Review of deterministic geostatistical mapping methods in Croatian hydrocarbon reservoirs and advantages of such approach

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REVIEW

In the last decade, many geostatistic mapping methods have been done in the Croatian part of the Pannonian Basin System. Great number of those maps has shown clastic reservoirs of Miocene age, mostly containing sandstones. All of those mappings have been based on data collected from Sava and Drava depression. In some earlier studies, as well as here, it has been shown that geostatistic maps are more appropriate for display of the distribution of reservoir variables. Because of different calculation theory and results interpretation in general, for stochastical geostatistical methods, the advantages of deterministical geostatistical methods for mapping porosity and reservoir thickness are displayed (techniques of Ordinary Kriging and Cokriging).

Key words: determinism, geostatistics, Miocene, clastites, Sava Depression, Drava Depression

1. INTRODUCTION

Data sources, number of data and type of data are extremely important for reservoir mapping when using subsurface geological maps. Two of the most common sources are seismic measurements and well data, also referred commonly as „*hard data*" (especially well data), because according to practice they are most reliable. Reliability of maps can be estimated visually, based on the interpretation of the shapes of isolines (geological map shape assessment) or by numeric methods (most commonly cross-validation). Because of the different number of measurements that enter the estimation, data grouping in clusters, and interpolation on map borders, manual interpolation or mathematic equations can be used (computer algorithms). Referring to the algorithms, geostatistic and simpler mathematic methods of interpolation are discerned. Geostatistics has been studied as a set of methods, primarily defined as an advanced interpolation algorithms. The most significant advantage of geostatistics is the variogram function itself. There are several spatial interpolation methods by which one can calculate the weighting factor for a number of measured points in relation to their relative position to the location that is being analysed. However, kriging is the only method that takes into account the spatial anisotropy data estimated through focused variograms. Spatial anisotropy data indicates a strong dependence of the location, whose value is estimated on the basis of the measured points, with the direction of observation. Without that kind of variograme, it would be impossible to estimate the distribution of variables such as secondary porosity.

2. SOME INTERPOLATION METHODS

2.1. SIMPLER INTERPOLATION METHODS

Estimation or interpolation of variable values in places where not measured can be based on similar values of the observed primary variable (autocorrelation) but also the use of one or more secondary variables in the same area, under the condition that they are correlated with the primary variable (ref.[15]). There are three interpolation methods reported with simple mathematical models that have been widely used for defining the reservoir variables dispersion.

2.1.1. Inverse Distance Method

That method is based on the assumption that the value of the variable being evaluated affects mostly the nearest measured value. The impact of each point is inversely proportional to the distance between that point and the location of the estimated value. Number of points included in the estimation is determined by radius of a circle described around that location. The result depends on the value of the exponent distances, usually that value empirically chosen as 2, because then the simplest calculation method is used (ref.[1]). That method is often used as an alternative to geostatistical methods. It is very successful if the measured values are not strongly clustered because then the number of data is less than 15.

2.1.2. Nearest Neighbourhood Method

In that method each node of the grid gets assigned value of the nearest point (ref.[1]) what shows the zonal distribution of values. It is useful when there is a small number of data, or when there are relatively large areas where is no data, and they need to be mapped schematically. Although the map does not provide a reliable display, approximate distribution of the values of variables in the analysed area can be determinate through the zones.

2.1.3. Moving Average Method

When the moving average method is being used value is calculated for each grid point as the middle of the measured data within a specific area. Estimation point is at the centre of ellipsoid or a circle, and all the measured data within those areas are included in its assessment. There is a need to define the minimum amount of data that can be taken into account when averaging of the values is being done. If the number of data within an ellipsoid or circle is below the threshold, the point value will not be estimated.[1]

2.2. GEOSTATISTICAL INTERPOLATION METHODS

2.2.1. Variogram analysis

Variograme is a basic geostatistical tool. It is used to determine the spatial dependences, and thus to better define the interconnection point data that has to be jointly mapped. The result of the variogram creation is an experimental variogram, which is further approximated by a theoretical model. Such a model is an input for kriging method by which is being interpolated, as it is considered to be, the best maps (Ref. [11]). Variogram equation can be simplified by eliminating the number 2 from the denominator and the resulting function 2γ is then called semivariograms (Expression 1):

$$2\gamma(h)=\frac{1}{N(h)}\cdot\sum_{n=1}^{N(h)}\left[z_n-z_{n+h}\right]^2 \tag{1}$$

where are:

$2\gamma(h)$ variogram value;

$N(h)$ number of data pairs compared with distance 'h';

z_n variable value on location 'n';

z_{n+h} variable vale on a location on distance 'h' from observed location 'n'.

2.2.2. Kriging

Kriging method is the most known geostatistical procedure or algorithm (e.g.[13, 14]). It is preceded by the determination of spatial dependence, i.e. variogram analysis. Kriging is considered an advanced method for estimating the value of a regionalized variable at selected points of the grid. Regionalized variable is often a random variable, since the grid of point samples for any variable can never be completely safe from a representative sample of a volume (e.g. rock) that is analysed. Kriging estimation can be described by a simple linear expression (Expression 2), which is later announced as a matrix equation. Variable values at a selected location (Z_k) are being estimated based on existing data (z_i). Corresponding weight coefficient (λ) is being associated with the all data, which describes the influence of the measured data in the value of the variable to be estimated (2):

$$Z_k=\sum_{i=1}^{n}\lambda_i\times z_i \tag{2}$$

Kriging weighting coefficients are being calculated by system of linear equations (described for example in refs.[3, 5, 7, 11]), and mainly depend on the distance from the data point to be estimated and their distribution. There are different Kriging techniques such as simple kriging, ordinary kriging, indicator kriging, universal kriging and disjunctive kriging. For simple kriging, as basic techniques, matrix equation written in full form (Expression 3) is:

$$\begin{pmatrix}\gamma(Z_1-Z_1) & \gamma(Z_1-Z_2)\ldots & \gamma(Z_1-Z_n)\\ \gamma(Z_2-Z_1) & \gamma(Z_2-Z_2)\ldots & \gamma(Z_1-Z_n)\\ \gamma(Z_n-Z_1) & \gamma(Z_n-Z_2)\ldots & \gamma(Z_1-Z_n)\end{pmatrix}\times\begin{pmatrix}\lambda_1\\ \lambda_2\\ \lambda_n\end{pmatrix}=\begin{matrix}\gamma(X_1-X)\\ \gamma(X_2-X)\\ \gamma(X_n-X)\end{matrix} \tag{3}$$

where are:

γ variogram value on distance between two points;

λ weighting coefficient for location 'i';

$Z_1 \ldots Z_n$ measured values in points.

All other kriging techniques have some "restriction factors" (constraint) added. That has fully complied with the condition that they can be called the best linear unbiased estimator (abbr. BLUE). However, when Simple Kriging is used the requirement that the estimation is unbiased is not fulfilled.

2.3. COKRIGING

Cokriging is an upgrade of kriging methods. Kriging uses spatial correlation on a set of control points. It also takes into account the correlation between the primary and the dependent variables, secondary ones. It is considered that secondary variable is sampled denser than the primary and at the same time in a dependence on the primary variable. A number of secondary variables data is the main reason for its introduction and computation in correlation with primary variable (ref.[17]). Significance or strength to do the primary and secondary variables are usually calculated by using the correlation, either linear (Pearson correlation coefficient) or nonlinear correlation coefficient (Spearman's correlation coefficient). The Pearson correlation coefficient is used in cases where the variables of the model observed are in a linear relationship and a continuous normal distribution. However, such cases in the analysis of hydrocarbon reservoirs are rare, since relations between the reservoir variables, if they exist, are usually nonlinear. That is why every Spearman correlation coefficient is used in the transformation which translates to a linear relationship (e.g., relationship between seismic attributes and well geology data of hydrocarbon reservoirs) by determination the rankings of those data. When the ranking order is done, the minimum value of each variable is assigned a rank of 1, the next largest rank 2 and so on until the last which is assigned the highest rank. Specificity of that method is the existence of so-called Collocated Cokriging, or the formation of two groups of the same type of matrix equations for the two dependent variables (Expression 4), i.e. one group for the primary and secondary variables (e.g., ref.[12]).

$$Z_C=\sum_{i=1}^{n}\lambda_i\cdot z_i+\sum_{i=1}^{n}x_j\cdot s_j \tag{4}$$

where are:

Z_c value estimated by cokriging;

x_j weighting coefficient of the secondary variable for each location 'j';

s_j known value of the secondary variable, control point (hard-data).

2.4. CROSS-VALIDATION METHOD

Cross-validation is a numerical error estimation method, i.e. simple numerical method used to verify the performance assessment of a particular interpolation method or technique. It is based on the neglect of one existing value in each location, and calculating new at that same location. The procedure is repeated sequentially or randomly for each measured point. The value of the new appraisal, in the previously measured point, is based on an assessment of the selected method (or technique) from any remaining measured values. At the end squared difference from all existing sites is summed and the final result of cross-validation is obtained (Expression 5). It is also called the mean square estimation error (MSE). If the same set of input data is used in different methods of assessment then the lower values obtained by cross-validation mean a better method for the particular case (ref.[2]).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(real\ measured\ value - estimated\ value\right)^2 \qquad (5)$$

where are:

MSE mean square error;

real measured value onto location *'i'* (from totally *'n'*);

estimated value for location *'i'* by interpolation algorithm.

3. DETERMINISTICAL GEOSTATISTICAL MAPS PUBLISHED UNTILL TODAY FOR CROATIAN HYDROCARBON RESERVOIR

Geostatistical deterministical methods, kriging and cokriging, are often applied in the last ten years in the Sava and Drava Depressions.

3.1. MAPS INTERPOLATED IN THE SAVA DEPRESSION

In the Sava Depression, for the Ivanić and Kloštar Fields, highly reliable data interpolation by kriging and cokriging has been achieved because there were available relatively large dataset. (refs.[1, 12, 19]).

3.1.1. The Ivanić Field

The Ivanić Field is located in the northwestern part of the Sava Depression. Reservoirs are part of the Miocene sedimentary systems with dominant members presented by sandstone and marl. Mapped reservoir age is Upper Pannonian. The chosen variable for mapping using geostatistics is porosity. Porosity maps interpolated by kriging (Figure 1) displays the more precise results compared to the porosity map obtained by other methods. Given the similar lithological composition and structure of other deposits of the same age in the Sava Depression, it was found that the use of Ordinary Kriging for mapping porosity (with sufficient data) throughout the depression always gave the best maps of that variable.

3.1.2. The Kloštar Field

The Kloštar Field is also situated in the northwestern part of the Sava Depression and represents one of the largest fields, which produces more than 50 years. The largest reservoirs are sandstones of the Upper

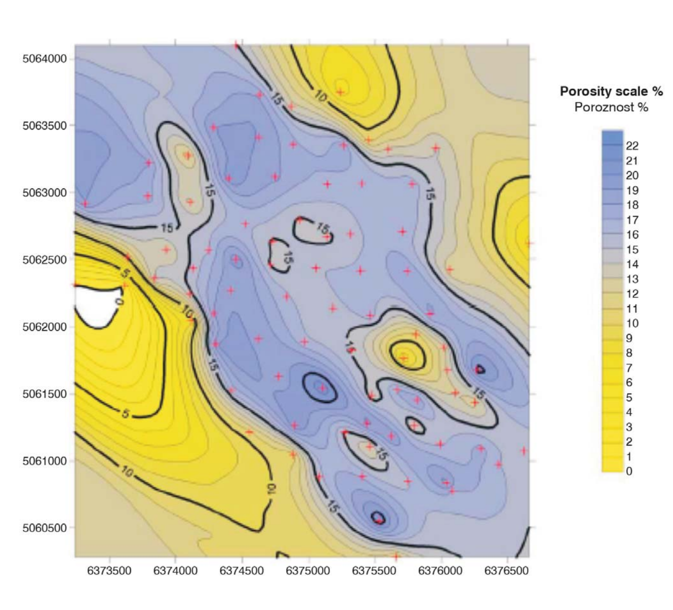

Fig. 1. Map porosity interpolated by kriging with anisotropic variogram model, the Ivanić Field (ref.[12])

Sl. 1. Karta poroznosti interpolirana krigingom s anizotropnim variogramskim modelom, polje Ivanić (lit. [12])

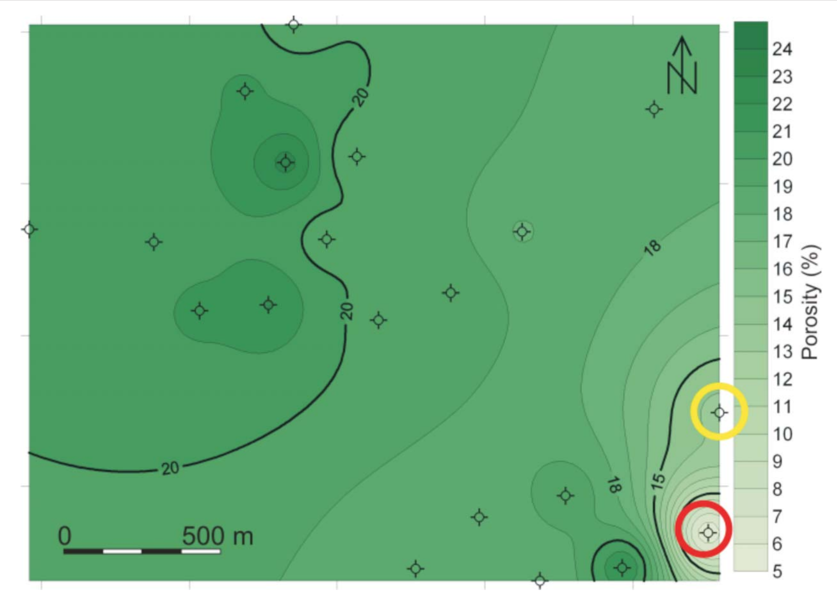

Fig. 2. Map porosity interpolated by kriging with isotropic variogram model, the Kloštar Field (ref.[1]). Yellow circle shows on the most under-estimated, and red on the most over-estimated data.

Sl. 2. Karta poroznosti interpolirana krigingom s izotropnim variogramskim modelom, polje Kloštar (lit. [1]). Žuti krug označava najpodcjenjeniji, a crveni najprecjenjeniji podatak.

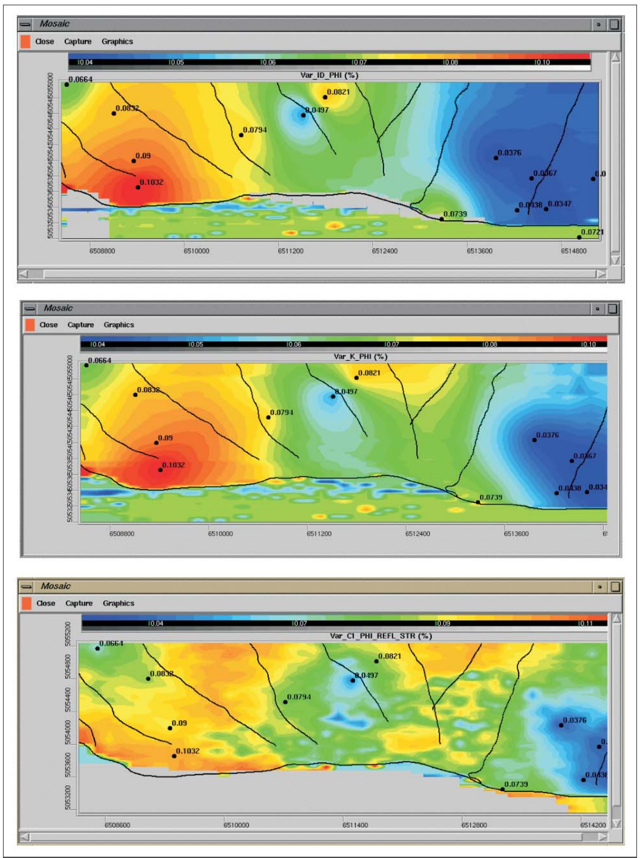

Fig. 3. Distribution of porosity calculated by inverse distance (above), ordinary kriging (centre) and collocated cokriging (below) in the Badenian breccias, the Beničanci Field (ref.[15])

Sl. 3. Raspodjela poroznosti izračunata metodama inverzne udaljenosti (gore), običnim krigingom (u sredini) i kolociranim kokrigingom (dolje) u badenskim brečama, polje Beničanci (lit. [15])

Pannonian and Lower Pontian. Analyses in that field were focused on the largest oil reservoir operationally called "T", of the Lower Pontian age. Mapping was done on a set of 25 well's averaged porosity values. They were mapped by Ordinary (Figure 2) and Indicator Kriging. Again, the kriging method was evaluated as the best method for mapping reservoir variables (porosity, thickness and depth of the reservoir).

3.2. MAPS INTERPOLATED IN THE DRAVA DEPRESSION

In the Drava Depression the Stari Gradac-Barcs Nyugat, Molve and Beničanci Fields were analysed. In those fields kriging and cokriging were applied equally.

3.2.1. The Beničanci Field

The field consists of coarse clastics (mainly breccia) of Badenian age. Cokriging and Ordinary Kriging were used to interpolate porosity. From several seismic attributes reflection strength was chosen as a secondary source of information in the cokriging interpolation porosity[16]. By use of secondary information more reliable estimation of porosity distribution in the reservoir was obtained. The resulting solution (Figure 3) shows that Collocated Cokriging gave significantly heterogeneous (and hence realistic) picture than the porosity maps made with ordinary kriging and inverse distance[10, 15]. Due to the relatively small number of inputs (14) on the map with use of cokriging is still relatively easier to identify the location of wells, but the effect of the concentric lines of equal values in their surroundings is not longer markedly accentuated. Also in the area between the wells was highlighted the feature of seismic attributes and heterogeneity, which is the characteristic of that reservoir. Accuracy of the method was tested with cross-validation equation, and the result of cokriging was the lowest compared to the other two cards (cokriging <inverse distance <kriging = 2.19 <2.78 <2.97).

3.2.2. The Stari Gradac-Barcs Nyugat Field

The Stari Gradac-Barcs Nyugat Field has heterogeneous reservoirs whose lithological composition comprises clastic rocks, dolomite, quartzites and metavolcanites. Age reservoir extends from the Ordovician to Badenian, and the results of mapping the porosity of the reservoir, which is the Lower Triassic are displayed here (Figure 4). Method used for mapping was Ordinary kriging. The accuracy of the results is determined by geological evaluations isoline porosity forms and results of cross-validation.

3.2.3. The Molve Field

The Molve Field is marked with geologically very heterogeneous reservoirs whose lithological composition varies from clastic rocks (breccias), dolomite, quartzites (metamorphosed sandstones) and metavolcanites. Reservoir age ranges from the Ordovician, then Lower and Upper Triassic, to Badenian, with frequent unconformities. Therefore it is divided into four lithofacies. Due to the heterogeneity of the reservoir it was very difficult to correlate seismic attributes and reservoir parameters in each lithofacies individually so that was made in only one of them (Figure 5). Porosity within the Lower Triassic

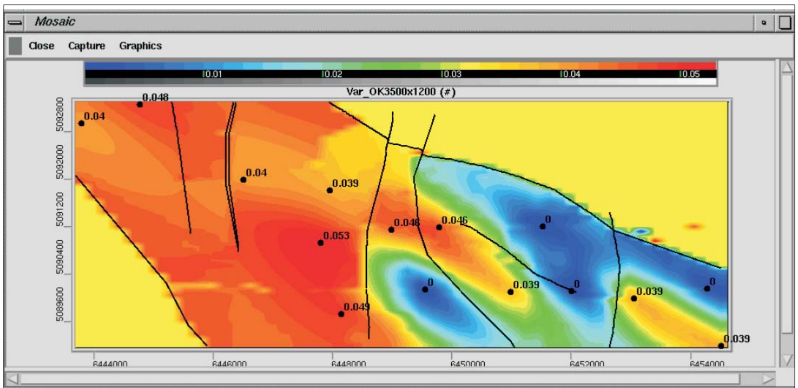

Fig. 4. Distribution of porosity, Ordinary Kriging ellipsoid 3 500x1 200, Stari Gradac-Barcs Nyugat - lithofacies I, Badenian breccia (ref.[15])

Sl. 4. Raspodjela poroznosti, obični kriging elipsoid 3 500x1 200, Stari Gradac-Barcs Nyugat - litofacijes I, tj. badenske breče (lit. [15])

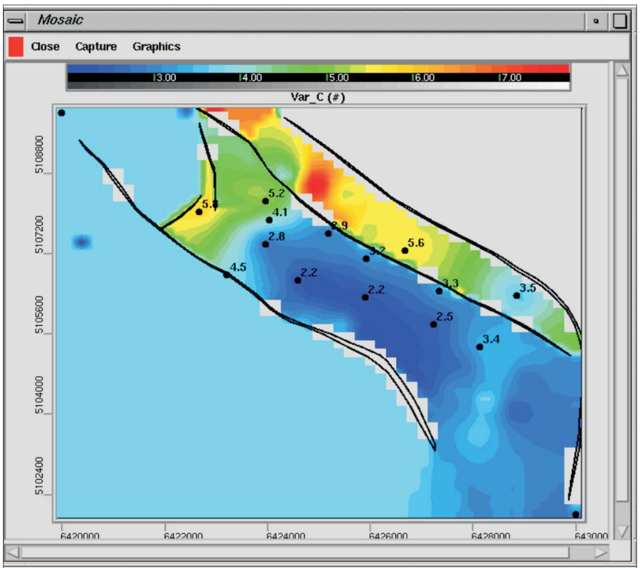

Fig. 5. **The distribution of porosity, Ordinary Cokriging, Molve, lithofacies III, i.e. Lower Triassic clastics (ref.[17])**

Sl. 5. Raspodjela poroznosti, obični kokriging, Molve, litofacije III, tj. donjotrijaski klastiti (lit. [17])

clastics was mapped using cokriging, and seismic reflection strength attribute was used as a secondary figure. In other lithofacies Ordinary Kriging was used.

4. TABULAR REVIEW OF PREVIOUS RESULTS

In Table 1 is presented a brief overview of depressions and fields within those depressions, their age, lithology, and deterministical geostatistical methods with whom porosity mapping was done. Fields within the Sava Depression are Ivanić and Kloštar and they contain the Upper Miocene sandstone reservoirs. In the Drava Depression were analysed Stari Gradac-Barcs Nyugat, Molve and Beničanci Fields. Stari Gradac-Barcs Nyugat and Molve reservoir age is ranging from Palaeozoic to Cenozoic, and in Beničanci only Cenozoic. In the Stari Gradac-Barcs Nyugat Field by geostatistically was mapped only one part of reservoir located in the Badenian clastics, whereas in the Molve lithofacies were mapped all reservoir lithofacies, from Palaeozoic to Cenozoic eras, i.e. metavolcanites, quartzites, dolomites and breccias. The Beničanci Field reservoir age is Badenian, and lithology those are breccias.

5. EXAMPLE OF INVERSE DISTANCE VS. KRIGING MAPS FOR BED THICKNESS AND ADVANTAGES OF GEOSTATISTICS

In order to make mapping, which would also be a model and example of the use of deterministical geostatistical interpolation methods compared with simpler algorithms, a set of point data was generated. They are interpolated in the SURFER 8 program. The set contains 25 observations that by their characteristics are: a) geographically belong to the northwestern part of the Sava Depression, b) contain the point information on the bed thickness within the maximum and minimum values that were identified in sandstone reservoirs of the Sava Depression.

5.1. Bed thickness map interpolated by Inverse Distance

Bed thickness map was made based on the input data by Inverse Distance Method (Figure 6). The isotropic radius search data within the grid was assumed. Distance exponent value is set to 2, because it was the most commonly used value of that method in most applications in geosciences. By method of cross-validation squared estimation error (MSE) was calculated and the most under-estimated and over-estimated data were given, isolated during cross-validation.

Cross-validation results are:

a) Square error of the variable "thickness" 4020.68;

b) The root mean square error of the variable "thickness" 63.41;

c) The most underestimated data is at X = 6376000, Y = 5068000 where the measured value of "thickness" Z = 90, and the estimated value of "thickness" E = 46.30;

d) The most overestimated data is at X = 6376050, Y = 5068050, which is measured by the value of "thickness" Z = 45, and the estimated value of "thickness" E = 85.01.

5.2. Bed thickness map interpolated by Ordinary Kriging

Based on the input data (values in X, Y, Z axes) bed thickness map was made by kriging method (Figure 7). The

Table 1. Table view of age, lithology and used geostatistical methods for reservoirs porosity deterministical mapping [20]

DEPRESSION NAME	FIELD	RESERVOIR AGE	LITHOLOGY	METHOD
SAVA	Ivanić	Upper Pannonian to Lower Pontian	sandstone	Ordinary kriging
	Kloštar	Palaeozoic to Lower Pontian	sandstone	Ordinary and Indicator Kriging
DRAVA	Stari Gradac-Barcs Nyugat	Badenian	breccias	Ordinary Kriging
	Molve (lithofacies I)	Badenian	breccias	Ordinary Kriging
	Molve (lithofacies II)	Upper Triassic	dolomites (fractured)	Ordinary Kriging
	Molve (lithofacies III)	Lower Triassic	quartzite (fractured)	Ordinary Cokriging
	Molve (lithofacies IV)	Ordovician	metavolcanites (fractured)	Ordinary Cokriging
	Beničanci	Badenian	breccias	Ordinary Kriging, Ordinary Cokriging

simplest linear model variogram with slope 1 was made. Mean square estimation error (MSE) was calculated by using the cross-validation, and again most underestimated and most overestimated data while performing cross-validation.

Cross-validation results are:

a) MSE of the variable "thickness" is 3980.83;

b) The root mean square error of the variable "thickness" 63.09;

c) the most underestimated data X = 6376000, Y = 5068000 where the measured value of "thickness" Z = 90, and the estimated value of "thickness" E = 46.01;

d) the most overestimated data is at X = 6376050, Y = 5068050, where the measured value of "thickness" Z = 45, and the estimated value of "thickness" E = 83.64.

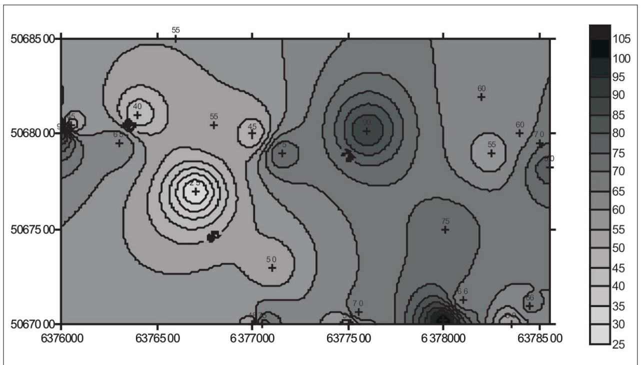

Fig. 6. Map of the thickness distributions made by Inverse Distance (legend shows metres)
Sl. 6. Karta razdiobe debljina napravljena metodom inverzne udaljenosti (legenda predstavlja metre)

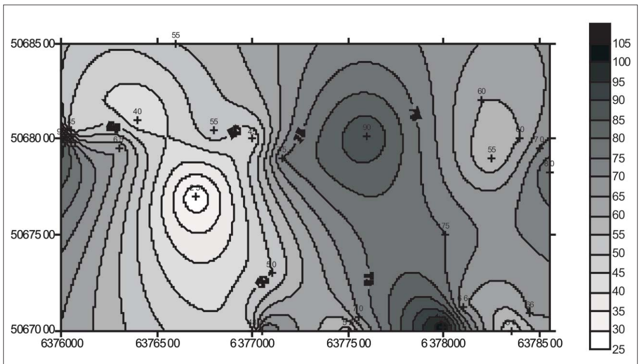

Fig. 7. Map of the thickness distributions made by kriging method (legend shows metres)
Sl. 7. Karta razdiobe debljina napravljena metodom kriginga (legenda prikazuje metre)

6. RESULTS REVIEW AND CONCLUSION

An example of the three most common, mathematically simpler, mapping methods (methods of Inverse Distance, Nearest Neighbourhoods, and Moving Average) was given in the work. Porosity map obtained by Inverse Distance was proven to be most successful. That method is also the most common alternative to the application of geostatistics, especially when there are too few input parameters for the variogram analysis. For the use of geostatistics, previously published results from the Sava and Drava Depressions are showed. For those mapped fields reservoirs age ranged from Palaeozoic to Cenozoic (Upper Miocene), and lithological composition varied from metavolcanite, quartzite, dolomite, breccia to sandstone. The Sava Depression reservoirs were characterized by homogeneous lithological composition (sandstone) as compared to the Drava Depression reservoirs (clastics and metamorphites magmatites). Similarly, for the Sava Depression was also easier to recommend a mapping method as the most appropriate (Ordinary Kriging). Due to the heterogeneity of the reservoir lithology in the Drava Depression, particularly in the Molve Field, the importance of application of seismic attributes as secondary variables was highlighted, of course, where a significant correlation with the primary could have been established.

In the second part of that work two thickness maps were made in SURFER 8 on an imaginary set of 25 data, which, by the values of coordinates (X, Y), and the approximate thickness of the reservoir, belongs to the Sava Depression. For creation of those maps methods of Inverse Distance and kriging were used. On the visual assessment basis maps obtained immediately implies that in that case the kriging method was appropriate because it was showing a particular trend (giving the same value isoline along north-south line, and the downward trend in thickness towards the west) in the distribution of thickness, which could not be clearly seen on map obtained by inverse distance. Comparing the results of cross-validation is also evident that the kriging method had a lower value of the mean square error or regionally better estimates the required variables. On the basis of examples, one can conclude that the mapping sets of fifteen and more information is almost always better to use a geostatistical interpolation methods in order to obtain more precise insights into structural and stratigraphic forms on the subsurface geological maps and into geological variables of the hydrocarbon reservoirs.

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ACKNOWLEDGMENTS

The presented results, data and synthesis are made as part of a research project entitled "Stratigraphical and geomathematical research of petroleum geological systems in Croatia" (project no. 195-1951293-0237), which is financed by the Ministry of Science, Education and Sports of the Republic of Croatia.

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