History of geostatistical analyses performed in the Croatian part of the Pannonian Basin System

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REVIEW

Development of geostatistics, applied in the analyses of the hydrocarbon reservoir in Croatia, can be followed through four main stages. The first included variogram analysis in one dimension mostly performed in the area of the Bjelovar Subdepression. The second encompassed Simple and Ordinary Kriging techniques for porosity mapping, the first cokriging map and calculation of mean square error as validation tool for maps. It was followed by work on application of "jack-knifing" sampling technique and making algorithm for Lagrange multiplicator estimation. The last stage was period of work with Indicator Kriging for lithofacies mapping, and using of simulation (Gaussian and Indicator) mostly for estimation of zonal uncertainty. The selection of reservoir variables applicable for geostatistical mapping mostly included porosity (variable with theoretically normal distribution) and thickness (with normal distribution in special cases). Geostatistical maps are the best visual outcomes for reservoir properties when 20 or more hard data is available. This limit often can be reduced on datasets of 10 points when secondary variable is available.

Key words: geostatistics, kriging, cokriging, simulations, Pannonian Basin System, Neogene, Croatia

1. INTRODUCTION IN SET OF GEOSTATISTICAL ANALYSES PERFORMED IN THE CROATIAN PART (CPBS) OF PANNONIAN BASIN SYSTEM (PBS)

The different geomathematical, mostly geostatistical analyses, had been performed in two largest Croatian depressions, i.e. in the Sava and Drava Depressions. The most of the geostatistical calculations had been based on 10-25 data points, also including the descriptive statistical analyses. The analysed localities in the Sava Depression were the Kloštar, Ivanić and Okoli Fields, and, in the Drava Depression, the Stari Gradac-Barcs Nyugat, Molve, Beničanci and Galovac-Pavljani (Figure 1.1). Particularly, the entire Bjelovar Subdepression had been covered with 1D vertical variograms of porosity calculated in the numerous exploration and production wells.

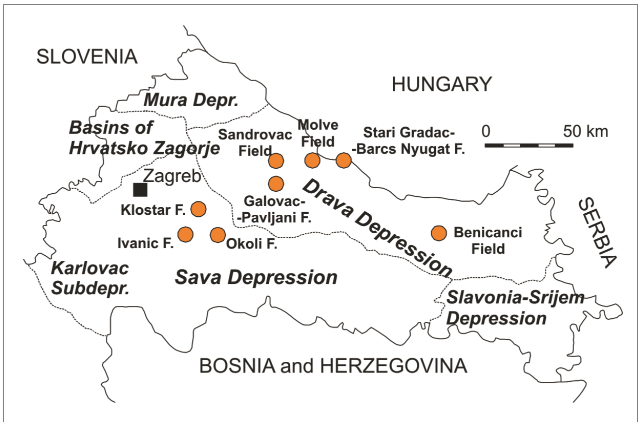

Fig. 1.1. Croatian part of the Pannonian Basin System and locations with the results of geostatistical analyses presented in this review

Sl. 1.1. Hrvatski dio Panonskoga bazenskoga sustava te lokacije za koje su rezultati geostatističkih analiza prikazani u ovome pregledu

In the Sava Depression, the Kloštar Field is the most comprehensive geostatistical (and geomathematical) analysed fields. The results are published in numerous references.[1, 2, 7, 12, 13, 14, 17] The results obtained in the Ivanić Field are given in one reference.[4]

In the Drava Depression the geostatistical analyses had been performed for Beničanci in the eastern part and Stari Gradac-Barcs Nyugat and Molve Fields in the western. The results had been published into numerous references.[3, 5, 8, 9, 10, 11, 15, 16]

2. THE FIRST PERIOD OF EARLY RESEARCHING UNTIL 2003

The very first variogram sets in CPBS had been made between 2002 and 2003 and included the set of vertical variograms for porosity measurements collected in the Bjelovar Subdepression (Figure 2.1).

The data had been collected from Badenian, Pannonian and Pontian sediments. In the Badenian the largest porosity and variogram ranges are obtained in the Galovac-Pavljani field (Figure 2.2), where values average are respectively 7.99% and 0.64 m. Pannonian sandstones (Figure 2.3) are characterised with significant total thickness of poor permeable or impermeable sediments. It is why for relatively high average porosity (23.3%), low average range had been calculated (0.57 m). Younger Lower Pontian sandstones (Pepelana Sandstones) have generally more uniform lithology than older

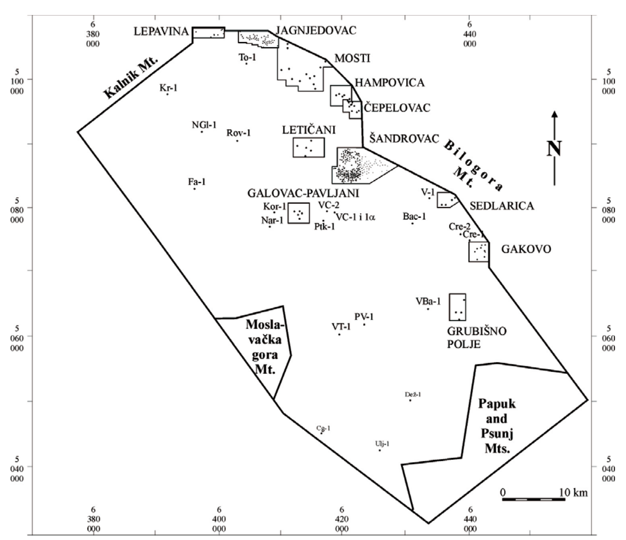

Fig. 2.1. Location map of the Bjelovar Subdepression (from[6])
Sl. 2.1. Položajna karta Bjelovarske subdepresije (iz[6])

Lower Pontian sandstones (Poljana Sandstones). The most favourable reservoir properties are described in the Šandrovac field, where are documented generally the highest values of 29.99% and 0.95 m (Figure 2.4).

3. THE SECOND PERIOD OF INTERPOLATION ALGORITHMS TESTING (2003-2008)

The very first time variograms that were applied for geostatistical interpolations in the CPBS and related maps was done in 2003 (ref. [11]), in the Drava Depression comparing results of Inverse Distance Weighting, Ordinary Kriging and Collocated Cokriging method/techniques. The accuracy of particular approach is determined by the geological evaluation of the isoporosity line shapes and calculation of the mean square error (MSE). As the most appropriate map for porosity distribution is calculated used Collocated Cokriging maps (Figures 3.1).

The similar comparison had been done in the Lower Pontian reservoir of the Kloštar Field, using Ordinary Kriging, Moving Average, Inverse Distance Weighting and Nearest Neighbour methods/techniques. MSE value obtained by Ordinary Kriging (Figure 3.2) was 366.93, Moving Average 369.26, Inverse Distance Weighting 371.97 and Nearest Neighbour 389.00. The relatively low differences resulted from relatively small input dataset, which can not reflect the true advantage of using exact interpolators, especially kriging.

The most comprehensive interpolation, regarding available point data, had been performed in the Late Pannonian Ivanić Field sandstone reservoir. There were collected 82 point data of porosity with average porosity 15.13% and variance 16.41 (ref. [4]). The obtained and approximated variograms are given in Figures 3.3 and 3.4. The porosity map had been interpolated using Ordinary Kriging technique, clearly outlining the strike of the main depositional channel filled by medium and fine-grained sand during Upper Pannonian stage. The direction of channel follows the isoporosity lines with values 15% and larger (Figure 3.5).

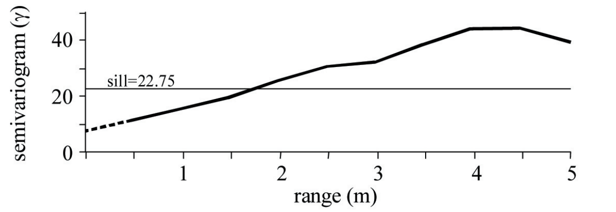

Fig. 2.2. Experimental variogram in the Galovac-Pavljani Field Badenian reservoir (from[6])
Sl. 2.2. Eksperimentalni variogram u polju Galovac-Pavljani izračunati u badenskom ležištu (iz[6])

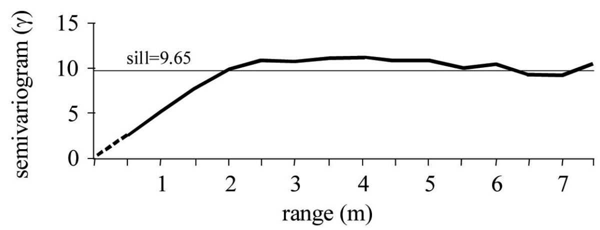

Fig. 2.3. Experimental variogram in the Galovac-Pavljani Field Late Pannonian reservoir (from[6])
Sl. 2.3. Eksperimentalni variogram u polju Galovac-Pavljani izračunati u gornjopanonskom ležištu (iz[6])

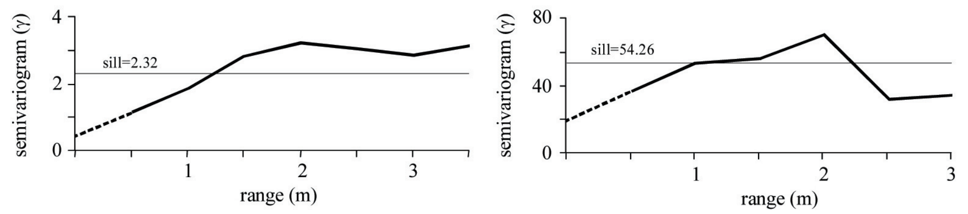

Fig. 2.4. Experimental variograms in the Šandrovac Field Early Pontian reservoir (from[6])
Sl. 2.4. Eksperimentalni variogram u polju Šandrovac izračunati u donjopontskom ležištu (iz[6])

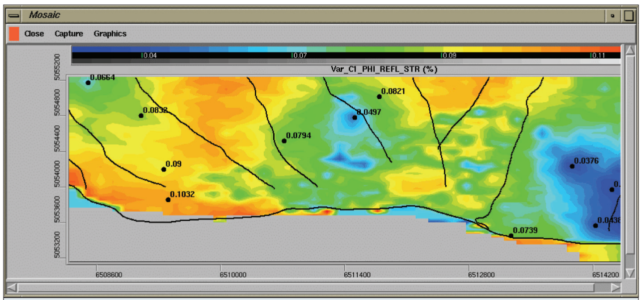

Fig. 3.1. Porosity distribution in the Beničanci Field Badenian reservoir interpolated by Collocated Cokriging. Mean square error of estimation is 2.185 (from[10, 11])

Sl. 3.1. Razdioba poroznosti u polju Beničanci unutar badenskog ležišta interpolirana kolociranim kokrigingom. Srednja kvadratna pogrješka procjene je 2,185 (iz[10, 11]).

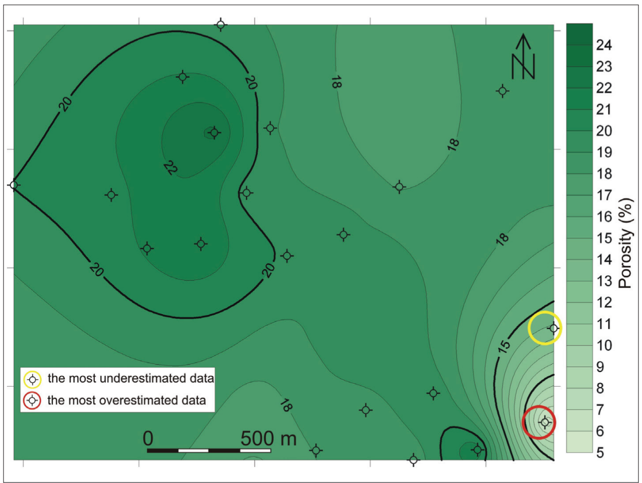

Fig. 3.2. Porosity distribution in the Kloštar Field Late Pannonian reservoir interpolated by Ordinary Kriging. Mean square error of estimation is 366.93 (from[2]).

Sl. 3.2. Karta poroznosti u polju Kloštar u gornjopanonskom ležištu interpolirana običnim krigingom. Srednja kvadratna pogrješka procjene je 366.93 (iz[2]).

4. THE THIRD PERIOD OF IMPROVEMENTS IN GEOSTATISTICAL THEORY APPLIED IN THE CPBS (2008-2009)

There are two theoretical papers representing the main improvements in theoretical geostatistical work done in ref.[9] published application of jack-knifing algorithm on the small dataset (up to 15 point data) in the CPBS. Later, Malvić and Balić[7] analysed the principle of calculation of Lagrange coefficient into Ordinary Kriging equations, and proposed algorithm for its calculation.

4.1. Jack-knifing methodology applied onto small porosity dataset in the CPBS

Variogram analysis is a standard tool in the spatial analysis of hydrocarbon reservoir parameters, which include several sources of uncertainties. The first reason is the imperfection of measuring devices. The second (and more frequent) is the result of a (too) small number of wells and their irregular pattern, insufficient for reliable analysis of spatial dependence. Such source of uncertainty can be empirically quantified using a method called 'jack-knifing', example of which is given in ref.[9] for the Stari Gradac-Barcs Nyugat Field. In that case omnidirectional experimental semivariogram has been calculated for data derived from clastics lithofacies of Badenian age, approximated by a spherical model. Set of "n" 'jack-knifed' experimental semivariograms were calculated. Based on this set, error bars (Figure 4.1) can be graphically constructed around each point of the experimental semivariogram.

It made possible to observe a particular well's name as characterised by the highest influence on the error bars. There such locations are spatially outlined well zones in the Badenian reservoir of the Stari Gradac-Barcs Nyugat Field where the lack of data has the most influence (Figure 4.2). Those are zones that lead to the highest estimation error using the spatial model.

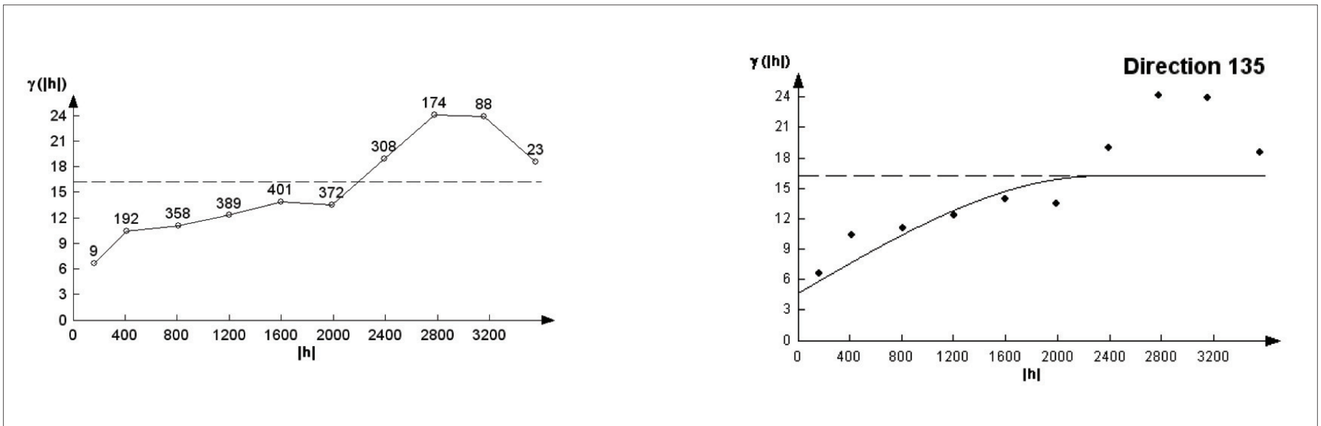

Fig. 3.3. Variograms of the primary axis of the Late Pannonian reservoir in the Ivanić Field (from[4])

Sl. 3.3. Variogrami na primarnoj osi za gornjopanonsko ležište u polju Ivanić (iz[4])

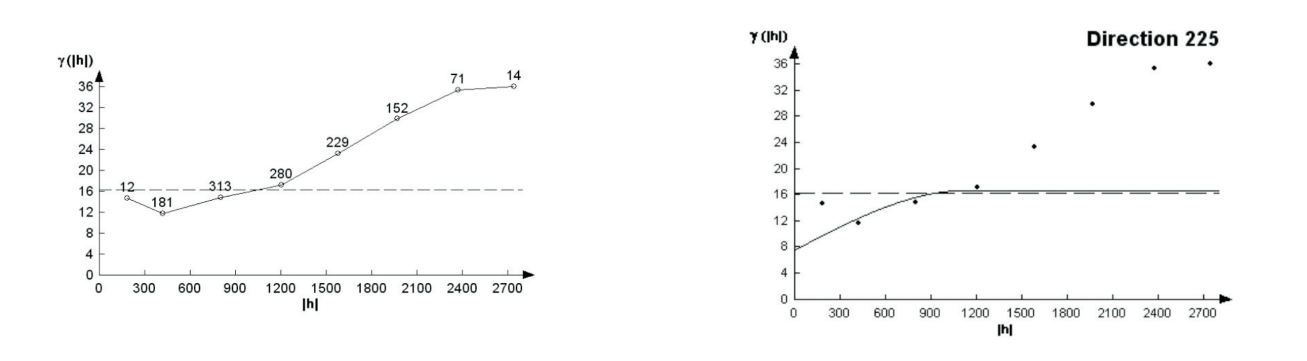

Fig. 3.4. Variograms of the secondary axis of the Late Pannonian reservoir in the Ivanić Field (from[4])
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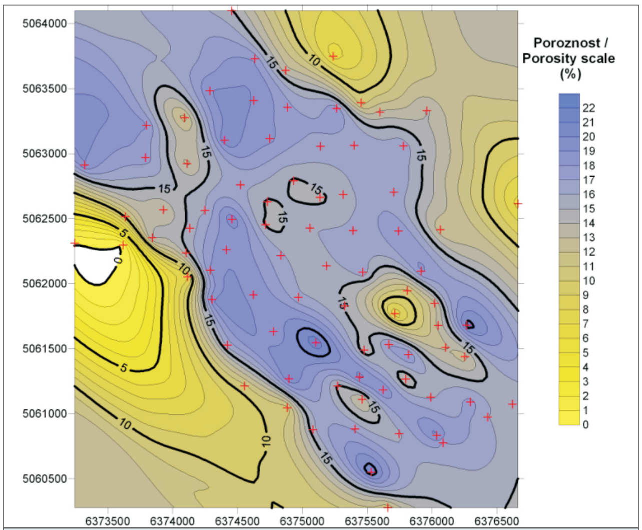

Fig. 3.5. Porosity map of the Late Pannonian reservoir in the Ivanić Field (from[4])
Sl. 3.5. Karta poroznosti gornjopanonskog ležišta u polju Ivanić (iz[4])

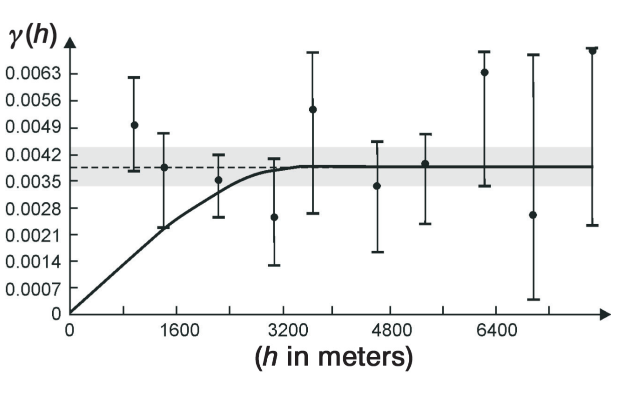

Fig. 4.1. "Jack-knifed" semivariogram of the Badenian clastics lithofacies in the Stari Gradac-Barcs Nyugat Field (from[9])
Sl. 4.1 "Jack-knifed" semivariogram podataka iz klasičnog litofacijesa badenske starosti polja Stari Gradac-Barcs Nyugat (iz[9])

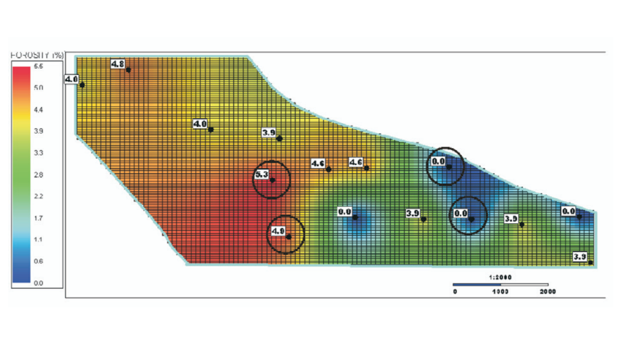

Fig. 4.2. Location of well data with the highest influence on "jack-knifed" semivariogram (from[7])
Sl. 4.2. Smještaj bušotina koje su imale najveći utjecaj na izračun "jack-knifed" variograma (iz[9])

4.2. Algorithm for calculation of Lagrange multiplicator in Ordinary Kriging equations

The Lagrange multiplicator allows the minimization of variance in Ordinary Kriging. So the knowing this values in the kriging matrices, and way how to calculate it, gives the real advantage in the understanding of interpolation for each particular dataset. The role of multiplicator has been shown in ref.[7] as comparisons of estimation in point (Figure 4.3) using Simple and Ordinary Kriging. Value of -0.931 9 for Lagrange multiplicator resulted in the lower kriging variance for Ordinary (6.70 m^2) than Simple (7.63 m^2) Kriging.

Another test included calculation of Ordinary Kriging matrices several times for the single grid of 4 midpoints of the box lines and unknown value in the centre (ref.[7]). Using of experimental variogram approximated by a spherical model, sill 1, range 200 m and without nugget effect, the Lagrange values of 0.06, 0.9 and -0.9 had been tested. The minimal variance was obtained for the first one. The algorithm for estimation of Lagrange value that corresponds to minimal kriging variance had been given in Figure 4.4.

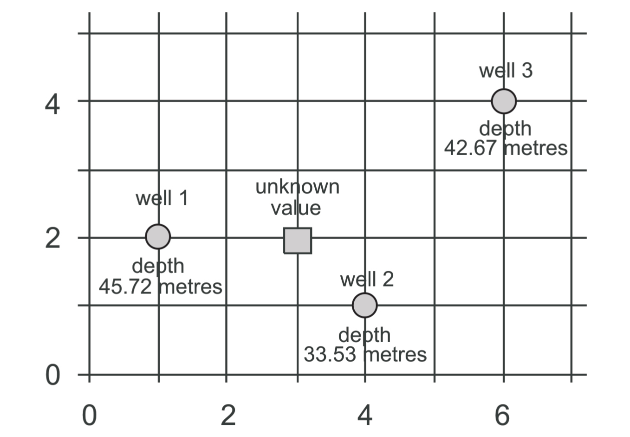

Fig. 4.3. Control and estimation points for calculation of kriging variance with Simple and Ordinary Kriging (from[7])

Sl. 4.3. Kontrolne te točke procjene uporabljene za izračun varijance jednostavnog i običnog kriginga (iz[7])

5. THE FOURTH PERIOD OF ADVANCE APPLICATION OF COKRIGING; INDICATOR KRIGING AND SIMULATIONS (FROM 2009)

This period included application of other geostatistical deterministical techniques than Simple and Ordinary Kriging. It is specially characterised with extensive application of stochastical simulation, mostly for interpretation of depositional features and reservoir's lithofacies.

5.1. Application of cokriging in reservoir with secondary porosity

Cokriging as mapping method showed its full advantages in the analysis of one of the reservoir lithofacies into in the Molve Field. The heterogeneity of reservoirs asked separately observation of even four such lithofacies. Into

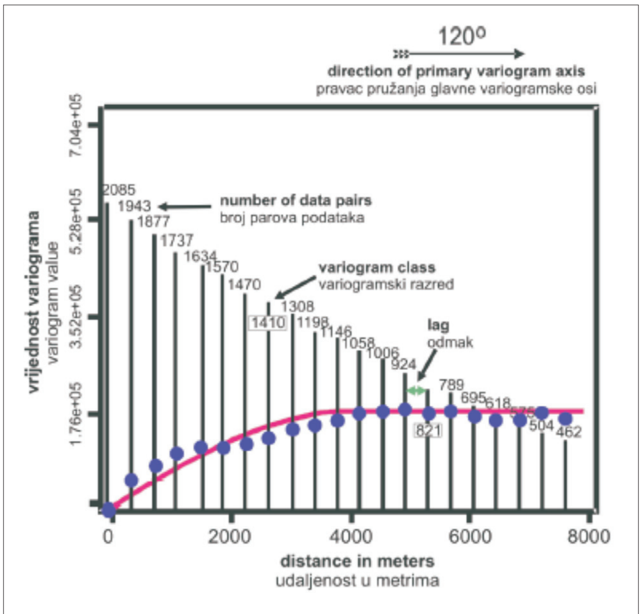

Fig. 5.1. Experimental variograms on primary axis in lithofacies "III" of the Molve Field (from[8,10])

Sl. 5.1. Eksperimentalni variogrami na primarnoj osi u litofacijesu "III" u polju Molve (iz[8, 10])

lithofacies "III" of Lower Triassic age (lithologically mostly quartzites) was established correlation between porosity as primary and reflection strength as secondary variable (refs.[8,10]) with R=0.51. Correlation is statistically significance, what was confirmed using t-test. How secondary variable was sampled at much more grid nodes than primary (2500 vs. 16 points), anisotropic experimental variogram is modelled for secondary dataset (Figure 5.1). So, variogram parameters could be much better estimated.

For primary variogram axis of 120° lag spacing was about 350 m, range 4 000 m, and spherical approximation had been done. Range of secondary axis was 2 900 m. Using that variograms the porosity was interpolated by Ordinary Cokriging technique (Figure 5.2).

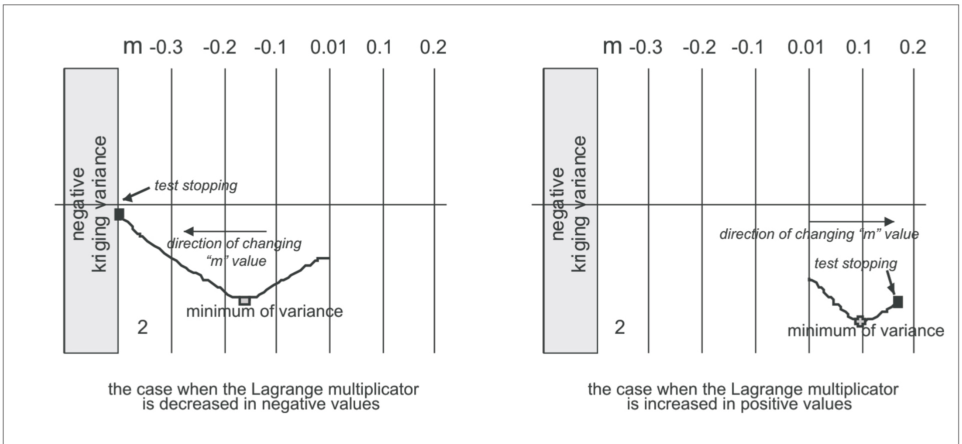

Fig. 4.4. Graphical representation of how to select the most appropriate value for the Lagrange multiplicator using random sampling (from[7])

Sl. 4.4. Grafički prikaz odabira najprimjerenije vrijednosti Lagrangeovog multiplikatora uporabom slučajnog uzorkovanja (iz[7])

5.2. Application of Indicator Kriging for reservoir's lithofacies mapping

Indicator Kriging is specific interpolation technique based on data transformation, i.e. applied on non-linear transformed data. Novak Zelenika et al.[14] presented indicator analysis made for from Upper Miocene reservoir porosity data in the Kloštar Field (Figure 5.3). Each cutoff had been analysed with own variogram model, which was conse-

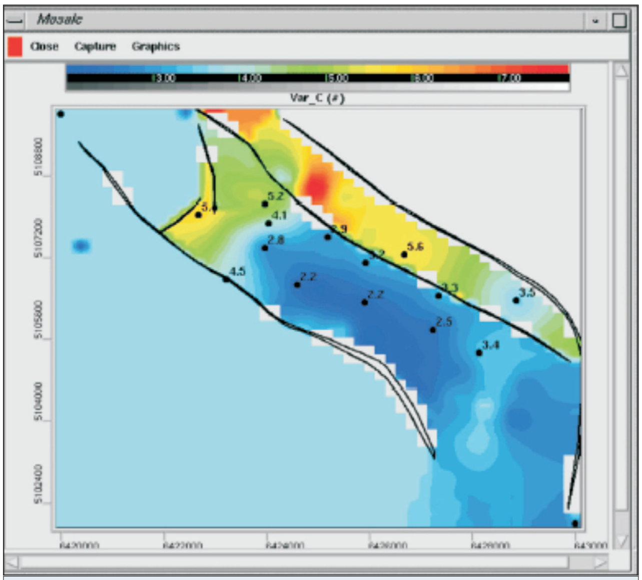

Fig. 5.2. Porosity interpolation obtained by Ordinary Cokriging in lithofacies III of the Molve Field (from[8,10])

Sl. 5.2. Poroznost interpolirana običnim kokrigingom u litofacijesu "III" u polju Molve (iz[8, 10])

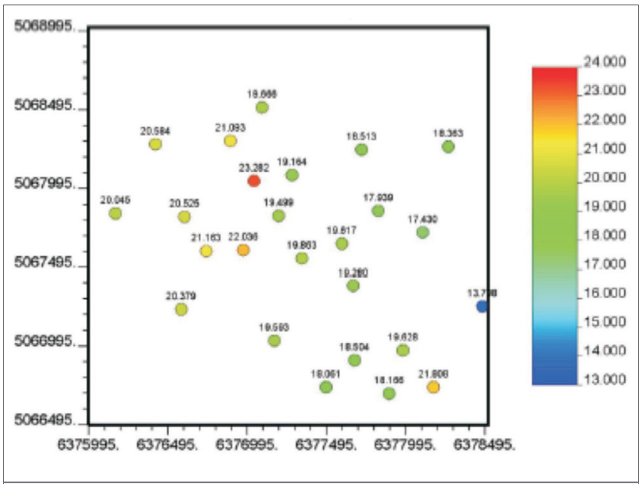

Fig. 5.3. Hard-data porosity value map of 25 wells in Kloštar Field, including 6 artificial hard-data (from[14])

Sl. 5.3. Raspored 25 točkastih ("čvrstih") podataka poroznosti u polju Kloštar u kojima je uključeno i 6 "umjetno" generiranih vrijednosti (iz[14])

quently used for obtaining probability maps (Figure 5.4). Such maps were basis for interpretation of present-day strike of different reservoir's lithofacies, from which could be concluded about palaeo-transport directions and depositional environment during Late Pannonian and Early Pontian on the Kloštar structure.

5.3. Simultaneous application of the Indicator Kriging (IK), Sequential Indicator Simulation (SIS) and Sequential Gaussian Simulation (SGS)

Such simultaneous analysis and comparison of deterministical and stochastical results had been again done on the data from the Kloštar Field (refs.[12,13]). Two similar datasets were available; one was collected into Late Pannonian (23 data) and other in Early Pontian (19 wells) reservoir sandstone "series". Here are given results from ref.[12], obtained for thickness, porosity and depth as selected variables. The porosity had been estimated with Sequential Gaussian Simulations to get insight in the area of the maximum reservoir heterogeneity as well as general directions of the highest porosities that correspond with strike of the main depositional channel (Figure 5.5). The similar simulations are done for thickness and depth (Figures 5.6 and 5.7), with goal to confirm assumptions derived from porosity modelling.

One of the important post-processing results that could be derived from set of realizations is new histogram (Figure 5.8) of mapped variable. In simulation, all simulated values are treated as the hard-data, and it is valid sequentially what means that during simulation number of "hard" data is continuously increased. Consequently, at the end of that process the histogram can be re-calculated from the much more data than it was available in the input set.

A stochastic approach is especially useful when the amount of input data is moderate, i.e. larger than minimum for application of geostatistics. In the most of stochastical analyses in the CPBS that varies between 18 and 23 input points, when consequently variogram models include large uncertainties. Using stochastic maps for outlining zonal uncertainties can significantly improve further analyses (not necessarily geostatistical). When variograms have a large nugget the stochastic approach

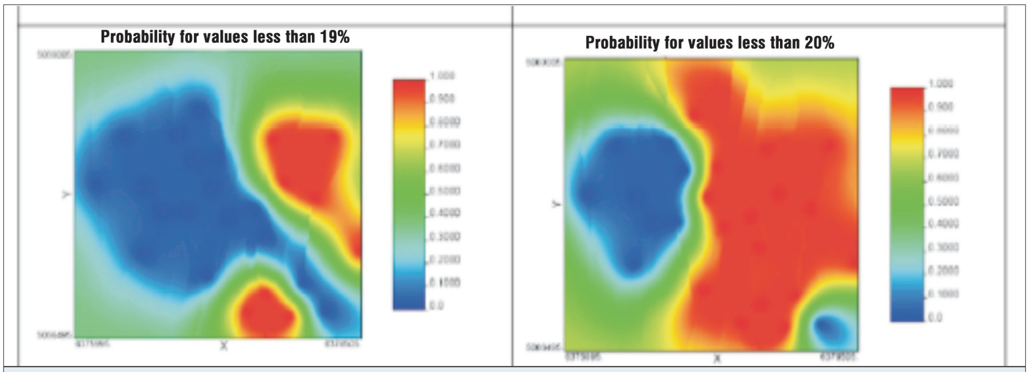

Fig. 5.4. Probability maps for porosity cutoffs (14, 18, 19, 20, 22%). Probability '1' means that cell's value is lesser than selected cutoff (from[14])

Sl. 5.4. Karte vjerojatnosti za granične vrijednosti poroznosti (14, 18, 19, 20, 22%). Vjerojatnost '1' znači da je vrijednost ćelije manja od odabrane granične vrijednosti (iz[14])

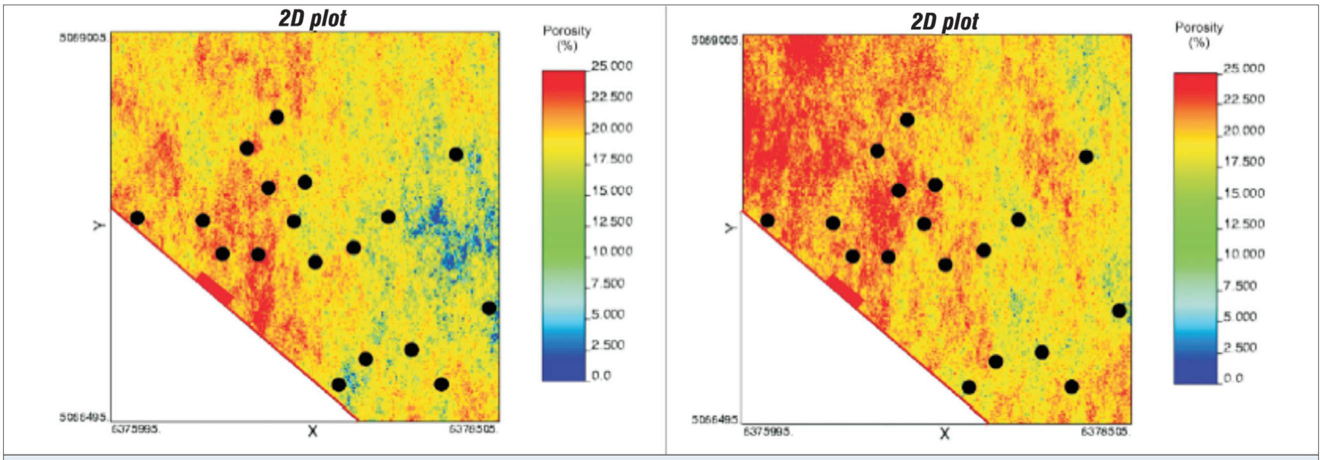

Fig. 5.5. The 1st (left) and 100th (right) realizations for porosity (scale 0-25%) obtained by SGS in the Early Pontian reservoir (from[12])
Sl. 5.5. 1. (lijevo) i 100. (desno) realizacija poroznosti (interval 0-25%) dobivene uporabom SGS-a u donjopontskom ležištu (iz[12])

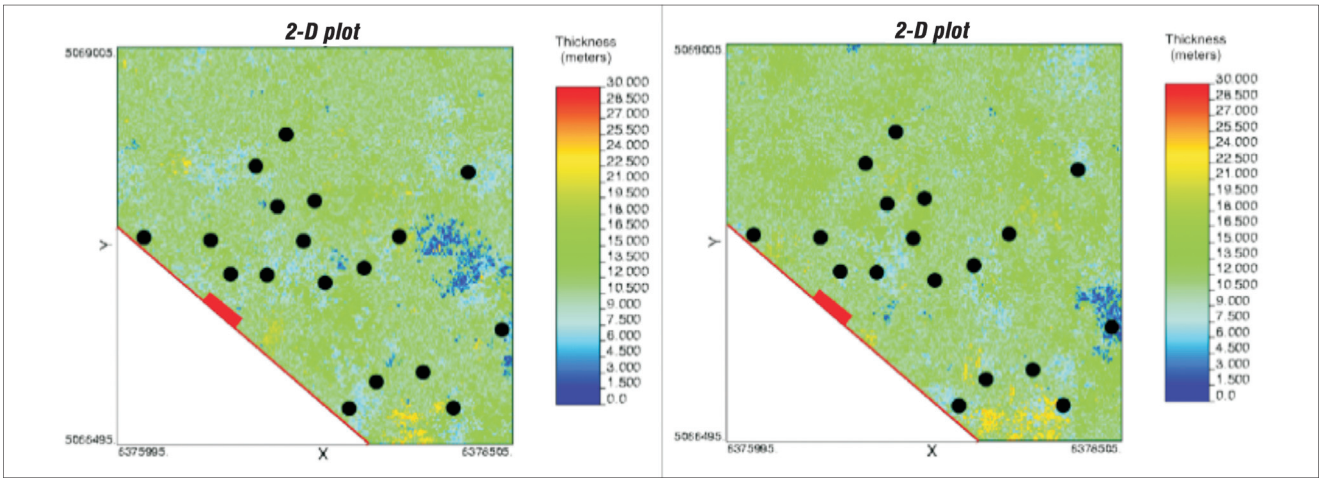

Fig. 5.6. The 1st (left) and 100th (right) realizations for thickness (scale 0-30m) obtained by SGS in the Early Pontian reservoir (from[12])
Sl. 5.6. 1. (lijevo) i 100. (desno) realizacija debljine (interval 0-30 m) dobivene uporabom SGS-a u donjopontskom ležištu (iz[12])

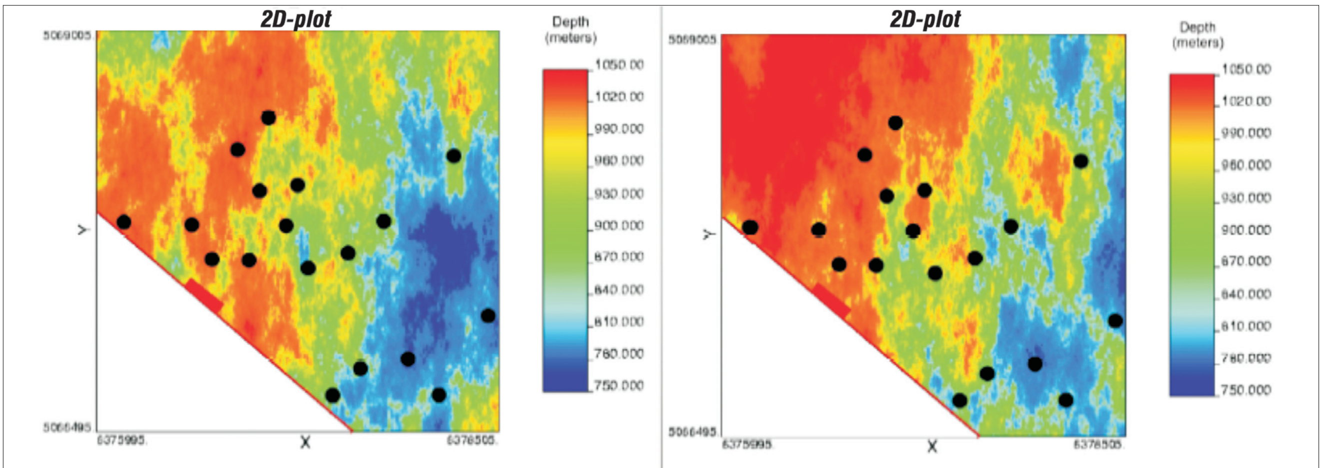

Fig. 5.7. The 1st (left) and 100th (right) realizations for depth (scale 600-1100m) obtained by SGS in the Early Pontian reservoir (from[12])
Sl. 5.7. 1. (lijevo) i 100. (desno) realizacija dubine (600 - 1 100 m) dobivene uporabom SGS-a u donjopontskom ležištu (iz[12])

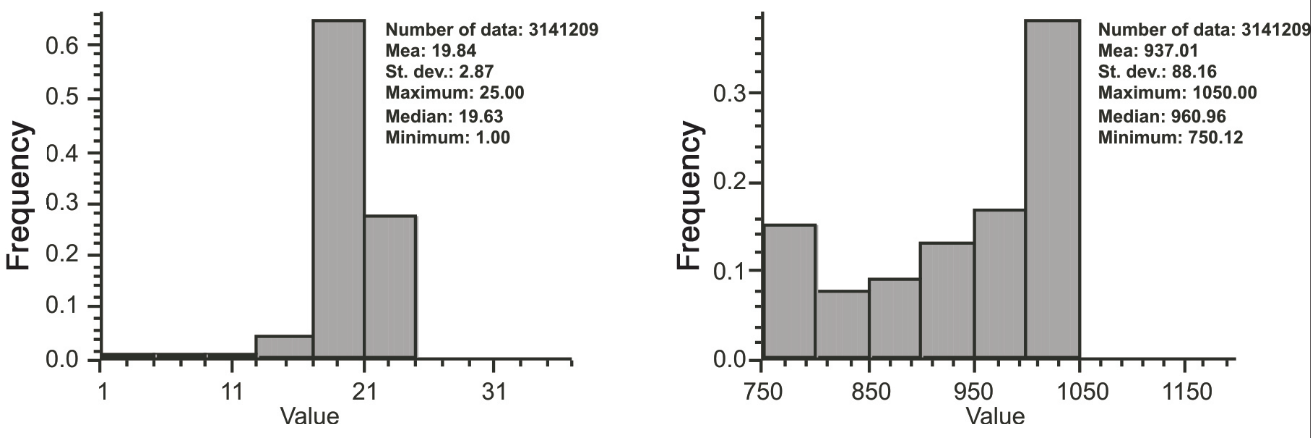

Fig. 5.8. Histogram of porosity (left) and depth (right) values calculated from 100 SGS realizations for Early Pontian reservoir of the Kloštar Field (from[12])

Sl. 5.8. Histogram poroznosti (lijevo) i dubine (desno) izračunat iz 100 SGS realizacija načinjenih u donjopontskom ležišta polja Kloštar (iz[12])

will partially remove the "bull's-eye" effect, like it is visible on Figures 5.5 and 5.7.

6. CONCLUSIONS

In presented examples can be easily followed development of geostatistics through four main stages of their application in the analyses of the hydrocarbon reservoir in the CPBS:

- The first stage included simple and comprehensive application of variogram analysis (modelling) in the one dimension, mostly performed in the area of the Bjelovar Subdepression.
- The second period was characterised by using of Simple and Ordinary Kriging techniques for mapping, mostly for interpolation of reservoir porosities. Also, this was time when the first cokriging maps had been done and, for different geostatistical and non-geostatistical methods/techniques applied for the same datasets, mean square error had been calculated as way to choose "the most appropriate" map.
- The third period encompassed the work on theory of "jack-knifing" sampling technique application and defining of areas with the largest uncertainties in variogram modelling and mapping. Also, the algorithm for estimation of Lagrange multiplicator value in the Ordinary Kriging equations had been constructed.
- The last, forth stage, was period of work with "non-linear" technique of Indicator Kriging, and using of simulations (Gaussian and Indicator).

Any kind of presented geostatistical analyses always ask for carefully selection of geological variable that wish to be mapped. It means that such variable need to be measured in statistically significant number of data, correctly averaged and has the property of normal distribution. The exceptions are indicator methods that are designed for non-normal distribution. Also, log-normal distribution could be often processed into normal distribution. In the case of indicator methods, i.e. Indicator Kriging and Sequential Indicator Simulation, there is need for careful selection of cutoff values. With too many classes (e.g., more than 10) of mapped variable, processing time drastically increases, requiring some minimum size of input dataset (e.g., more than 30). On contrary, using just few cutoffs (less than 5) can result in impossibility to observe some geological features of the mapped variable. Definition of classes based on cutoffs that approximately follow normal distribution is useful, because it makes possible to calculate the descriptive statistics of input data assuming Gaussian distribution and improve interpretation of indicator maps that are regularly based only on 3rd order stationarity.

Based on experience (i.e., examples presented in this paper), geostatistics can be the easiest applied for reservoir porosity or thickness mapping. Porosity is "by definition" defined with normal distribution. However, this property is also valid for thickness in some special situation, e.g., when it is regularly sampled in palaeo-environments of special shapes. The smallest dataset that could be geostatistically mapped can be also derived from experience. The datasets lesser than 10 points can not be object of variogram analysis, so it means that they can be appropriate mapped only with mathematically simpler methods like Inverse Distance Weighting or applying zonal estimation like Nearest Neighbour. In the range of 10-20 points the Ordinary or Simple Kriging can be regularly applied, but knowing that variograms still include significant uncertainties around some experimental points. Even then, the mean square error of estimation will be the lowest for geostatistical methods. However, Indicator Kriging, based on non-linear transformation of input data (more than 5) will be applied when dataset has about 20 or more points. For larger datasets the geostatistical approach is always primary option. Cokriging always can replace the same kriging algorithm if the correlative secondary variable is available. The existence of such secondary variable even can help in using geostatistics when number of data (10-15) is questionable for kriging application.

The similar "rules of thumb" are valid for application of simulations. However, here is also the need for defining number of equiprobable realization. For the dataset with 30 or more points the abundant number of realizations (some tens or 100 in usual approach) is welcome. Such set can be easily post-processed with goal to select median, the smallest, the largest etc. realization (based on, e.g., total sum of all estimated cells) and use it in further processes. However, in the limited datasets (10-20 points), and intention only recognizing the areas of the largest uncertainties, it is enough to calculate 5-10 realizations for such purpose.

NOTE

The most of those results are first time compiled for the invited lecture given in Department for Geology and Palaeontology at the University of Szeged, Hungary, on 9th December 2011. It was part of regular program for the subject about geostatistics, lead by Prof. Dr. János Geiger.

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