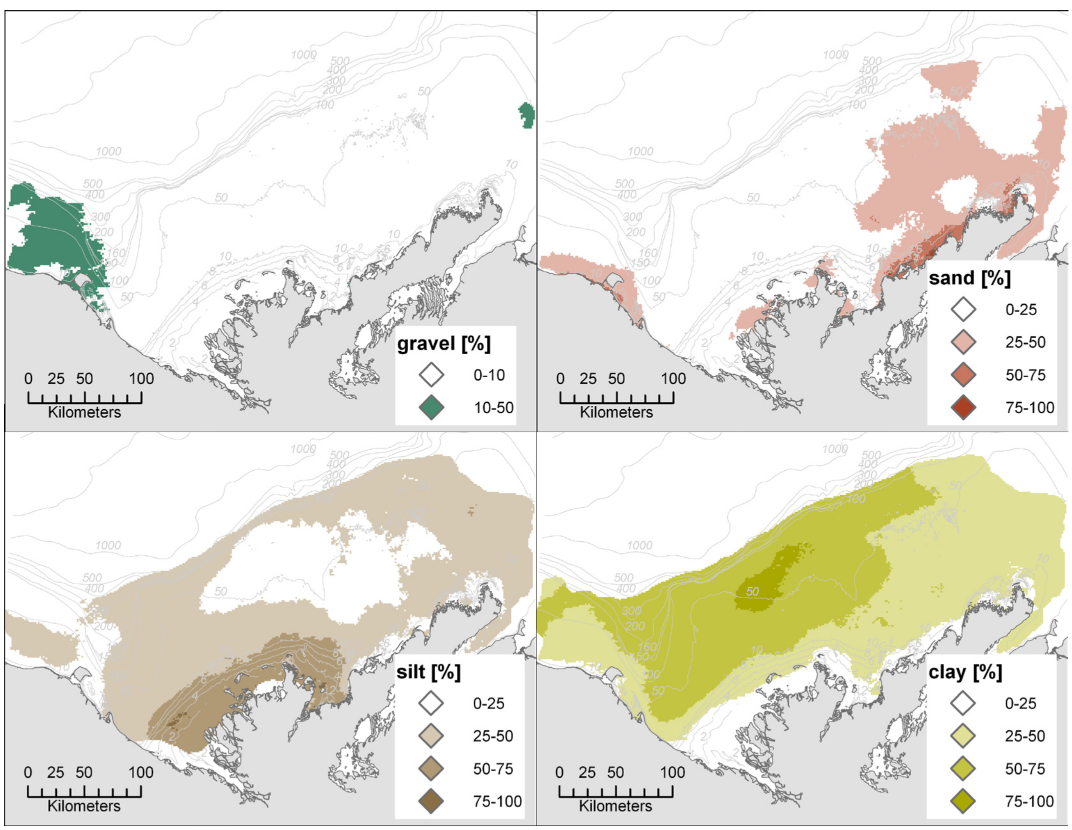


Figure 12 Grain size maps classified according to Shephard‘s (1954) sediment texture system in order to calculate a sediment type map which considers all grain size ranges.

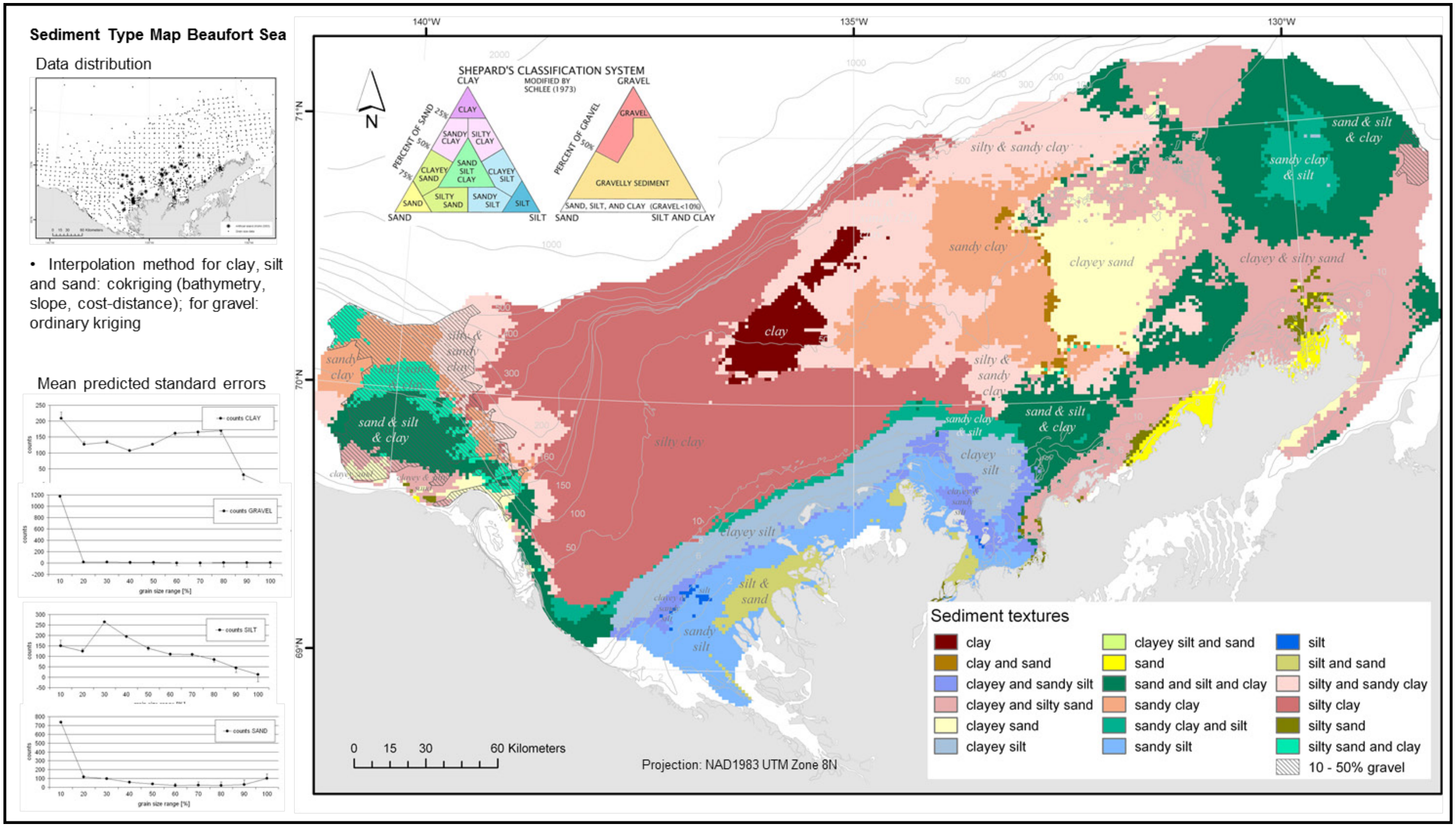


Figure 13 Sediment type map of the Beaufort Shelf compiled by applying raster calculations. In general, the sediment classes follow the Shephard classification system (1954), but include additional classes as well. See Table 2 for the identification of the grain size percentages that each sediment type consists of.

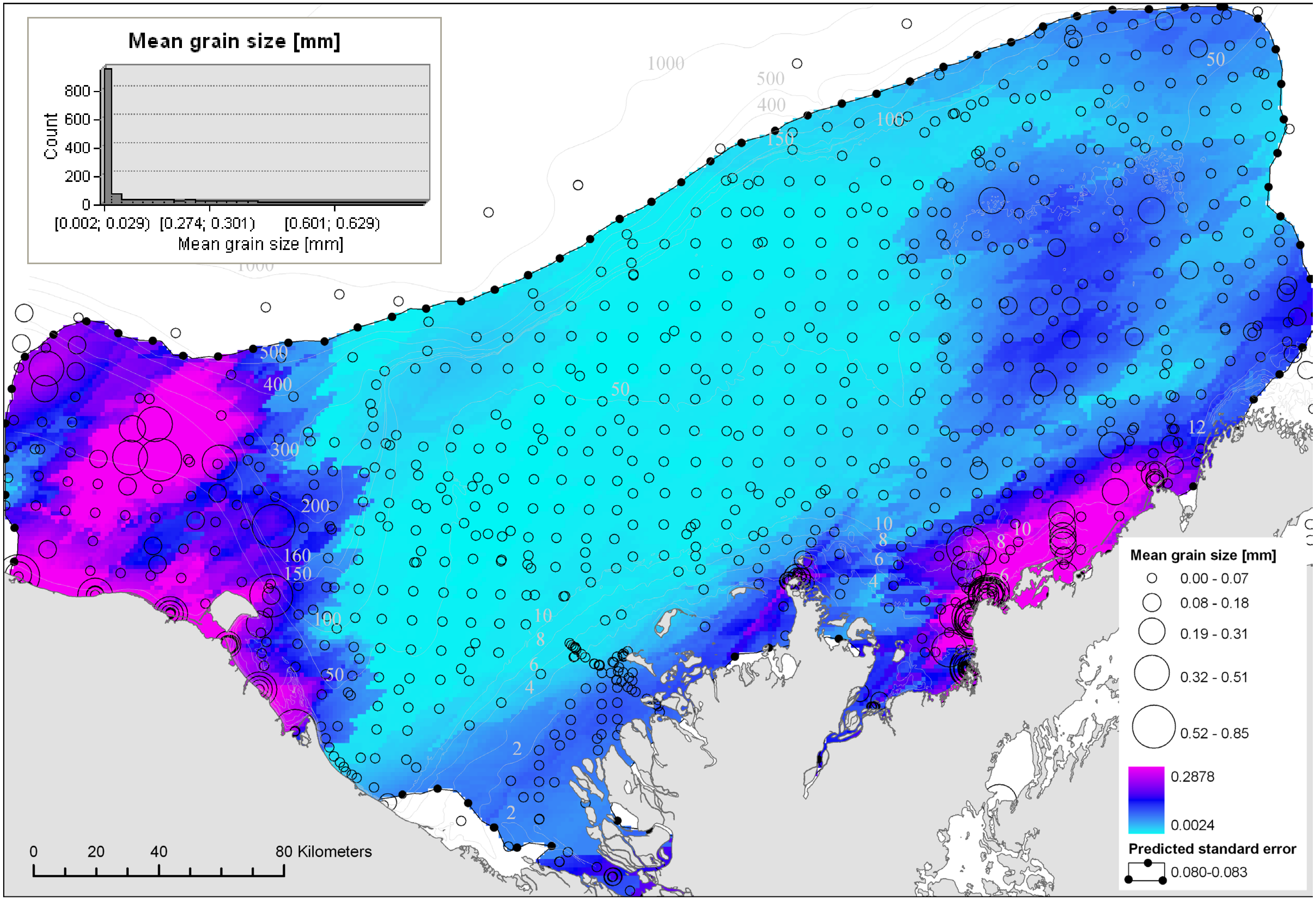


Figure 14 Mean grain size map of the Beaufort Shelf compiled by the cokriging application (considering bathymetry, slope and cost-distance from Mackenzie Delta and anisotropy) as performed for the grain size range maps.

5 Discussion

5.1 Quality Assessment

The maps in Figures 11, 13 and 14 are interpolation results and their purpose is to provide predicted seabed sediment texture values. The sediment distribution is the result of a defined and calculable probability, based on PSE maps, and provides a guide to the distribution of sediment textures on the seabed. However, subsampling is necessary to provide groundtruth for further seabed texture verification.

For an additional increase the predictions the measurements were reduced following expert recommendations respecting outliers in general and close to artificial islands in particular. The results in Figures 11 are comprehensible by providing the distribution of the measurements in Figure 9.

The PSE values in Figure 10 show an increasing quality of prediction from gravel to clay to silt to sand, respectively. The reason for this is the very distinctive distribution of gravel in the Beaufort Shelf. Large areas are gravel-free, thus, the requirements of the gravel cokriging model are comparably low. The other grain sizes show a slight trend: the smaller the grain size, the more precise the prediction of unsampled areas when applying the interpolation method (clay predictions are better than silt; silt predictions are better than sand). This is caused by varying degrees of homogeneity and similarity in the data values. When comparing sand, silt and clay, sand was the most demanding parameter for the prediction because it was affected by increased numbers of small-scale variations in data values. The PSEs have been reduced by considering important influence factors as depth and slope, but mainly by the Mackenzie River's silt input and anisotropy.

5.2 Comparison with Existing Grain Size Maps (Pelletier, 1984)

Pelletier (1984) published a comprehensive sediment atlas of the Beaufort Sea. Therein, he presents sediment maps of clay, silt, sand and gravel in 10 % intervals but the method of mapping is not described. His sediment texture map also combines the four sediment grain sizes following Shephard's (1954) grain size classification system.

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 (Figure 15). 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) as shown in Figure 16.

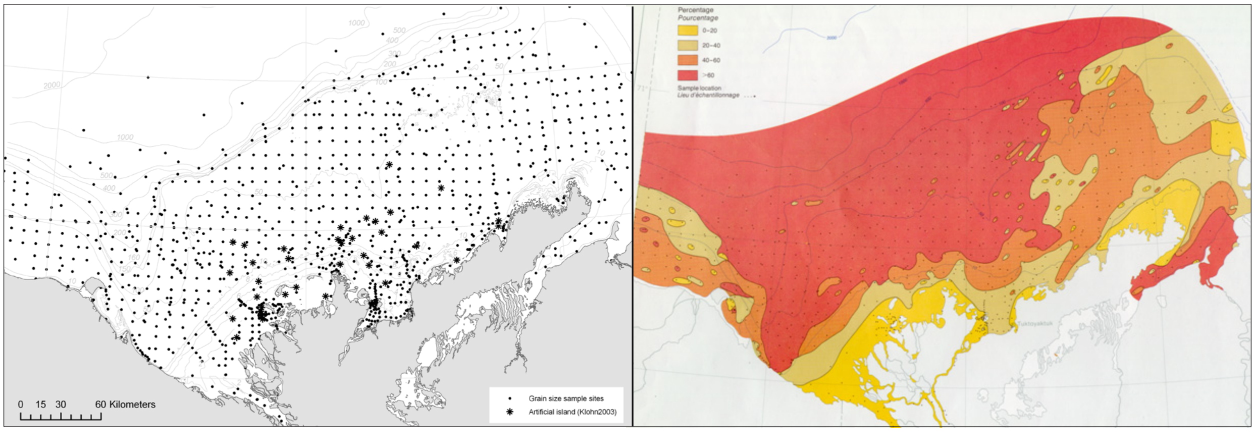
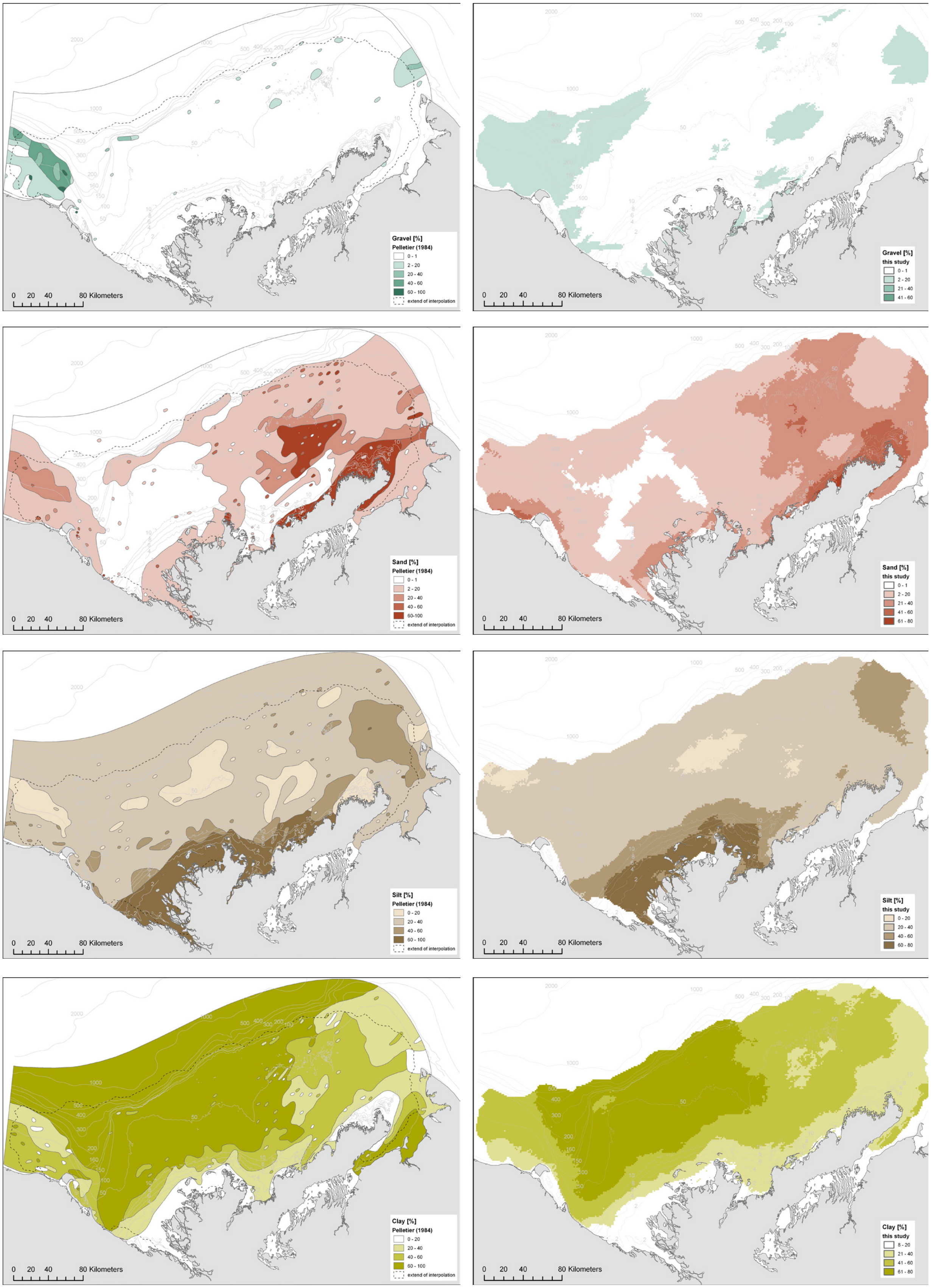


Figure 15 Comparison of the sample site distributions: on the left the ones used in this study (2010) and on the right those used by Pelletier (1984) shown on his clay distribution map. To some extent the same data sets were used.

In general, the grain size maps show similar pattern, however, regional differences can be recognized from the map pairs. Pelletier highlights single measurements with considerable gradients by drawing circles around them, while cokriging tends to smooth measured gradients (Figure 16). The variogram values for gravel are suboptimal; Pelletier‘s method might present superior results than the interpolation. This is caused by the sparse occurrence of gravel in the data set (from a statistical point of view) as well as by a reduced correlation of gravel to the cokriging parameters. Analyzing the sand map, some but not all of the Pelletier (1984) elongated ovals around single point data might be explained by an artificial island. The occurrence of others may be a result of bottom currents exposing older beach deposits (Pelletier, 1984). When comparing the silt and clay map pairs, the variogram analyses were more reliable and this corroborates the frequency distribution of the grain size classes for the Beaufort Shelf (Figure 4).

Figure 16 next page 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 facing the interpolated results. Class ranges are defined consistent with Pelletier (1984) for comparability reasons.



Gravel [%]
Pelletier (1984)
0 - 1
2 - 20
20 - 40
40 - 60
60 - 100
extend of interpolation
Gravel [%]
this study
0 - 1
2 - 20
21 - 40
41 - 60
Sand [%]
Pelletier (1984)
0 - 1
2 - 20
20 - 40
40 - 60
60-100
extend of interpolation
Sand [%]
this study
0 - 1
2 - 20
21 - 40
41 - 60
61 - 80
Silt [%]
Pelletier (1984)
0 - 20
20 - 40
40 - 60
60 - 100
extend of interpolation
Silt [%]
this study
0 - 20
20 - 40
40 - 60
60 - 80
Clay [%]
Pelletier (1984)
0 - 20
20 - 40
40 - 60
60 - 100
extend of interpolation
Clay [%]
this study
8 - 20
21 - 40
41 - 60
61 - 80
0 20 40 80 Kilometers

6 Conclusions

The geostatistical concept of cokriging was used to predict and map the occurrences of sediment textures in the Beaufort Sea. Geostatistics is not an exact science; it is an applied science and relies, to a certain degree, on expert knowledge. This knowledge is expressed in the analysis of the data set, the preprocessing to adapt it to the algorithm, and the tuning of the model's parameters to avoid any remaining difficulties. Especially in nearshore regions, like the Beaufort Shelf, geostatistical interpolation techniques are very useful because the sampling is often difficult or impossible due to ice conditions or even prohibited near oil platforms.

Grain size raster maps were developed for a range of grain size data (clay, silt, sand and gravel). Cokriging provided superior interpolation results for silt, clay and sand, when compared to ordinary kriging, by using secondary variables (bathymetry, slope and sediment input of the Mackenzie River).

The two main issues with the grain size datasets used in this study are 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. This method, as well as the inclusion of recent data, provided an improved mapping of the surficial sediments of the Beaufort Shelf.

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