Significance of the amplitude attribute in porosity prediction, Drava Depression Case Study

T. Malvić and S. Prskalo

PRELIMINARY COMMUNICATION

All types of reservoirs are characterized by difficulties in predicting their petrophysical properties mainly due to frequent lithological heterogeneity. It is particularly valid for coarse-grained clastic reservoirs, which include different matrixes, granulometry and different portions of primary and secondary porosities. Several methods could help their description. One of them is the several physical attributes seismic analysis , which provides more or less reliable rock, pore space and pore fluid description. The seismic amplitude, as well as reflection strength, is one of the most frequently used attributes in the analysis. This attribute is especially useful in porosity prediction. It may be applied in different geostatistical and neural interpolation methods as a very valuable secondary source of information.

This article describes the amplitude attribute analysis performed in the main reservoir of the Beničanci oil field. The reflection strength attribute was used as a secondary variable, applied in cokriging interpolation of porosity selected as the primary variable. Spearman rank correlation was r=-0.64 calculated for the pair porosity-reflection strength.

The use of secondary information led to significantly better porosity prediction. Such analysis may be considered a very favorable procedure for describing the clastic reservoir in the Drava depression.

Key words: seismic, amplitude, porosity, cokriging, Beničanci field, Drava depression

1. INTRODUCTION

The Beničanci oil field (Fig.1) is the largest hydrocarbon reservoir in the Beničanci oil zone, where four oil fields – Bizovac, Crnac, Števkovica, Obod-Lacići – were developed. Three of them are oil and gas fields (Beničanci, Bokšić, Obod), one gas field (Obradovci) and one geothermal field (Bizovac). The total geological oil reserves in the Beničanci reservoir are 34 x 10^6 m^3 with oil recovery factor of 52.5 %. Gas reservoirs of the Beničanci field are structurally shallower and represent the secondary production target. The geologically proven reserves are estimated at 2 700 x 10^6 m^3 with recovery of about 58 %. The remaining recoverable reserves are small, but the field is still in production that could be assumed higher than expected from mathematical balance and some older history matches. In addition, total recoverable reserves are difficult to predict accurately, due to the relatively complex Neogene clastic depositional model, especially of Middle Miocene breccia.[1]

The Beničanci oil and gas field is an E-W anticline with slightly dipping flanks (12-18°) as shown in Fig. 2. Its area size is equal to 8 x 1.3 km. The main fault system is reverse, striking NW-SE/E, bordering the southern field margin. The structure encompasses four structural highs, sinking toward E. The majority of extensional faults are characterized by normal displacement.

The stratigraphic section includes basement rocks of Permian and Triassic age and Neogene clastic sediments. Basement is determined only in several deep wells (more

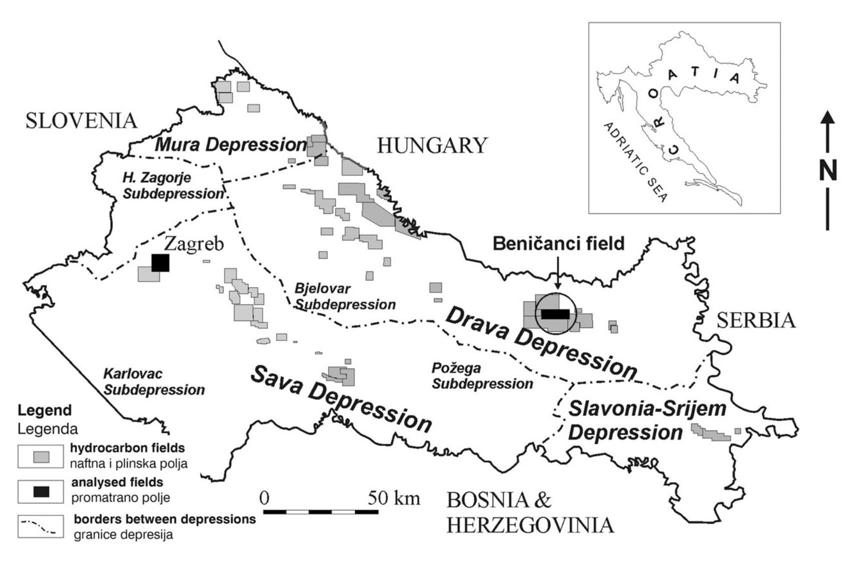

Fig. 1. Regional map of the Croatian part of the Pannonian Basin
Sl. 1. Regionalna karta hrvatskog dijela Panonskog bazena

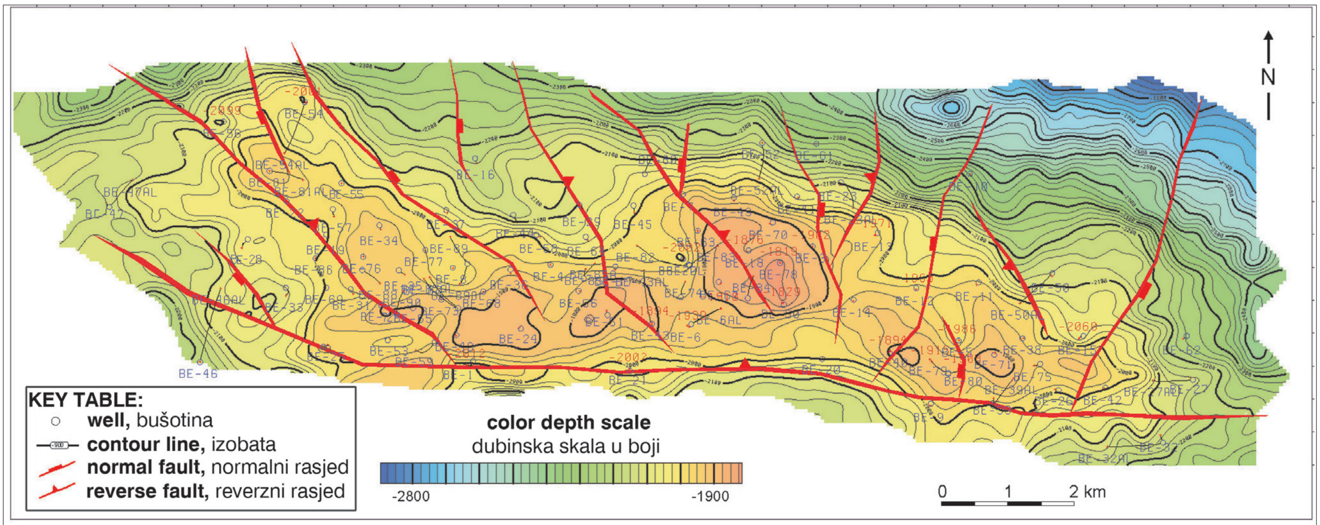

Fig. 2. Paleorelief map (ref. 2 and company archive, 2004)
Sl. 2. Karta paleoreljefa (lit. 2, te arhiva tvrtke, 2004.)

than 2 500 meters) and is represented by schist. The reservoir lithology is of Miocene age and very heterogeneous. The oldest clastics are effusive and volcanic rocks (Miocene magmatic cycle) like andesite, pyroclastics and effusive breccia. Also, the sediments of this age can be (re)deposited clastics of Mesozoic age. These clastics can be fragments of Triassic marls and limy breccia, or quartzite of the same age. Such rocks are subsequently weathered and re-deposited in the Lower Miocene.

The main reservoir rocks are of Badenian age, mostly represented by dolomitic and limestone breccia (Fig. 3). Dolomitic detritus is dominant, but of different genetic types. Somewhere such clasts can reach several meters in diameter. The matrix is also of micro to crypto dolomite, tectonically crushed, petrified and crystallized. The reservoir breccias were primarily very hard, but later tectonics and dissolution resulted in high secondary porosity and accompanied permeability. The shallow parts are characterized by a mixture of breccia and conglomerate, with carbonate and siliciclastic detritus. Microfossils indicate shallow, marine and active environment.

The Miocene sedimentation was continued by typical lithostratigraphic units for the Croatian part of the Pannonian Basin (Fig. 3). Lower Pannonian calcitic marls ("Croatica beds") mostly consist of fine-grained, hard sandstones. Sediments of this age are lacking in the southern part of the field. It is followed by Late Pannonian sediments ("Banatica beds") of similar lithology. The hard, calcitic marls are Late Pannonian sediments, thicker in the southern part of the structure. Early Pontian sediments ("Abichi beds") are mostly sandstone (mixture detritus) intercalated with hard marls. Late Pontian "Romboidea beds" are mostly weak sandstone and medium to weak marl, sometimes clayey. A coal bed was also found. The youngest sediments of Pliocene age are mostly unconsolidated clay, sand, as well as Quaternary gravel, sand and clay by limestone concretion.

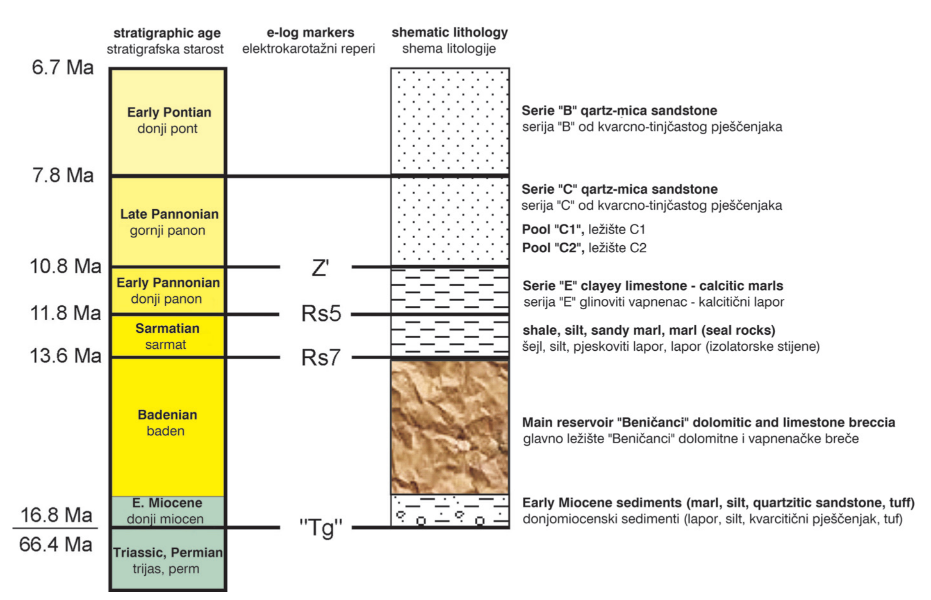

Fig. 3. Schematic stratigraphy section of the Beničanci field
Sl. 3. Shematski stratigrafski stup na polju Beničanci

Coarse-grained reservoir rocks of the Beničanci field are sedimentary and genetically related to Miocene paleogeomorphology, extensional synsedimentary tectonics and Middle Miocene transgression. The main types of the reservoirs and sedimentary bodies are[19]:

1. Clinoform bodies of carbonate rockfall and debrite breccias originated from accumulation of carbonate detritus along the slope and cliffs made of tectonized Mesozoic carbonate massifs on land, shore, and partly below sea level;
2. Nearshore conglomerates originated from the re-depositioning of carbonate rockfalls and debrite in nearshore marine shoals;
3. Channel and fan bodies made of breccia-conglomerates and sandstones which originated in submarine fans and/or deltas(?), and,
4. Tectonic breccias, generated by crushing and tectonization of already lithified Miocene turbidite sedimentary rocks, were accumulated in deeper environments below the storm wave base simultaneously with kerogene pelitic (marlitic) rocks (hydrocarbon source rocks - oilshale).

In this analysis, porosity is selected as the important reservoir variable with high influence on reservoir volume, OGIP ("Original Gas In Place") and production. The analyzed reservoir is also described in detail by seismic attribute analysis as a result of 3D seismic cube interpretation. Attribute analysis was targeted precisely for the interval that begins at 20 m from the reservoir seal and continued to the reservoir base or the well bottom.[15] Seismic attribute analysis included amplitude, frequency and phase analysis. Fourteen out of 106 wells were selected based on the quality and reliability of log-curves analysis, quality of interpretation software and their relatively regular distribution across the reservoir zone.

2. PHYSICAL MEANING OF SEISMIC AMPLITUDE

The theoretical background for seismic amplitude interpretation was already established at the beginning of last century. In Knott's[9] and Zoeppritz's[20] research the seismic amplitude dependence on seismic velocity and density in the two layer medium were analyzed. Based on these works, the equations were developed describing amplitude changes as functions of P and S wave velocities, density and angle of incidence of seismic arrival on the reflector. These equations were rather complex and therefore it was very difficult, practically almost impossible, to find their solutions. The change of attribute values is primarily functionally connected with geology and geological changes. However, it also partly depends on the technical conditions of measurements and equipment.

In later years, attempts were made to simplify them in order to make them usable in practice. The petrophysical link to seismic data was described by Gassmann.[4] In his article, published in 1955, Koefoed[10] presented an expression describing offset dependent amplitude change, and established the theoretical background for the very popular AVO method. The first systematic attempt in lithology prognosis through reflection coefficients analysis was described by Rosa[16]. Further development in practical use of amplitudes in lithology and fluid saturation is connected with the work of Ostrander[13, 14]. In 1985, Shuey[17] published an article on linear approximation equation later widely used in practical application of AVO method.

The velocities of P and S waves depend on the elastic properties of rocks, and consequently on the porosity and fluid saturated in the rock. Reflection coefficients of seismic amplitudes are calculated from these properties. Accordingly, seismic amplitude analysis should provide more useful subsurface data, particularly in already discovered oil and gas accumulations.[5]

Seismic wave characteristics, measured or calculated from originally surveyed data, are seismic attributes. Some of them are sensitive on specific hydrocarbon reservoirs status, other proved to be very useful in subsurface anomalies recognition, while some other, under favorable conditions, are practically used in direct hydrocarbon – particularly gas – detection. However, the seismic attributes are not mutually independent entirely and, in order to achieve more reliable subsurface evaluation, it is preferred to analyze more attributes at the same time.

Input data for attribute calculation are CDP trace clusters. Instantaneous amplitude is equal to the sum of real and imaginary traces in complex seismic presentation following the already established procedure (Taner and Sheriff).[18] Amplitude of real seismic trace depends on particle motion caused by seismic wave arrival, and as such is the function describing kinetic seismic energy. Accordingly, the amplitude on imaginary trace is the function that describes the potential seismic energy, while the complex trace – sum of both mentioned traces – represents total seismic energy.

The seismic wave reflection process occurs at boundaries between rock layers with different acoustic impedances, which are equal to products of seismic velocities, V_1 and V_2, and corresponding densities, namely, ρ_1 and ρ_2. The reflectivity function on the two layers boundary is usually defined with the amplitude ratio of input and output seismic waves, R, which for normal incidence is equal to the following Equation 1:

$$R = \frac{z_2 - z_1}{z_2 + z_1} = \frac{\rho_2 \cdot V_2 - \rho_1 \cdot V_1}{\rho_2 \cdot V_2 + \rho_1 \cdot V_1} \qquad (1)$$

In the "soft" materials, or the rocks with low acoustic impedance, due to lower density and greater porosity, the seismic wave arrival causes longer particle movements and a little pressure increase. The same seismic arrival in the "hard" rocks with higher acoustic impedance due to lower porosity and greater density values, results in shorter particle movements and pressure increase. The resulting reflected seismic wave amplitude changes are a good indicator for elastic characteristic changes in the subsurface. This is particularly valid for porosity evaluation where the methods based on amplitude changes have been proved as an especially valuable tool in reservoir status determination before and during exploitation. The amplitude analysis proved to be successfully applied in sand/shale ratio determination as well as in sand bodies and turbidite fans mapping.

3. CORRELATION BETWEEN AMPLITUDE AND POROSITY

Porosity was chosen as a reservoir variable interpolated in the Beničanci field. Interpolation was performed using geostatistic methods of kriging and cokriging. The most advanced cokriging requires the determination of an additional, secondary variable that describes the behavior of the primary one. Such a secondary variable is mostly selected from seismic attributes. The level of mutual describing between primary and secondary variables can be determined from correlation, based on the level of significance.

3D seismic data on the Beničanci field were interpreted in 2002. Seismic measurements were distributed on a grid of 50 x 50 nodes, where each contained the calculated average reservoir value for the following six attributes: absolute amplitude, instantaneous frequency, instantaneous phase, reflection strength, the highest amplitude and RMS amplitude (“Root Mean Square”). Lately, these nodes were again averaged at 14 well locations with mean porosities. It means that correlation could be done for 14 pairs between attributes and porosity values. This number of 14 inputs was not large enough to determine true distribution of inputs. Consequently, we cannot approximate these datasets by normal (Gaussian) curve, what is a precondition for Pearson’s correlation coefficient calculation. Moreover, this encouraged the use of non-parametric rank correlation, i.e. calculation of *Spearman ranking correlation coefficient* (Eq. 2), which used median value instead of mean and standard deviation:

$$r' = 1 - \frac{6\sum_{i=1}^{n}\left[R(x_i) - R(y_i)\right]}{n\left(n^2 - 1\right)} \qquad (2)$$

The highest correlation was reached between porosity and reflection strength values, which are ranked in Table 1.

Spearman rank correlation was r'=-0.64, which led to reflection strength being accepted as a secondary variable.

4. POROSITY INTERPOLATION

Porosity in the Beničanci reservoir was interpolated by Inverse Distance Weighting, kriging and cokriging methods (Malvić and Đureković)[11] as well as by backpropagation neural network (Malvić and Prskalo).[12] The short review of applied methods as well as results is presented, emphasizing the importance of reflection strength as secondary variable that improved our knowledge on reservoir heterogeneity. Generally, variogram analysis is based on variogram function calculation (Eq. 3):

$$2\gamma(h) = \frac{1}{n}\cdot\sum_{i=1}^{n}\left[z(x_i) - z(x_i + h)\right]^2 \qquad (3)$$

Where :

$2\gamma(h)$	variogram
n	number of data pairs compared to h distance
$z(x_i)$	variable value on chosen location (x_i)
$z(x_i+h)$	variable value on the location with "h" distance from the initial location (x_i+h)

Variogram value depends only on the spatial distribution of locations, e.g. on the number of known values on a chosen distance. The results are experimental variogram curves. Almost all such curves can be approximated by theoretical models defined in mathematical equations. Such a theoretical model, with certain variogram parameters, represents the necessary input for kriging and cokriging methods. The most common theoretical models in petroleum-geological analyses are spherical, exponential and Gaussian models.[6]

Kriging and cokriging are geostatistical interpolation methods (Deutsch,[2] Dubruble,[3] Isaaks and Srivastava,[7] Kelkar and Perez[8]). The variogram results offer spatial input for both methods. The difference is in the number of modeled variables. In the case of kriging there is always one spatial model of primary variable. However, cokriging includes two (sometimes even more) variables. The is an option to model a common variogram model based on a primary variable (our target) or on a secondary variable that “describes” the primary (but not 100 %) and includes much more measured data. In this analysis, we used the variogram model of the primary variable, even in cokriging method that had been considered as Collocated Cokriging. The term “collocated” means that the secondary variable was relocated (extrapolated) only at locations of the primary variable. It also means that the model was calculated by the same number of primary and secondary variables, in this case the 14 averaged well data.

Mathematically, kriging is a linear interpolator (Eq. 4), where each hard-data is weighted by corresponding coefficient for obtaining the most appropriate point estimation. The indicator of the most “appropriate” estimation is the lowest value of kriging variance. The general kriging formula is:

$$z_K = \sum_{i=1}^{n}\lambda_i \cdot z_i \qquad (4)$$

Table 1. Ranks of porosities and reflection strength

Porosity	6.64	4.38	10.30	8.32	7.94	8.21	4.97	0.90	4.10	3.67	3.47	7.39	3.76	7.21
Rank	7	5	14	12	10	11	6	13	4	2	1	9	3	8
Reflection strength	6 176	7 427	7 537	4 914	5 729	3 174	10 333	4 572	9 480	11 999	8 068	5 322	6 051	4 776
Rank	8	9	10	4	6	1	13	2	12	14	11	5	7	3

Where :

z_K	estimated value from *'n'* surrounding values
λ_i	weighting coefficient on location *'i'*
z_i	actual value on location *'i'*

The calculation of weighting coefficients for all the included surrounding values represents the result of solving the kriging matrix equations (Eq. 5), including the variogram results (y).

$$\begin{bmatrix} \gamma(x_1-x_1) & \gamma(x_1-x_2) & \cdots & \gamma(x_1-x_n) & 1 \\ \gamma(x_2-x_1) & \gamma(x_2-x_2) & \cdots & \gamma(x_2-x_n) & 1 \\ & & & & 1 \\ \gamma(x_n-x_1) & \gamma(x_n-x_2) & \cdots & \gamma(x_n-x_n) & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} x \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \\ \lambda_n \\ \mu \end{bmatrix} = \begin{bmatrix} \gamma(x_1-x) \\ \gamma(x_2-x) \\ \\ \gamma(x_n-x) \\ 1 \end{bmatrix} \tag{5}$$

Where :

$\gamma(x_1\text{-}x_2)$	value difference variogram on locations $x_1, x_2 \ldots x_n$
$\gamma(x_1\text{-}x)$	value difference variogram on locations $x_1, x_2 \ldots x_n$ and on location x which is being estimated
μ	Lagrange parameter
$\lambda_{1\text{-}n}$	weighting coefficients

Cokriging equation (Eq. 6) extends the form of kriging weighting of hard-data to additional weighting of the secondary variable, which is significantly correlated by the primary one.

$$z_C = \sum_{i=1}^{n} \lambda_i \cdot z_i + \sum_{j=1}^{m} \chi_j \cdot s_j \tag{6}$$

Where :

$\sum_{i=1}^{n} \lambda_i \cdot z_i$	identical to equation (5)
$\sum_{j=1}^{m} \chi_j \cdot s_j$	identical to equation (5), while applicable to the second variable

Cross-validation is a relatively simple and widely used technique for evaluation of estimation quality. It is based on removing the value measured on a selected location and estimating a new value in the same place considering the remaining existing data, popularly called "one-moved-out". It is expressed mathematically in Equation (7).

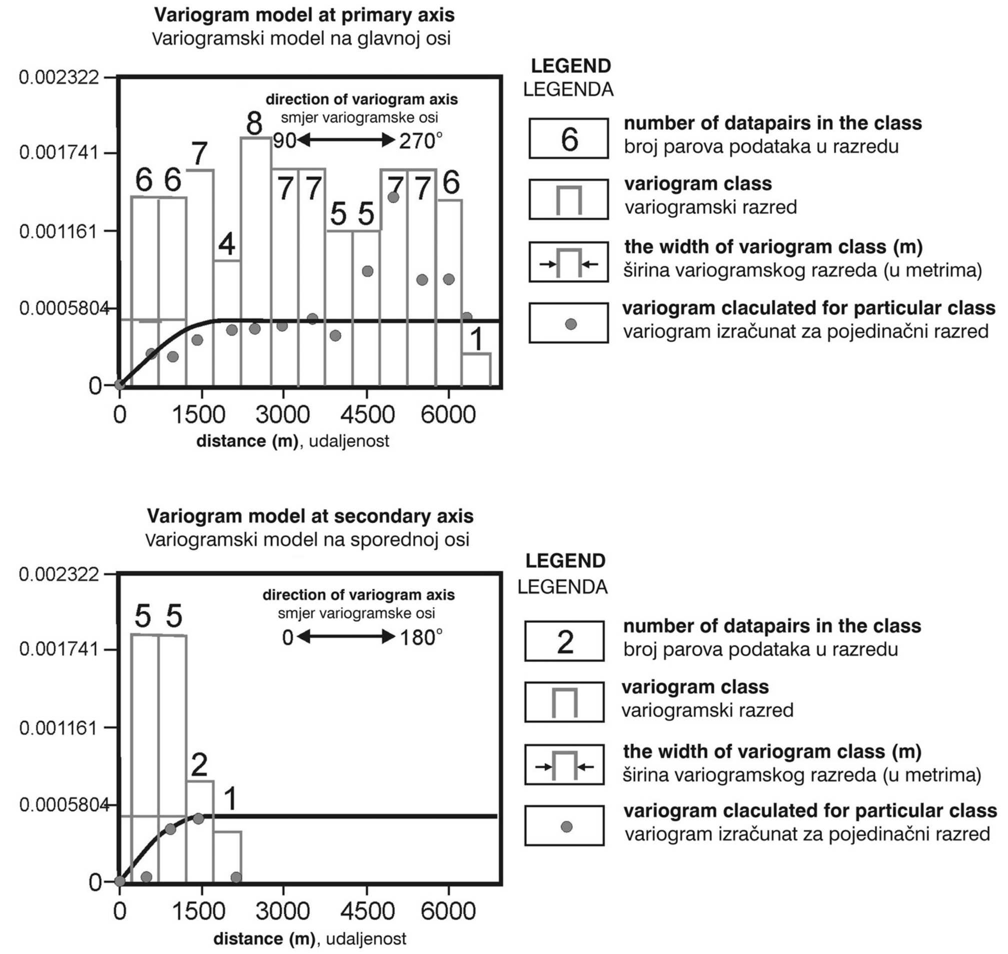

Fig. 4. Experimental directional variograms
Sl. 4. Eksperimentalni usmjereni variogrami

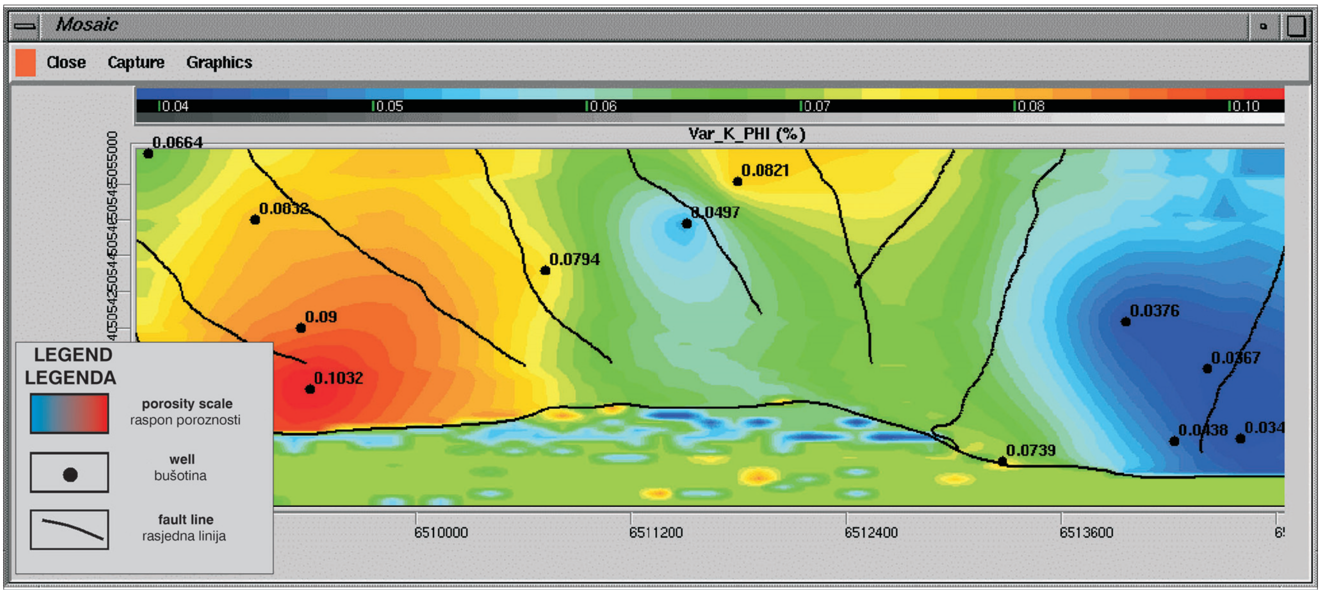

Fig. 5. Kriging porosity map
Sl. 5. Karta poroznosti interpolirana krigingom

The disadvantage of this method could be its particular insensitivity to the number of analyzed wells, i.e. results do not really reflect the variance increasing as a result of larger dataset. A very popular paper about cross-validation as well as the jack-knifing technique is given by Davis.[1]

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(real\ value - estimated\ val.\right)_i^2 \qquad (7)$$

Where :

MSE	cross-validation result also called mean square error
real value	value measured at location «*i*»
estimated val.	value estimated at location «*i*»

Interpolated kriging and cokriging maps are also compared based on cross-validation results and expressed through *MSE* values (MSE_{OK} for kriging and MSE_{CC} for cokriging method).

4.1. Variogram model of porosity of Beničanc field

The variogram models of the Beničanci reservoir are the first spatial result necessary for geostatistical interpolation. Due to structural anisotropy, and lithological heterogeneity, the related variograms are also modeled across the primary and secondary axis. The primary has direction 90-270° (E-W), while the secondary spreads along the direction 0-180° (N-S). These directional variograms are characterized by the maximum angle tolerance of 45°, for decreasing the disadvantages of a low number of input data. The variograms of the Beničanci reservoir is shown in Figure 4.

The range on the primary axis is 1 750 m, determined from 7 and more data pairs per class. The secondary axis range is subjectively estimated on 1 500 m, due to 5 and less data pairs per class.

4.2. Kriging and cokriging maps

Experimental variogram curves are approximated by spherical theoretical model that represented the input for Ordinary Kriging and Collocated Cokriging methods. Ordinary Kriging map is shown in Figure 5, and accompanied Mean square error was MSE_{OK}=2.969.

Using reflection strength as the secondary variable, the porosity distribution was mapped with the **Collocated Cokriging method** in the same reservoir. Figure 6 shows the acquired map. Accompanied error was MSE_{CC}=2.185.

5. DISCUSSION AND CONCLUSIONS

Collected were fourteen averaged porosity and seismic attribute values at well locations, regularly distributed across coarse-grained Badenian reservoir of the Beničanci field. The geostatistical methods of kriging and cokriging were applied to interpolate porosity in the reservoir. These methods represent an improvement even if a single (primary) variable is used, which is confirmed by the kriging results.

Introducing the secondary attribute (reflection strength derived from amplitude attribute) resulted in better estimation as it showed porosity values posted on the relevant map and decreased the cross-validation error. The mean square error of the kriging map was 2.97, while that of the cokriging map was 2.19. Based on the results, the following conclusions may be given:

- The secondary variable enabled the use of advanced geostatistical algorithm of Collocated Cokriging;
- The porosity model is very sensitive to the spatial model. Such a model was represented by anisotropic variogram by axes 1 750 x 1 500 meters;
- The possible variogram model in the coarse-grained reservoir can be only slightly anisotropic and may be

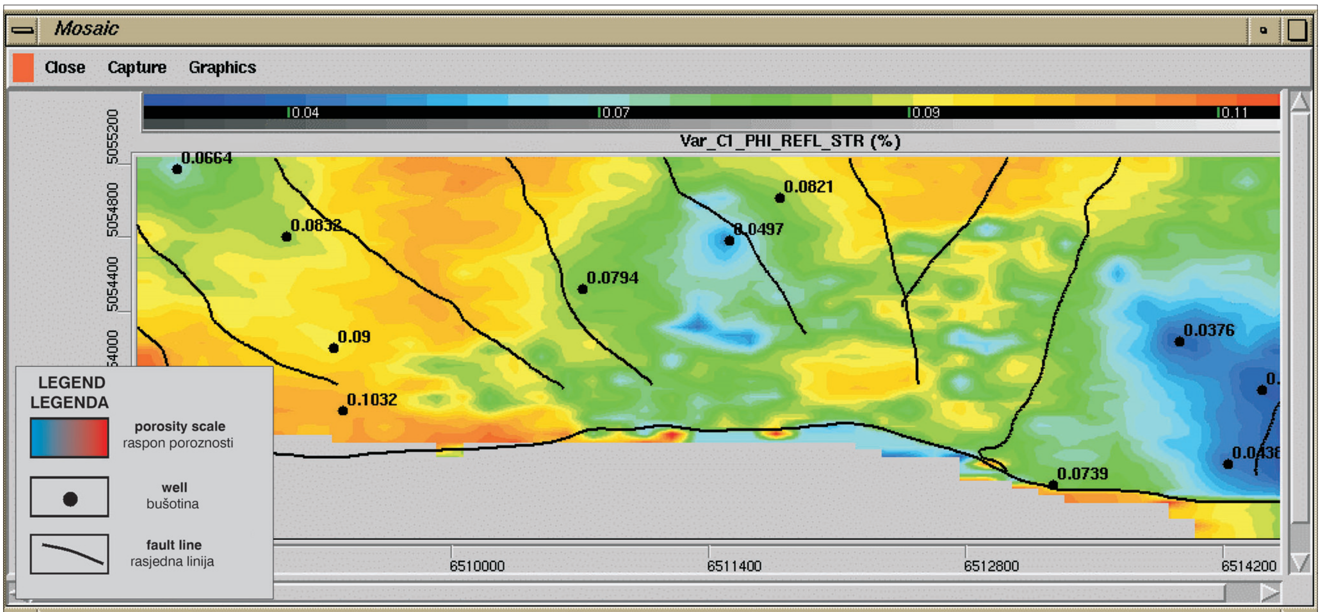

Fig. 6. Cokriging porosity map
Sl. 6. Karta poroznosti interpolirana kokrigingom

modelled using analogy between the principal and secondary structural axes;

- More information on spatial anisotropy may be obtained exclusively from very detailed analysis of depositional paleoenvironments, which is very often unavailable;
- In such a case, seismic amplitude may partially substitute such an analysis, because seismic reflections are influenced by distribution of different lithologies (and porosities of course) in reservoir;
- Seismic amplitude or reflection strength may be successfully used if significant correlation of the attribute and petrophysical parameter is achieved, like it was calculated in the presented analysis;
- Rank correlation is a very acceptable tool for dataset with a low number of data, as it is not necessary to apply normal distribution analysis.

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Authors:

Tomislav Malvić, DSc, graduate engineer in geology, PhD in Natural Sciences, INA-Industrija nafte d.d., Exploration and Production Division, Reservoir Engineering & Field Development Department, expert, Šubićeva 29, 10000 Zagreb, tomislav.malvic@ina.hr

Smiljan Prskalo, graduate engineer in geology, INA-Industrija nafte d.d., Exploration and Production Division, Exploration Department, chief geophysicist (now in retirement), Šubićeva 29, 10000 Zagreb, smiljan.prskalo@ina.hr