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Application of non-parametric geostatistical methods to the identification of aggregate deposits on the continental shelf

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ABSTRACT

More than 1 400 samples were used in the assessment of the sand and gravel potential of the continental shelf north of Espinho (northern Portugal). This study deals primarily with the determination of the probabilities of the occurrence of some textural (gravel, sand, silt and clay contents) and chemical (carbonate content) parameters and of some textural groups, according to Nickless' (1973) classification. Sediment samples were collected between 1986 and 1989, during several cruises sponsored by the Portuguese Hydrographic Institute.

For the purpose of the present study, a non-parametric geostatistical methodology was used on the whole set of samples, encompassing the following steps: a) a preliminary variography analysis based on the raw data, to determine structural features, such as trends, anisotropies and nested models; b) binary codification of the initial data, in 'less than' or 'equal to' specific cut-offs determined with economic criteria; c) calculation and modelling of variograms of this indicator; and d) application of indicator kriging to obtain probability (risk) maps.

The results obtained by the application of the methodology to the two data groups (sediment texture and Nickless classification) were compared in order to characterise the aggregate deposits which could be economically exploited in the near future.

This study should help decision-makers to define an exploitation strategy, to be implemented in the near future. However, this preliminary approach requires further studies, namely by using cross-variography procedures and conditional probabilities.

Key words: Aggregates, non-parametric geostatistics, variography, ordinary kriging, indicators, risk maps, sediment texture, Nickless classification.

RESUMEN

Aplicación de métodos de geoestadística no paramétrica a la identificación de depósitos de áridos en la plataforma continental

Más de 1 400 muestras sedimentarias fueron utilizadas en la evaluación del potencial en gravas y arenas que se pueden explotar para áridos naturales y de trituración para la construcción y obras públicas. El presente estudio se atiene a la determinación de la probabilidad de ocurrencia de algunos parámetros texturales (contenido en gravas, en arena y en fango) y químicos (contenido en carbonatos) y de determinados grupos texturales, según la clasificación de Nickless (1973). Las muestras fueron recogidas entre 1986 y 1989 en el transcurso de diversas campañas oceanográficas realizadas por el Instituto Hidrográfico de la Marina Portuguesa.

Se ha realizado un estudio de geoestadística no paramétrica incluyendo las siguientes etapas: a) variografía preliminar de los datos de base para identificar características estructurales (por ejemplo, tendencias, anisotropías y estructuras imbricadas); b) se codificaron los datos iniciales en formato binario, según valores infe-

riores a o iguales a un patamar específico determinado por un criterio económico; c) se calcularon y modelaron variogramas de esta indicatriz; y d) la indicatriz fue krijeada *para obtener mapas de probabilidad o riesgo.*

La referida metodología fue aplicada sobre los dos tipos de datos (granulometría sedimentaria y clasificación de Nickless). Se compararon los resultados obtenidos para caracterizar los depósitos de gravas y arenas que pueden ser explotados en un futuro próximo.

La presente aplicación pretende ayudar a los organismos decisorios a definir una futura estrategia de explotación. Sin embargo, éste es solamente un estudio preliminar. Se necesitan estudios más profundos, utilizando, por ejemplo, procedimientos de variografía cruzada y probabilidades condicionales.

Palabras clave: *Áridos, geoestadística no paramétrica, variografía,* krijeage *ordinario, indicatrices, mapas de riesgo, textura sedimentaria, clasificación de Nickless.*

INTRODUCTION

The assessment and dredging of offshore gravel and sand deposits have, over the last 20 years, become a common practice in many industrialised countries, such as the United Kingdom, France, Japan, Norway, and the United States. Several factors account for this: the increasing demand for these materials, due to strong industrial and urban growth; the progressive decrease in onshore resources; legal disputes arising from land use for profitable quarrying; the frequently negative environmental impacts induced by onshore exploitation; the increasing understanding of the mechanisms operating on the shelf; and the increase in dredging efficiency. Offshore sand and gravel deposits are dredged for four main applications (Selby and Ooms, 1996): for use as fill-in reclamations; for use in aggregates for construction and concrete; for beach nourishment; and to extract placers.

Although there are no serious supply problems in Portugal at this time, they are likely to occur in the near future, as onshore quarries become depleted and environmental protection laws become stricter. Under such a scenario, submarine deposits occurring in the portuguese continental shelf will be increasingly dredged.

Dredging of offshore deposits must be preceded by detailed environmental impact studies, essentially dealing with:

a) The possible interruption of presently active sedimentary cycles

b) The content in fine-grained material. Silts and clays will be resuspended during dredging, leading to an increase in water turbidity. This will, in turn, reduce light penetration, affecting animals and primary production (Shelton, 1973)

c) The destruction of benthic and fish communities (Ottman, 1985; Appleby and Scarrat, 1989)

d) Disturbances in bottom currents

e) More or less permanent changes in seabed topography, possibly affecting trawl fishing (Cressard, 1989)

f) Biological effects of siltation on fish eggs and larvae (Messieh *et al.*, 1991)

Despite all the negative impacts cited above, some positive impacts do sometimes occur. Biological productivity can increase as a result of these exploitations (Shelton, 1973; Cressard, 1989). Improvement in the environment and a substantial increase in the fish population was reported from gravel dredging in the Baltic Sea (Hill, 1974).

At this point, it must be emphasised that the complexity of environmental impacts induced by sand and gravel dredging requires a very thorough analysis, for which multidisciplinary studies are obviously needed.

Regional setting

The continental shelf north of Espinho (figure 1) is relatively narrow and deep, with an average width of approximately 45 km and an average shelf-break depth of 160 m (Musellec, 1974). The shelf is 35 km wide north of Póvoa do Varzim and widens southward, with a progressive decrease in slope. The Porto Submarine Canyon and the Beiral de Viana elevation are noteworthy features of the shelf. The great bathymetrical irregularity of the inner shelf is due to eruptive and poli-metamorphic outcrops from the paleozoic basement. The continental slope presents a mean slope of 5.7 m/km. The Porto Submarine Canyon is cut deeply into this steep surface.

Several blocks limited by major structural accidents occur on the shelf. Outcrops from the poly-metamorphic basement rocks on the inner shelf, the Beiral de Viana and the Pontal de Galega

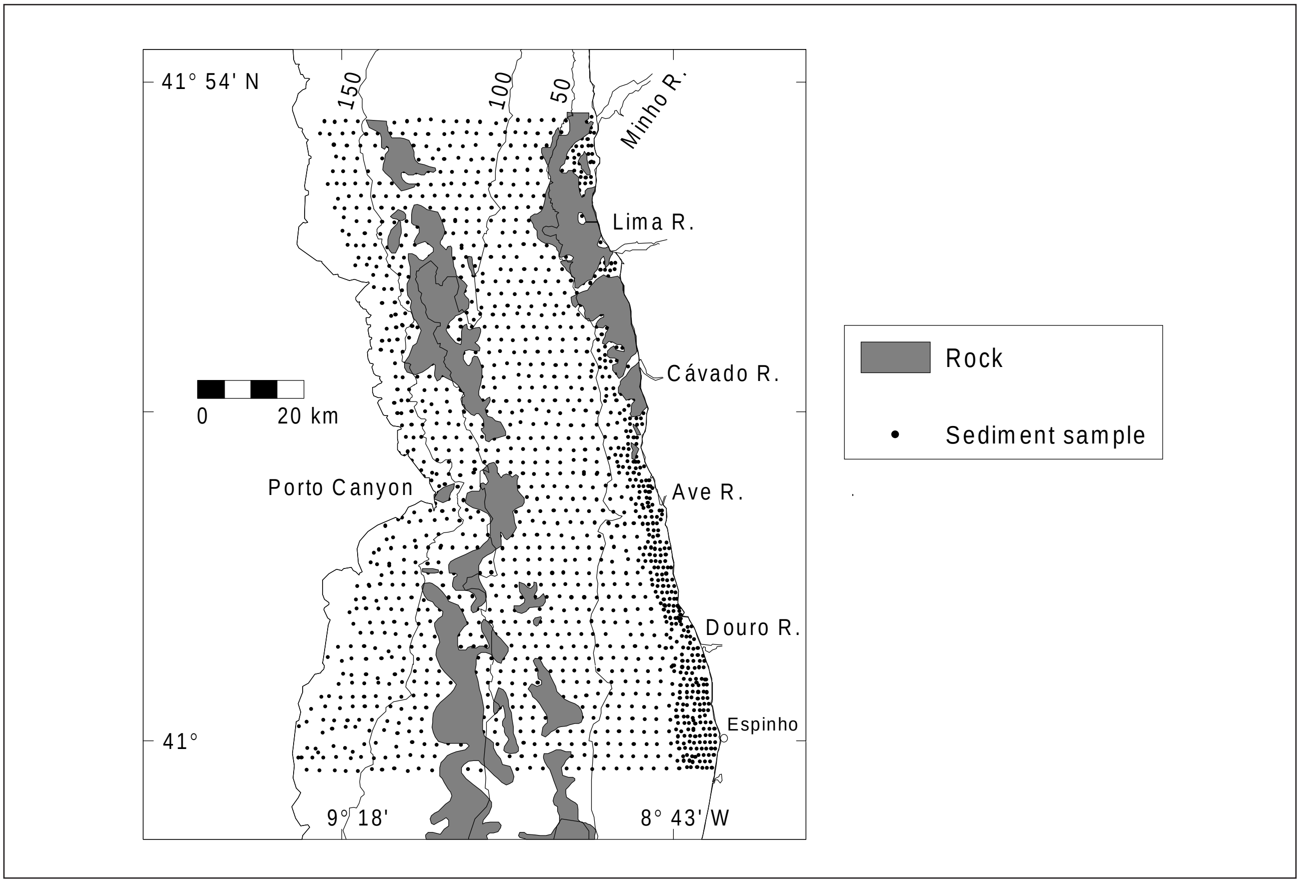

Figure 1. Location map

trench have a general south-southeast-north-north-west orientation. The poliymetamorphic basement is separated from the Pontal da Galega trench by the Porto-Tomar fracture zone. Very thick Tertiary formations overlie the basement. Outcrops of Upper Cretaceous marine limestones interrupt this thick series on the western side. Having a structural origin, the Beiral de Viana is the morphological expression of these outcrops. Mesozoic (Upper Cretaceous) rocks can also be found at the head of the Porto Submarine Canyon. Groups of faults with general directions of north-south to north-north-west-south-southwest and northeast-southwest to north-northeast-south-southwest occur on this shelf. On land, major rivers are usually controlled by faults (Teixeira, 1944), and probably extended onto the continental shelf when the relative sea level was lower than the present one.

Hydrographic basins that drain into this shelf have a total area of almost 120 000 km^2. The Douro and other rivers have relatively high discharges and steep gradients. The Douro run-off can be as high as 17 000 m^3/s during floods (Loureiro *et al.*, 1986).

Meteorological conditions along the coast are dominated by the Azores high pressure system, which supplies northwest winds to this area. Swells from the North Atlantic arrive from the west-north-west with periods frequently between 9-11 s and sometimes as high as 18 s (Carvalho and Barceló, 1966). Mean wave height and periodicity are, respectively, 2 m and 8 s (Pires and Pessanha, 1986). Storm events with mean wave heights higher than 5 m occur in winter with a probable frequency of one per year. These conditions result in southward alongshore transport (Dias and Nittrouer, 1984). Upwelling of subsurface waters is an important phenomenon along the Portuguese coast, and occurs primarily during summer (e.g. Fiúza, Macedo and Guerreiro, 1982).

Previous work

The first assessment of the sand and gravel potential of the Portuguese continental shelf was conducted by Dias, Monteiro and Gaspar (1980), who have also undertaken the study of a deposit located south of Peniche (Dias, Monteiro and Gaspar, 1981). However, the sampling grid that these authors used was inadequate for detailed studies.

It was only a decade after this preliminary research that the study of sand and gravel deposits was reconsidered. Magalhães, Rodrigues and Dias (1991) mapped the aggregate deposits present on the continental shelf north of Espinho, and conducted a preliminary reserves assessment, using a very dense grid of surface sediments (1 sq mile) and the analysis of several thousands of kilometres of light seismic reflection and of side-scan sonar profiles.

The evaluation of the wave-induced potential of remobilization of the particles forming the previously identified deposits (Magalhães, Dias and Taborda, 1991) appears to confirm their relict character.

The present paper is a preliminary approach to the use of structural analysis and probability maps in order to identify potentially interesting areas for aggregate exploitation and to help decision-makers to define an exploitation strategy to be carried out in the near future.

A brief introduction to geostatistical theory

Since giving a full account of the geostatistical theory is well beyond the scope of the present paper, readers are invited to consult seminal works, such as Journel and Huijbregts (1978).

The praxis in geostatistics generally encompasses three interrelated phases: structural analysis, kriging and/or conditional simulation.

In the first phase, the spatial structure of the regionalised variables under study (whose properties are intermediate between those of truly random and those of completely deterministic variables) is described by a variogram, defined as the expected squared difference between pairs of data values. This function characterises very well the continuity of the variable and the cross-correlation between variables. In particular, a sample's range of influence (i.e. the distance beyond which the variable is uncorrelated) and the magnitude of the measurement errors and small scale variability (the nugget effect) are estimated. Also, the behaviour of the variogram in specific azimuths highlights the anisotropies, if present, and the evaluation of multiscale effects (nested structures) and trends. For estimation purposes, the experimental functions are fitted with positive definite theoretical models and cross-validated with the experimental data.

Once the spatial variability is modelled, the kriging algorithm will estimate the unknown value of the parameter in unsampled locations by a linear combination of the known values, being the distances of the structural type. This phase has been related with spatial interpolation operations. The kriging operator has the property of exactitude, meaning that the estimation of the parameter at a location where it has been measured is identical to the observed value. It always provides a variance of the estimation error, which is zero at the measured points.

A more complete description of the model of uncertainty can be accomplished by using a approach called indicator geostatistics, through the calculation of the probability distribution function of the unknown value in any location, conditional to the available information. This methodology is not restricted to any particular Gaussian distribution (as in the case of the parametric approach). The initial data is encoded in different ways, e.g. binary code using 'less than' or 'equal to' specific cutoffs. The resulting kriging maps are values between 0 and 1, representing the probabilities that the variable is less than or equal to the selected cutoffs.

In Portugal, geostatistical techniques have been mainly applied to hydrogeology (cf. Chambel and Almeida, 1990; Ribeiro, 1992), in mining (cf. Pereira *et al.*, 1993) and in sedimentology (Magalhães and Taborda, 1995).

MATERIALS AND METHODS

Approximately 1 500 unconsolidated sediment samples were collected on the continental shelf north of Espinho area between 1986 and 1989, using Van Veen, Shipeck and Smith McIntyre grab samplers. Sampling was carried out during cruises sponsored by the Portuguese Hydrographic Institute.

After treatment with hydrogen peroxide to remove organic matter and careful washing with distilled water, samples were wet-sieved to separate gravel and sands (> 63 μm) from silts and clays (< 63 μm). Dry-sieving at 2 mm was performed to determine the gravel and sand contents. A standard pipette analysis of the mud fraction was made to determine the clay and silt contents. Carbonate content of the total sample was determined using a gasometric method (Hülseman, 1966).

For the purpose of the present study, a non-parametric geostatistical methodology was used on the whole set of samples, encompassing the following steps:

a) A preliminary variography analysis based on the raw data was made, in order to determine structural features, such as trends, anisotropies and nested models

b) Initial data was encoded into binary 'less than' or 'equal to' specific cut-offs determined using economic criteria. According to these criteria, cut-offs for mud (silt and clay) and carbonate were set at 40 % and 10 %, respectively

c) Variograms of this indicator were calculated and modelled

d) Indicator kriging was applied in order to obtain probabilities (risk) maps

Geostatistical analysis was also applied to a second set of data, which is related to Nickless' classification (1973). According to this author, sediment is not considered potentially workable when its mud content exceeds 40 %. For the purpose of the present study, only sediments with 40 % or less of mud were used. Four groups were considered, according to the ratio of sand to gravel: group 1 (sand), higher than 1:19; group 2 (gravely sand), between 1:19 and 1:3; group 3 (sandy gravel), between 1:3 and 1:1; group 4 (gravel), lower than 1:1.

RESULTS

Raw data

Some statistics for the variables used in the present paper are shown in table I. All variables are skewed, showing a strong deviation from symmetry, with values for skewness ranging from a minimum of −1.26 (sand) to a maximum of 3.05 (clay). Coefficients of variation are relatively high, from 34.7 % (sand) to 254.3 % (gravel).

Variogram analysis of the raw data was performed to study the patterns of the data's spatial correlation. The experimental variograms for gravel, sand and carbonate are represented in figure 2. These show different structural features:

a) A trend is detected for carbonate in the east-west direction. In fact, the values of this variable show a general eastward increase

b) There is always a clear geometrical anisotropy. The direction of maximum spatial continuity (i.e. maximum range) is north-south, according to the distributor processes which operate on this continental shelf. The highest range variability is found for carbonate, whereas the smallest corresponds to gravel

c) A hole effect is evident for gravel (and also, to a lesser extent, for carbonate). The gravel content of sediments found on this shelf is generally lower than 5 %. The detected hole effect is apparently related to irregular patches in which gravel contents frequently exceed 25 % (e.g. in the middle and outer shelf off the Lima, Ave and Douro River mouths)

d) The magnitude of irregularity, given by the estimated nugget effect (C0) is not similar for the three variables, ranging from 5.5 % (for carbonate) to 48 % (for gravel) of the *a priori* variance. The high gravel nugget/variance ratio is apparently related to the highly irregular distribution of this variable

e) Variograms for carbonate also reveal a zonal anisotropy, which is a phenomenon given by different sills and ranges in the two directions

f) Nested structures were detected in carbonate, particularly in the north-south direction

Table I. Statistics of variables used in this work

	Gravel	Sand	Silt	Clay	Carbonate
Mean	6.34	75.06	15.45	3.15	16.71
Median	0.10	86.9	6.50	1.60	8.5
Minimum	0.00	0.00	0.00	0.00	0.25
Maximum	89.30	100.00	88.20	42.70	79.8
Standard deviation	16.12	26.01	20.89	4.96	17.51
Coefficient of variation	254.26	34.65	135.21	157.46	104.79
Variance	259.99	679.54	436.53	24.57	306.5
Skewness	2.99	−1.26	1.85	3.05	1.54
Kurtosis	8.37	0.64	2.71	12.16	1.42

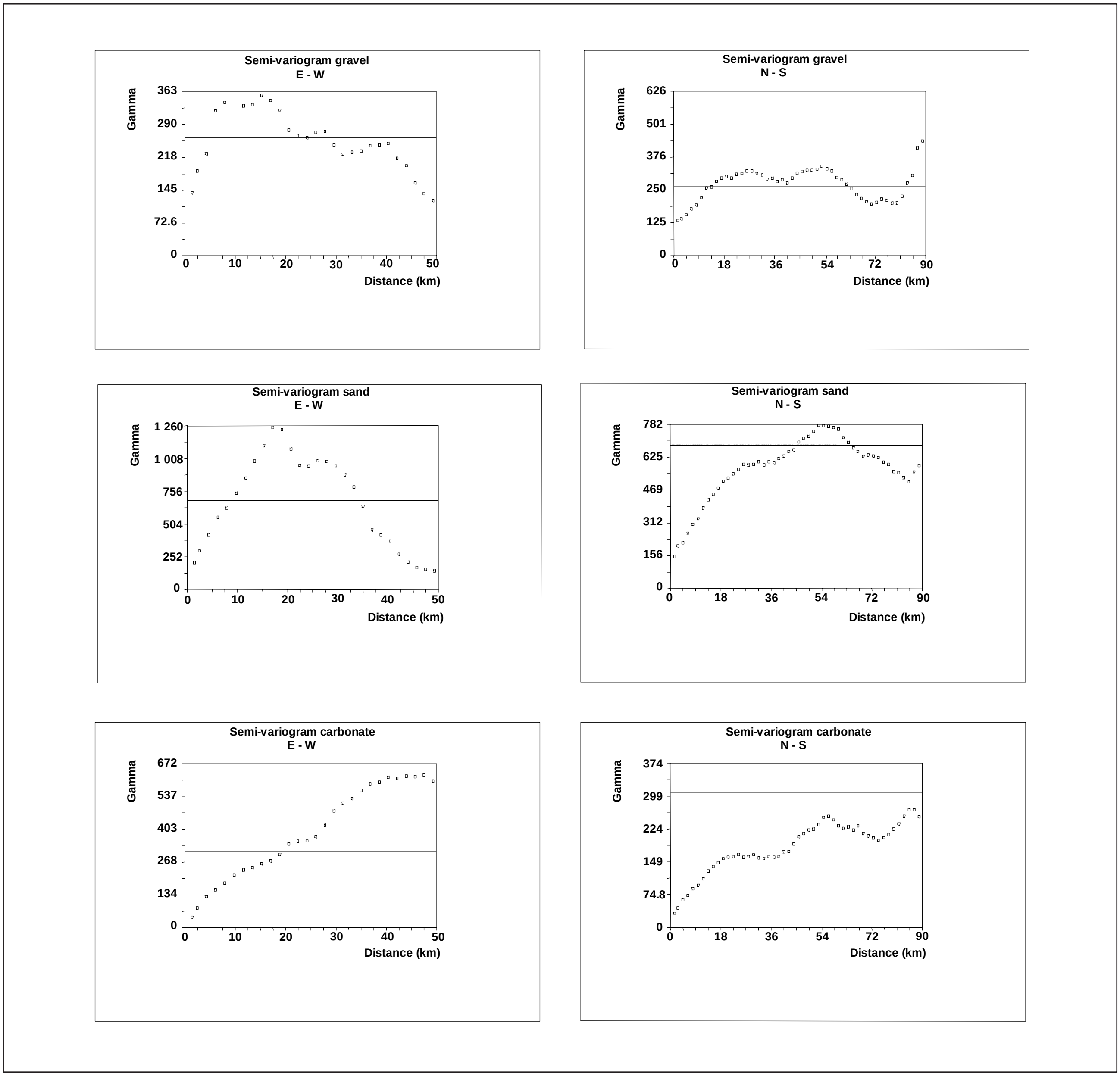

Figure 2. Experimental variograms for gravel, sand and carbonate. The squares represent experimental values and the straight line is the value of the *a priori* variance

Coded data (mud and carbonate indicators)

Table II shows that 16 % of the studied 1 467 samples have a mud content higher than 40 %, whereas the proportion of carbonates higher than 10 % is 44 %.

The variograms computed in the north-south and east-west directions reveal a similar structural behaviour to the previous ones, namely a strong anisotropy for both variables (figure 3). The direction of highest continuity is once again north-south. A zonal anisotropy is clear for the carbonate indicator.

Experimental variograms for the mud indicator were fitted to spherical models, of the form:

$$\gamma\ (h) = [1.5\ h/a - 0.5\ h^3/a^3] \text{ if } h < a; \text{ and } \gamma\ (h) = c$$

where a and c are the variogram's range and sill, respectively. A nugget structure C0, if present, can be added to this model. This transition model has a linear behaviour at the origin and reaches the sill

Table II. Statistics of coded mud and carbonates

	Coded mud	Coded carbonates
Mean	0.16	0.44
Median	0.00	0.00
Minimum	0.00	0.00
Maximum	1.00	1.00
Standard deviation	0.36	0.49
Coefficient of variation	225	111.36
Variance	0.13	0.25
Skewness	1.88	0.24
Kurtosis	1.54	–1.94

Table III. Variogram parameters and validation tests for mud indicator

CO - nugget effect	0.03
C1 - sill	0.1028
a1 (N-S) - range for the N-S direction (km)	40
a1 (E-W) - range for the E-W direction (km)	11
Anisotropy ratio	3.6
Estimated mean	0.199
Mean error	–0.005
Mean reduced squared error	1.708

at distance a. In fitting this model, it is useful to remember that the tangent at the origin reaches the sill at about two-thirds of the range.

The mud indicator variograms depicts two structural components (including the nugget effect, which accounts for 23 % of the overall variance) and were modelled by one spherical function (see figure 3). Table III shows the values of the model parameters, i.e. ranges and sills for the N-S direction and anisotropy ratio. This last value is the ratio between the ranges estimated for the N-S direction and for the orthogonal direction.

The results of the cross-validation show a good agreement of the structural model with the observed situation (table III). In fact, the mean error is close to 0, assuring a non-under or non-over estimation and, on the other hand, the mean reduced squared error is close to 1, meaning that the squared kriging errors are of the same magnitude of the calculated estimation variances.

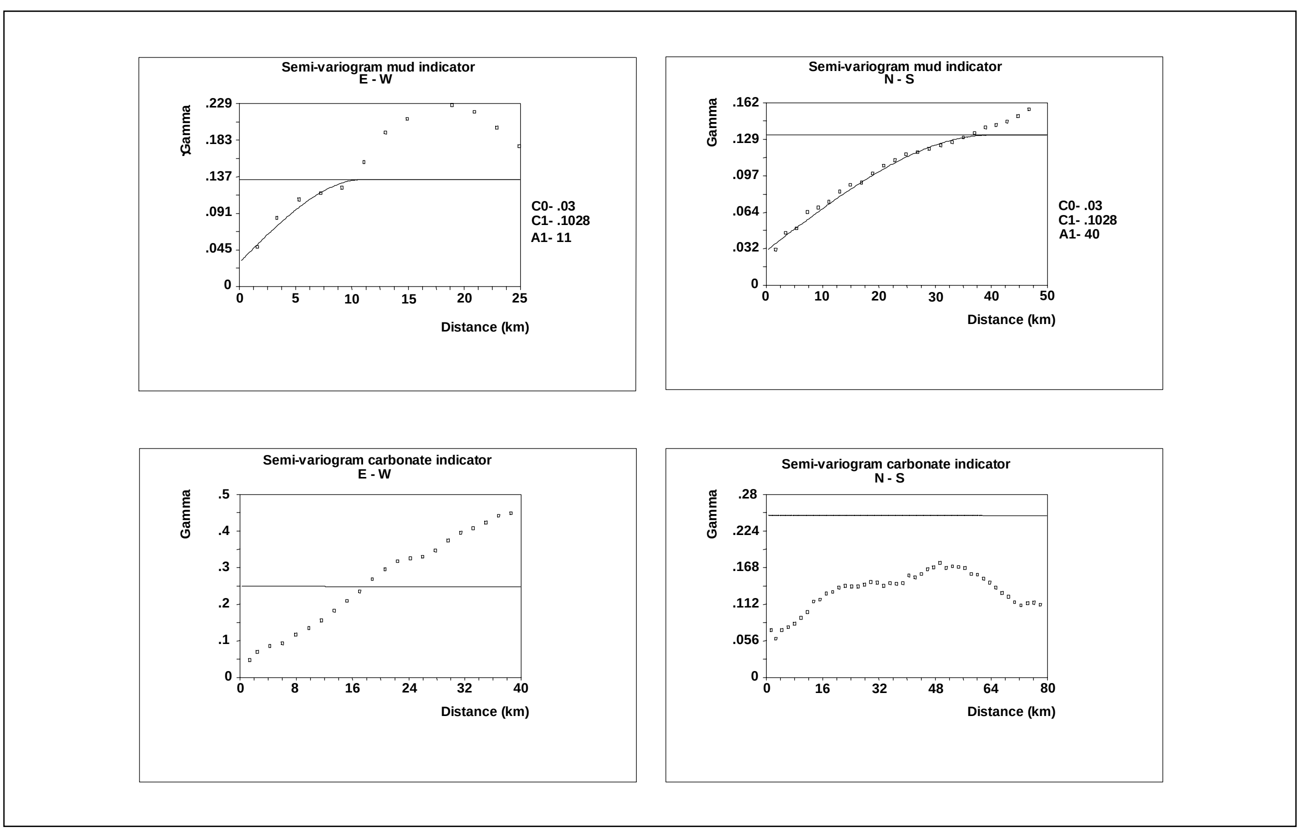

Figure 3. Experimental variograms and fitted models for the mud indicator and experimental variograms for the carbonate indicator. The straight line is the value of the *a priori* variance. The squares and the curves represent experimental and theoretical values, respectively

Table IV. Statistics of groups 1 to 4

	Group 1	Group 2	Group 3	Group 4
Mean	0.782	0.096	0.057	0.062
Median	1	0	0	0
Minimum	0	0	0	0
Maximum	1	1	1	1
Standard deviation	0.413	0.295	0.233	0.242
Coefficient of variation	52.813	307.292	408.772	390.323
Variance	0.171	0.087	0.054	0.058
Skewness	–1.365	2.742	3.810	3.628
Kurtosis	–0.135	5.529	12.539	11.181

The structural model obtained made it possible to use ordinary kriging to estimate the probability of the mud variable being greater than the selected threshold.

The estimation was done on a 0.5 km × 0.5 km block grid superimposed onto the study area, by using a maximum of 24 and a minimum of 8 neighbouring data.

The average of the kriged estimate is 0.199, very close to the average of the sample values (0.16).

The risk map is shown in figure 4. Given the codification of the mud content, the degree of exploitability decreases with the increase in the probabilities shown on this map.

Kriging Nickless groups

A similar geostatistical study was made for the data grouped following the Nickless classification.

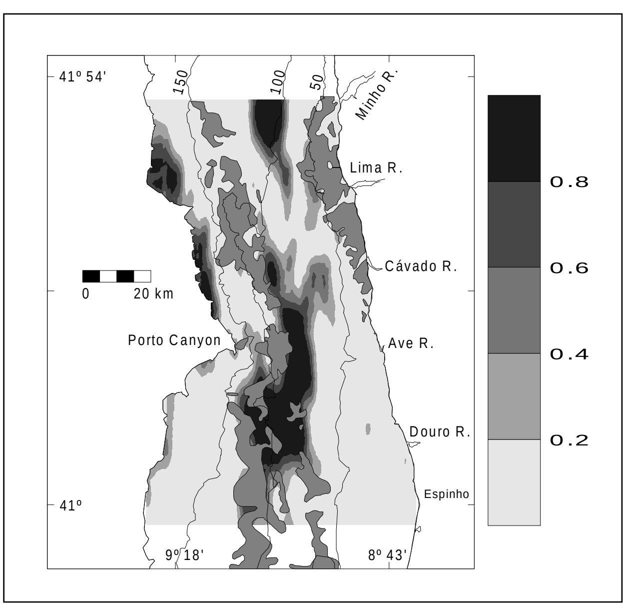

Figure 4. Distribution of the probability of mud contents higher than 40 %

Some statistics for these groups are shown in table IV. The greatest percentage corresponds to group 1 (78.2 %), and the smallest to group 3 (5.7 %).

For comparative purposes, only the results of the analysis for groups 3 and 4 are shown. These are the two groups in which the ratio of sand to gravel is lower, i.e. in which there is a relative enrichment in gravel. The corresponding variograms show that these variables are highly irregular. In fact, the nugget effects account for 74 % (group 3) and 52 % (group 4) of the total variances. The ranges in the north-south direction are important, and around 10 km and 18 km for groups 3 and 4, respectively. As already expected, an evident geometrical anisotropy was detected, with estimated anisotropy ratios of 5 (group 3) and 3 (group 4). Table V shows all these parameters.

The variograms were fitted with spherical models (figure 5) and cross-validated with the sample data. The analysis of the resulting mean error and mean reduced squared error show once again a good agreement with reality.

The same grid was used for kriging purposes. Averages of the kriged estimates in both cases are

Table V. Variogram parameters and validation tests for groups 3 and 4

	Group 3	Group 4
CO - nugget effect	0.04	0.03
C1 - sill	0.014	0.028
a1 (N-S) - range for the N-S direction (km)	10	18
a1 (E-W) - range for the E-W direction (km)	2	6
Anisotropy ratio	5	3
Estimated mean	0.0414	0.0526
Mean error	–0.0008	0.0001
Mean reduced squared error	1.038	1.16

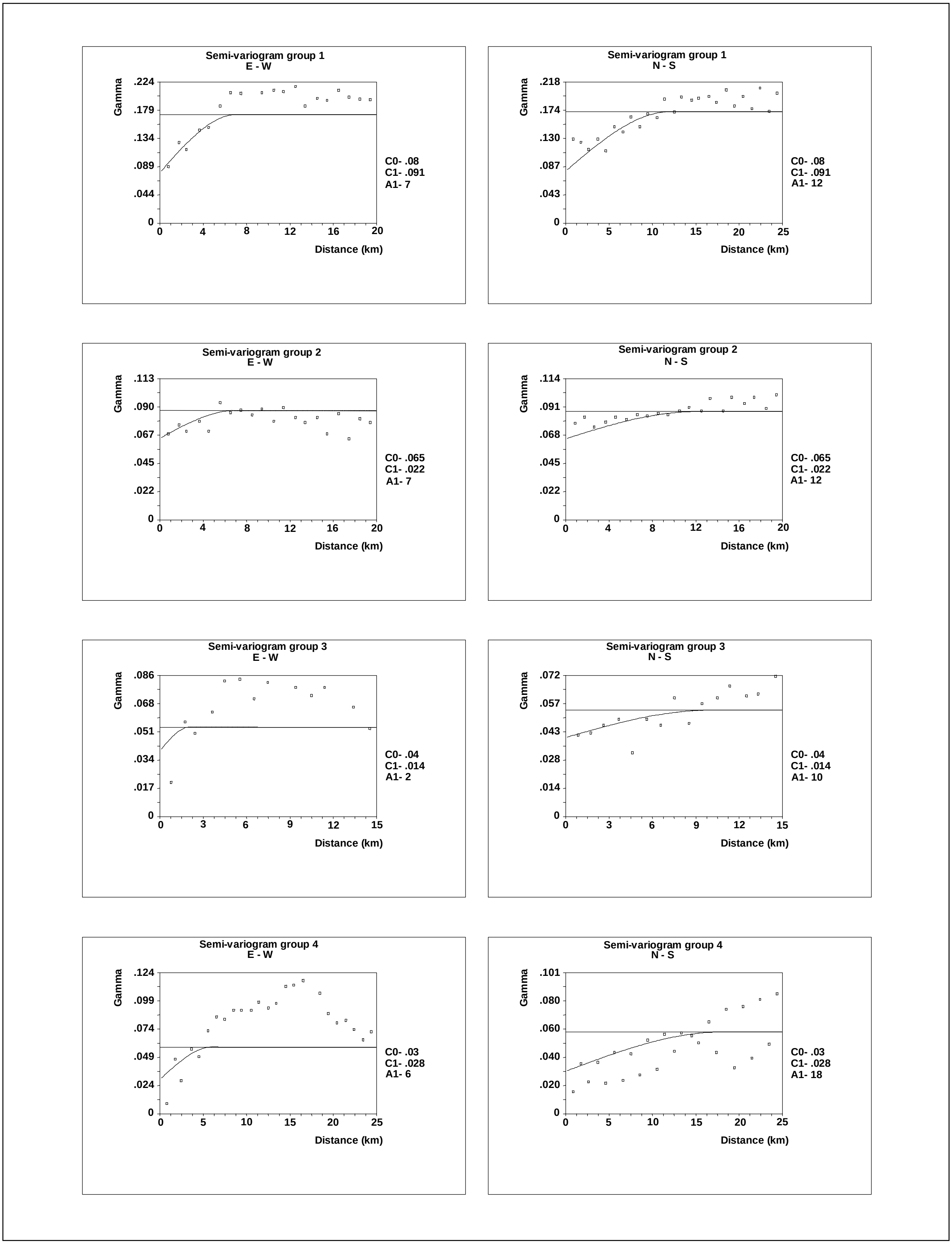

Figure 5. Experimental variograms and fitted models for the Nickless-based groups. The straight line is the value of the *a priori* variance. The squares and the curves represent experimental and theoretical values, respectively

very similar to the sample averages: 0.0414 for group 3 and 0.0526 for group 4.

The corresponding risk maps can be seen in figure 6. From the analysis of these maps, a relative enrichment in gravel should be expected in areas of higher probability of occurrence than groups 3 and 4.

DISCUSSION

The use of non-parametric geostatistics can be very useful in mapping aggregate deposits. The methodology outlined in the present study is based partly io the computation of probability distribution functions, making it possible to determine uncertainties related to each cut-off used. However, this preliminary approach requires further studies, namely by using cross-variography procedures and conditional probabilities.

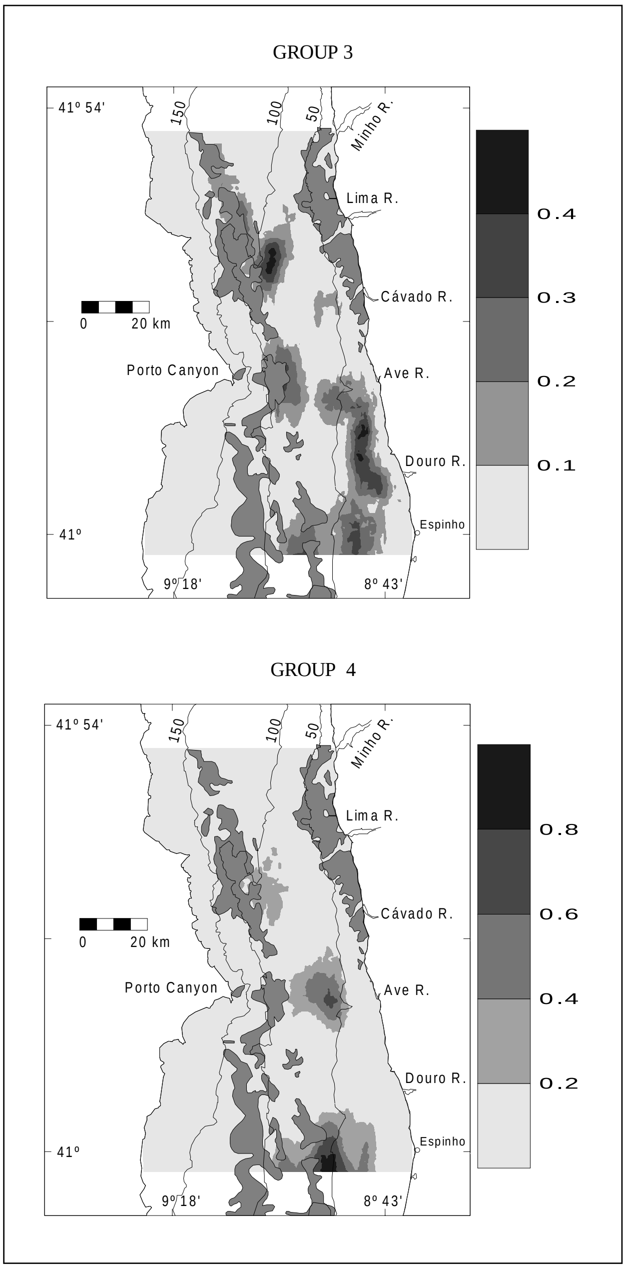

Figure 6. Probability distribution for groups 3 and 4

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