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Reducing variogram uncertainties using the 'jack-knifing' method, a case study of the Stari Gradac – Barcs-Nyugat field

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A variogram bizonytalanságának csökkentése jack-knife módszerrel Stari Gradac – Barcs-Nyugat mező példáján

Összefoglalás

A variogram elemzés a szénhidrogén telepek tároló paraméterei térbeli elemzésének egyik állandó eszköze. Ugyanakkor az ilyen vizsgálatok éppúgy, mint a tározók jellemzése sok bizonytalansági tényezővel rendelkezik. A bizonytalanság két okra vezethető vissza: 1) a mérőműszerek elégtelen volta; 2) a fúrások kis száma és szabálytalan elrendeződése. E két ok lehetetlenné teszi a térbeli kapcsolatok elfogadható elemzését. A második bizonytalansági tényező a jack-knife módszer segítségével tapasztalati úton számszerűsíthető.

A Stari Gradac – Barcs-Nyugat szénhidrogén mezőt, mint az elemzésre legalkalmasabbat, választottuk a jack-knife elemzés bemutatására. Ennek az adatbázisa a Pannon-medence horvátországi részéről származik. A badeni törmelékes litofáciesek adataiból tapasztalati irányfüggetlen (omnidirectional) kísérleti variogramok készültek, amelyeket szférikus elméleti modellel közelítettük. Ugyanebből az adathalmazból n db jack-knife félvariogramot állítottunk elő. Ez utóbbi variogram-halmaz alapján hibaintervallumok meghatározása történt a tapasztalati variogramok minden pontjára. A fúrásneveket a jack-knife eljárás lépéseiben mellőztük. Ez lehetővé tette a hibaintervallumok legnagyobb hatása által jellemzett egyedi fúrások megfigyelését.

A kapott eredmények alapján a vizsgált mezőben van egy olyan zóna, amelyben az adathiány a legerősebb hatást fejti ki. Ebben a zónában tapasztalható a térbeli modell legnagyobb becslési hibája. Feltételezhető, hogy két-három új fúráspont (vagy ezzel ekvivalens szeizmikus információ) lényegesen növelhetné a geostatisztikai térmodell megbízhatóságát, főleg ebben a zónában a porozitás becslését.

Tárgyszavak: jack-knife módszer, félvariogram, porozitás, szeizmika, Stari Gradac – Barcs-Nyugat mező

Abstract

Variogram analysis is a standard tool in the spatial analysis of hydrocarbon reservoir parameters. However, such analysis (as well as all reservoir characterisations), include several sources of uncertainties due to two reasons. The first is the imperfection of measuring devices. The second (and more frequent case) is the result of a (too) small number of wells and their irregular net pattern; this is not sufficient for reliable analysis of spatial dependence. This second source of uncertainty can be empirically quantified using a method called 'jack-knifing'.

The Stari Gradac – Barcs-Nyugat field was selected as beeing the most appropriate locality for applying 'jack-knifing' analysis on a dataset derived from the Croatian part of the Pannonian Basin. A new, omnidirectional experimental semivariogram has been calculated for data derived from clastics lithofacies of Badenian age. This omnidirectional semivariogram is approximated by a spherical-theoretical model. Also, from the same dataset a set of "n" 'jack-knifed' experimental semivariograms could be calculated. Based on this set, error bars can be graphically constructed around each point of the experimental semivariogram. It should be noted that the well names were omitted in each step of the 'jack-knifing'. This made it possible to observe a particular well's name as characterised by the highest influence on the error bars.

Based on the results obtained, there are spatially outlined well zones at the Stari Gradac – Barcs-Nyugat field where the lack of data has the most influence (i.e. zones that lead to the highest estimation error using the spatial model). It was also assumed that 2 or 3 new locations (i.e. wells or the reliable seismic equivalent of well data) would significantly increase the reliability of a geostatistical field's model, and especially the porosity estimation in these zones.

Keywords: 'jack-knifing', semivariograms, porosity, seismics, Stari Gradac – Barcs-Nyugat

Introduction

There are several methods for testing the reliability or significance of the variogram analysis. The non-parametric statistical methods 'jack-knifing' and bootstrapping are quite general. Non-parametric models differ from parametric ones in that the model structure is not specified a priori but is determined from data. Nonparametric models are therefore also called distribution free.

Jackknife is a less general method than the bootstrap, and explores the sample variation differently. However 'jackknife ' can be easier to apply to complex sampling schemes, with varying sampling weights. It is a statistical method for estimating and compensating for bias and for deriving robust estimates of standard errors and confidence intervals. 'Jack-knifed' statistical results are created by systematically dropping out data value step by step from the observed parameter dataset. In this way a series of pseudosamples is generated by deleting one or more data points from the original sample (like in case of cross-validation). So 'jack-knifing' can be regarded as sample method.

In geostatistics there is a long-standing confusion between 'jack-knifing' and cross-validation. Davis (1987) mentioned that "*...because Delfiner (1976) used both cross-validation and a bias-reduction technique called 'jack-knifing' in his paper, a tendency by others (e.g., Parker, Journel, and Dixon, 1979) has existed to refer to cross-validation as 'jack-knifing'*". 'jack-knifing' can be applied in sampling of experimental semivariogram. 'Jack-knifed' semivariogram is calculated for each of the pseudosample sets that contain 'n-1' data. The distribution of 'jack-knifed' semivariogram is compared to the semivariogram value obtained from the original data. Such distribution is described by error bars. 'Jack-knifed' results could be very similar to the original results, lead to relatively little new information about dataset. It is why this procedure may be considered as qualitative method, and not as method directly measuring uncertainty associated with an experimental semivariogram.

Mathematically there is only a single calculable $\gamma^*(h)$ for each lag, which is not a mean of squared differences, but a variance of the variogram values for that lag. It may be thought that $\gamma^*(h)$ could be bounded by estimating the variance of the squared differences about $\gamma^*(h)$. However this is not appropriate because this is the variance about a variance which is calculated, using exactly the same data. Such an approach circular and inappropriate, and as should be expected, the variance about $\gamma^*(h)$ increases with separation distance, yielding no useful information (Wingle, 1997). To circumvent this problem and observe uncertainties in earlier calculated semivariogram, a 'jack-knifing' method is used in calculation of a new set of experimental semivariograms for porosity data in clastics lithofacies (Badenian age) at the Stari Gradac – Barcs-Nyugat field. Such approach showed improvements regarding classical semivariogram calculation for relatively small dataset when experimental semivariogram may not be clearly defined. Lags were carefully selected by looking for more appropriate experimental semivariogram regarding data pairs and interpretation possibilities. In this 'jack-knifed' simulation, there was a large amount of errors for several lags, indicating that only omnidirectional semivariogram is approved to define spatial dependence in clastics lithofacies. 'Jack-knifed' results outlined lags where errors bars significantly overstep the sill and confidence intervals had been extremely wide. It made possible to select the wells in porosity dataset characterised with the largest spatial uncertainties. These are also places where new data acquisition is highly recommended.

Geological settings of the Stari Gradac – Barcs-Nyugat field

The Stari Gradac – Barcs-Nyugat gas and condensate field is located on the Croatian–Hungarian border (*Figure 1*), in the NW part of the Drava depression. Hydrocarbon reservoirs were discovered in 1980 and total of 15 wells were drilled until 2003.

This is an anticline formed above Mesozoic buried hills. Reservoir lithology comprises four lithofacies, connected in unique hydrodynamic unit. These reservoir lithofacies are informal lithostratigraphic units named as follows: Clastites (Badenian age), Dolomites (Early Triassic epoch), Quartzites (Early Triassic epoch) and Metavolcanites (Carboniferous to Permian period).

The size of the field, contoured by gas-water contact in the clastics lithofacies (informal named as Clastites), is 18.9

Figure 1. Location map
1. ábra. *Helyszínrajzi térkép*

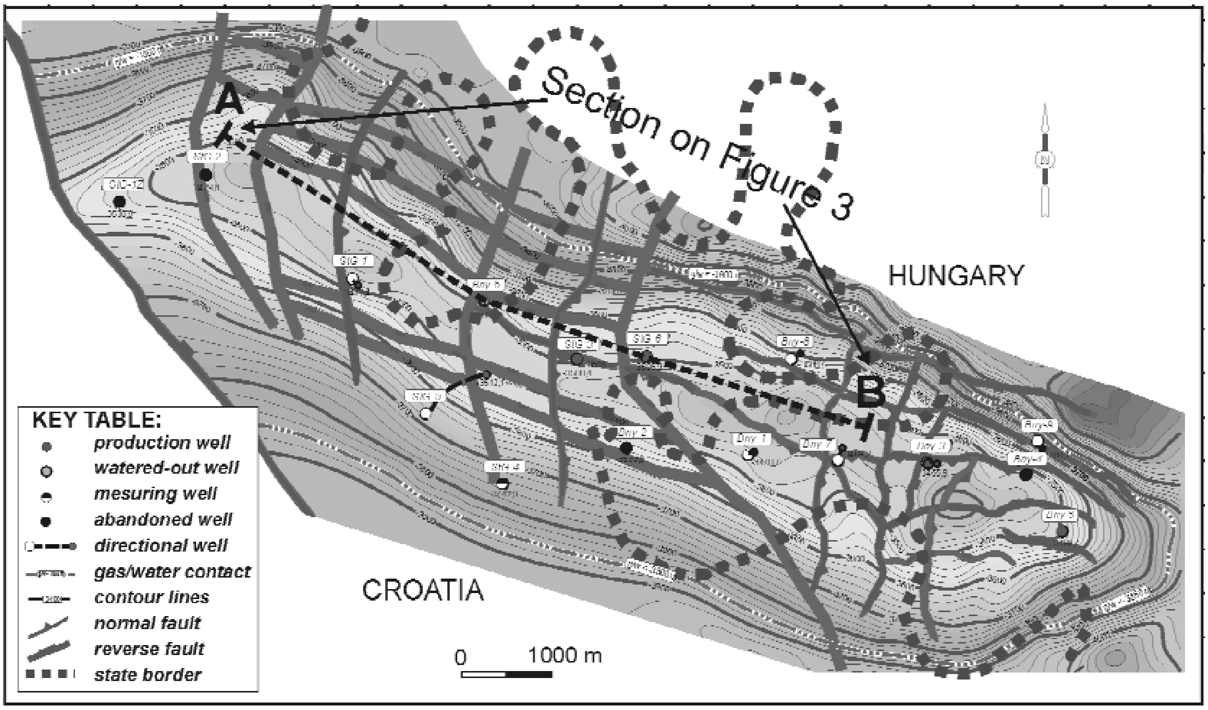

Figure 2. Structural map showing the top of clastics lithofacies (after GAĆEŠA et al. 2001)

2. ábra. *A törmelékes képződmények tetejének szerkezeti helyzetét ábrázoló térkép (GAĆEŠA et al. 2001 alapján)*

km^2. Structural map (GAĆEŠA et al. 2001) on *Figure 2* shows two fault systems by strikes NW–SE and NNE–SSW and four structural highs. All faults being perpendicular to the structure (strike NNE–SSW) are mostly completely permeable for fluid flow. It is assumed, that the fault being in the centre of structure with extremely curved fault line (its strike changed from the NNE–SSW to the NW–SE) played the major depositional role in this system, activated in the Middle Miocene as the normal one. Later in the post-extensional phase its character of displacement was changed to reverse fault.

Two major faults with direction NE–SW define field margins (the SW fault margin is visible on Figure 2). These faults existed before Neogene period, and reactivated in Badenian age as strike-slip extensional faults, defining and uplifting field' structure.

Review of geostatistical porosity modelling

Porosity and thickness are important reservoir parameters. Both are result of depositional mechanism, and sometimes these two variables can be multiplied in new reservoir attribute, useful in reservoir characterisation (total pore volume). Geostatistics offers strong tools for interpolation and extrapolation, spatial distribution analysis and uncertainty estimation for reservoir parameters (e.g. JOURNEL & HUIJBREGTS 1978, HOHN 1988, ISAAKS & SRIVASTAVA 1989) with the methods of different kriging, cokriging and stochastic estimations. Stari Gradac – Barcs-Nyugat dataset is relatively limited, but enough for geostatistical application. Geostatistical results have been previously published in MALVIĆ & SMOLJANOVIĆ (2004), SMOLJANOVIĆ & MALVIĆ (2004) and SMOLJANOVIĆ & MALVIĆ (2005). Due to only 15 inputs normal score transformation did not perform. Also it is accepted that porosity is characterised by the normal distribution.

New variogram analysis in clastics lithofacies

Three functions are used in geostatistics for describing the spatial or the temporal correlation of observations: correlogram, covariance and semivariogram (or variogram). The semivariogram is the key function used to fit a model of the spatial/temporal correlation of the observed phenomenon. Result of such analysis represents obligatory input for any geostatistical estimation methods — interpolation and simulation. Semivariogram analysis at Stari Gradac – Barcs-Nyugat field was performed in two directions, following the main field structural axes: 120°–300° as principal and 30°–210° as subordinate axis. Equivalence of structural and variogram axes were confirmed by the variogram surface map (*Figure 3*).

In previous geostatistical studies performed at the Stari Gradac – Barcs-Nyugat field the ranges of influence obtained for clastics lithofacies are 3500 meters for principal and 1500 meters for subordinate axis. Unfortunately, secondary axis could not be modelled using the *first sill crossing* approach, because range would be unrealistically low, due to small number of inputs. It is why the secondary range was assumed from ratio between orthogonal structural axes.

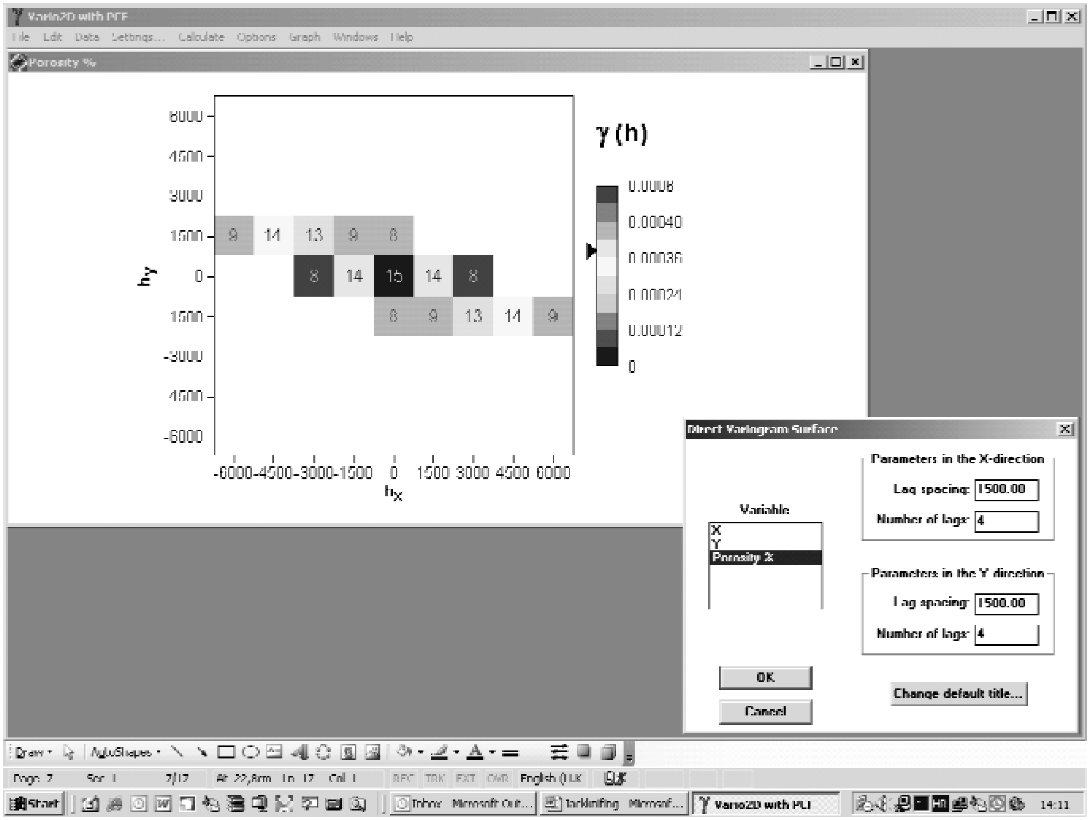

Figure 3. Semivariogram surface maps (calculated by Variowin; PANNATIER 1996)
3. ábra. *A félvariogram felszín (Variowin program, PANNATIER 1996)*

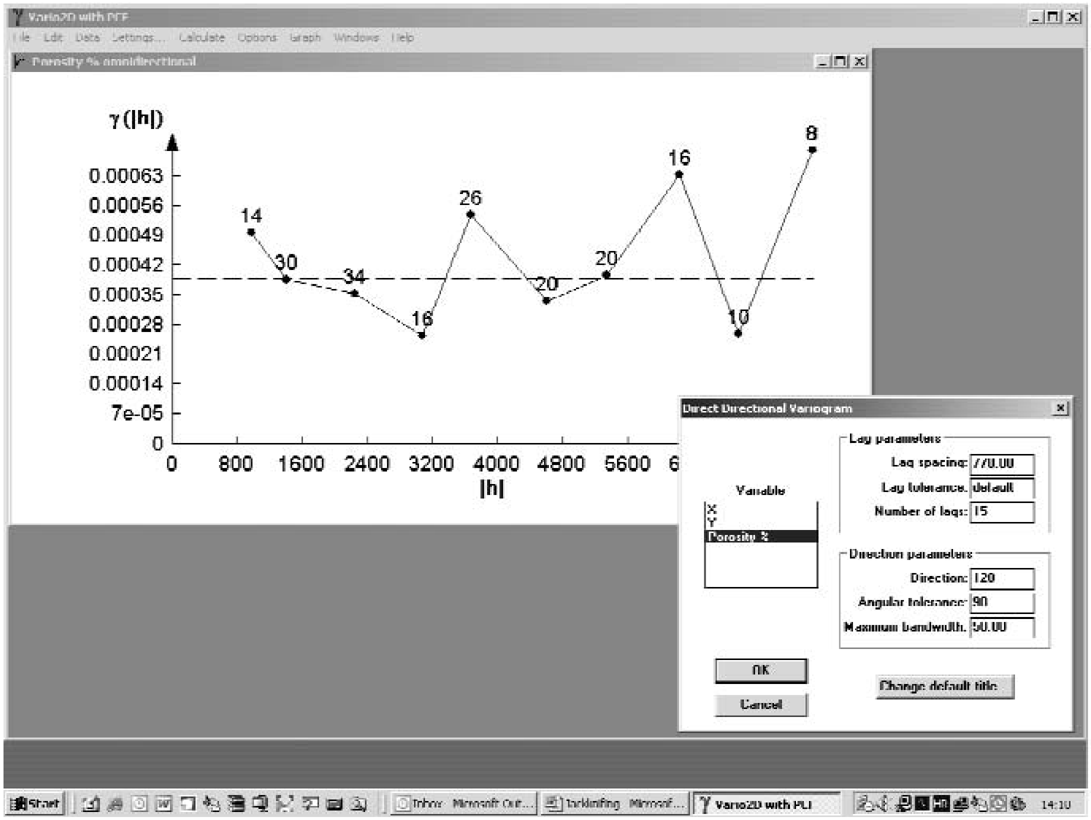

Figure 4. Omnidirectional semivariogram (calculated by Variowin; PANNATIER 1996)
4. ábra. *Irányfüggetlen félvariogram (Variowin program, PANNATIER 1996)*

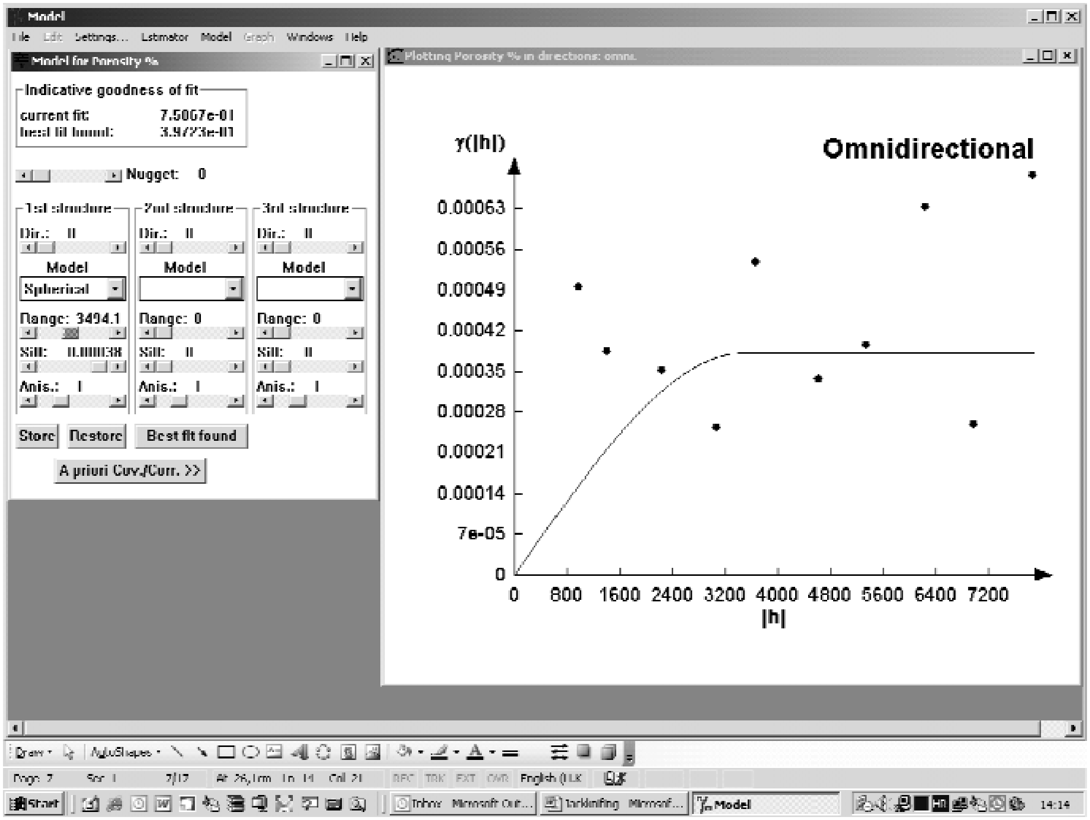

Figure 5. Spherical theoretical model (calculated by Variowin, PANNATIER 1996)

5. ábra. *Az illesztett szférikus elméleti modell (Variowin program, PANNATIER 1996)*

In any case, all studies indicated that secondary axis can not be reliable modelled. This value includes so many assumptions that all relevant uncertainties are very subjective to interpreter. 'jack-knifing' evaluation is meaningful only if we search for uncertainties through lags and semivariogram classes characterised with meaningful number of data pairs. It could be reached only using omnidirectional semivariogram being valid for entire Stari Gradac – Barcs-Nyugat structure (*Figure 4*).

That is why this semivariogram model is accepted for clastics lithofacies — omnidirectional with range 3500 metres.

Semivariogram model was approximated with spherical theoretical model (*Figure 5*) that could be described by range 3494 metres, sill 0.00038, anisotropy 1 (isotropy) and Equation 1 (from HOHN 1988):

$$\gamma(h) = C\left[\left(\frac{3h}{2a}\right) - \left(\frac{h^3}{2a^3}\right)\right] \qquad h \le a$$
$$\gamma(h) = C \qquad h > a \qquad \text{(Eq. 1)}$$

Where:
$\gamma(h)$ = semivariogram,
C = sill,
a = range,
h = semivariogram distance.

Kriging interpolation and relevant geological settings

The experimental semivariogram is an empirical estimate of the covariance of a Gaussian process. It may not be positive definite and hence not directly usable in Kriging. This explains why only a limited number of theoretical variogram models are used. The linear, the spherical, the Gaussian and the exponential models are the most frequently used ones.

Kriging interpolation of porosity was derived for 15 wells. Values lower than 3% were set to 0 (cut off value). The geostatistical approach is proved as more accurate linear interpolation tool than other traditional methods (MALVIĆ & ĐUREKOVIĆ 2003) for clastics lithofacies (kriging MSE=3.914 vs. inverse distance weighting MSE=5.279).

Porosity distribution in Badenian clastics is tightly connected by depositional environments and thickness of same sediments. Four anticline tops can be observed on structural map, two of them in the NW and two of them in the SE parts of the field (Figure 2). There is an assumption that Badenian palaeostructure was different from the present-day mapped structure. That is why porosity distribution does not coincidence with present-day geological framework. Moreover, porosity distribution follows different depositional facies that existed in Badenian (MALVIĆ 2006). Generally, the major influence on porosity distribution has well's locations regarding depositional area

(*Figure 6*). That generally means that well can be located in clastics sediments of upper, middle or lower part of alluvial fan (TIŠLJAR 1993).

In Badenian age, NW from the Stari Gradac – Barcs-Nyugat structure an uplifted Mesozoic basement existed (MALVIĆ 2006). This uplifted area was, in the beginning of the extension, weathered and cataclized by activity of strike-slip faults, which defined area of the Stari Gradac – Barcs-Nyugat structure. The Mesozoic basement was source of dominantly carbonate detritus, deposited at NW part of the field structure. Toward to the SE, sedimentation was changed to fine-grained carbonate clastics and deeper basin-plain pelitic sediments. This plain area consumed larger thickness of sediments through Badenian. Such reconstruction explained why the thickness contains larger values on the SW part, and contemporaneously, why porosity map includes even four wells where the average porosity in the Badenian interval is smaller than the cut-off (i.e. it is replaced by 0).

seismograms can be generated and appropriate 3D seismic model can be established which is very important for adequate seismic attribute study.

Generally, collected seismic data can be considered for the analysis of field parameters. Such data can be collected using vibroseis array, geophone array, sweep test, walkaway test etc. Recorded data pass every day in-field quality control. Some uncertainties as bad shots, dead traces or inverse polarity easily can be edited and/or omitted. Level of such uncertainties grow with data processing, hence bore-hole data (if there are any) are very important in seismic modelling. Appropriate seismic model (in time or depth scale) reveals appropriate seismic attributes that can be applied in spatial analysis of reservoir parameters. In this study porosity as primary variable has been interpreted from well logging data.

Previously mentioned reservoir heterogeneities could be additionally described by analysis of the existing seismic model of the Stari Gradac – Barcs-Nyugat field.

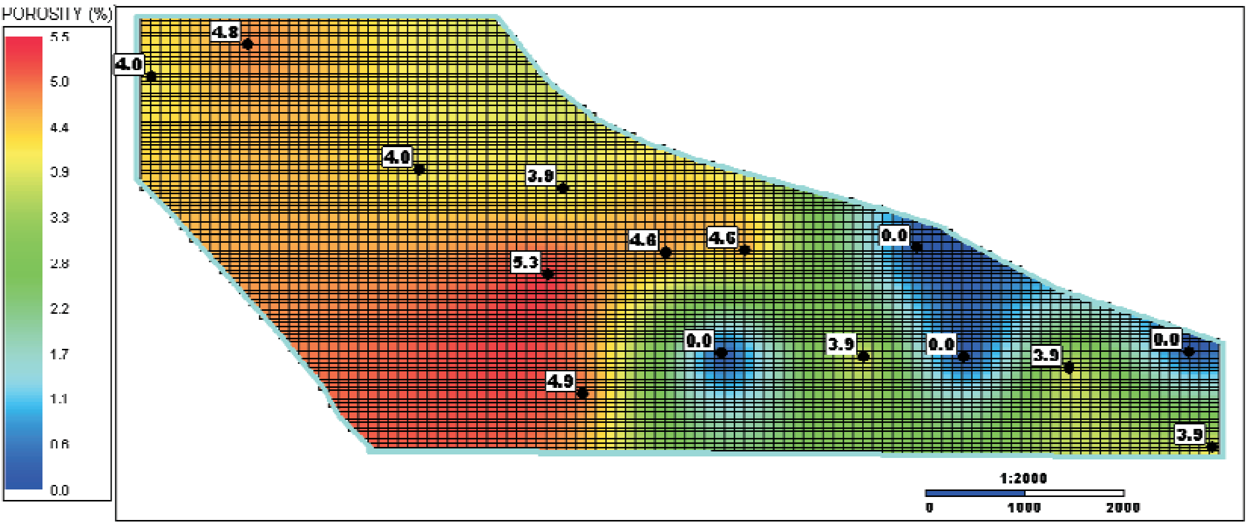

Figure 6. Porosity map of clastics lithofacies (from MALVIĆ 2006)
6. ábra. *A törmelékes litofáciesek porozitástérképe (MALVIĆ 2006)*

These relative small-scale porosity heterogeneities can be observed only on relevant maps that achieved maximum accuracy for available dataset. The Kriging is proven as the best linear interpolator for the Stari Gradac – Barcs-Nyugat field. The further improvements in analysing geostatistical results could be reflected through 'jack-knifed' semivariogram models, where main uncertainties connected to lags and well's locations could be detected.

Possible secondary variable selection

In sense to increase reliability of geostatistical field model and to predict physical rock properties, in this case porosity estimation, seismic attributes study can be very useful. 3D seismic acquisition gave us spatially continuous series of data. 3D seismic data can be correlated with borehole data (core and well logging) or synthetic

Maybe there will be possible in future to reach new seismic equipment testing and obtain new seismic attribute interpretation. It would make possible to select secondary variable and improve geostatistical mapping of the analysed clastics lithofacies as well as entire reservoir stratigraphic sequence.

'Jack-knifing' method

In mathematical statistics, the resampling process includes variety of methods for doing one of the following:

1. Estimating the precision of sample statistics (medians, variances, percentiles) by using subsets of available data (jack-knife) or drawing randomly with replacement from a set of data points (bootstrapping);

2. Exchanging labels on data points when performing

significance tests (permutation test, also called exact test, randomization test, or re-randomization test);

3. Validating models by using random subsets (bootstrap, decision trees).

Jackknife is an estimator introduced by QUENOUILLE (1956) to reduce bias. Moreover, the applications for using 'jack-knifing' to construct approximate confidence intervals were extended (TUKEY 1958). According DAVIS (1987) 'jack-knifing' procedure applied on variograms does not conform to the layout of the estimator given by QUENOUILLE (1956) or the generalized jackknife (GRAY & SCHUCANY 1972).

'Jack-knifing' is a procedure where the experimental semivariogram is calculated with one (or more) data point(s) removed from the dataset, using same procedure like cross-validation in mapping quality check. By repeating this procedure for every point in the dataset, a series of "n" (n = number of samples) experimental semivariograms is calculated. It means that at the end of this procedure "n"•*(h) values are available for each lag distance. These "n" values could be shown as error bars around •*(h) value of "regular" semivariogram, determining confidence limits at a particular lag.

The problem with this method is that each •*(h) value is naturally correlated with the other semivariogram values. It means that 'jack-knifed' set is auto-correlative at each specific lag, because data set differs only in one (removed) data point. Therefore the variance calculations are not strictly correct.

That is why 'jack-knifing' is not being used to select the best semivariogram model. Rather, it is used to guide the modeller in optimizing further data collection or identifying a likely range of reasonable model semivariograms (WINGLE 1997). 'Jack-knifing' the semivariogram, with small data sets (10's to 100's of samples), can be useful in describing the uncertainty associated with the definition of the theoretical semivariogram (WINGLE 1997). The more valuable 'jack-knifed' could be done using directional semivariogram (*Figure 7*), modelled along principle axes of variability. Unfortunately it was impossible to construct directional semivariogram at analysed field.

The estimator given by Equation 2 is called the 'jack-knife' (DAVIS 1987) and for the case of variograms, is the same as the generalized jack-knife (DAVIS 1987) in Equation 3:

$$J\left[\hat{\gamma}(h)\right] = N\cdot\hat{\gamma}(h) - (N-1)\cdot\left[\frac{1}{N}\cdot\sum_{j=1}^{N}\hat{\gamma}^{j}(h)\right] \qquad \text{(Eq. 2)}$$

$$\overline{\hat{\gamma}(h)} = \frac{1}{N}\cdot\sum_{j}\hat{\gamma}^{j}(h) \qquad \text{(Eq. 3)}$$

Axes of the anisotropy ellipse could be orthogonal, using same model adjusted with anisotropy factors. In the case of larger dataset, each direction can be modelled by independent semivariogram models. The computational

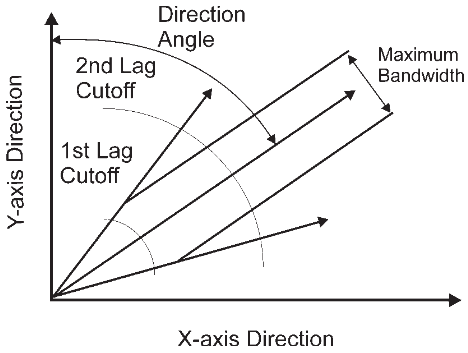

Figure 7. Parameters defining the semivariogram search area (after ENGLUND & SPARKS 1988)

7. ábra. *A félvariogram előállításának keresési paraméterei (ENGLUND & SPARKS 1988 nyomán)*

time for kriging will be longer, but modeller obtains higher freedom and the model is more accurate. Very often small dataset (10's to 20's points like at analysed field) could be described mostly by omnidirectional semivariogram models. Such models are primary target for 'jack-knifing' of semivariogram (*Figure 8a*) because uncertainties in small dataset are very normal and expectable.

Figure 8 shows that by increasing the number of samples, the 'jack-knifed' lag variances will decline, and ideally a 'jack-knifed' semivariogram will appear like that of *Figure 8c*. The lack of variation in the experimental 'jack-knifed' semivariogram allows the model semivariogram to

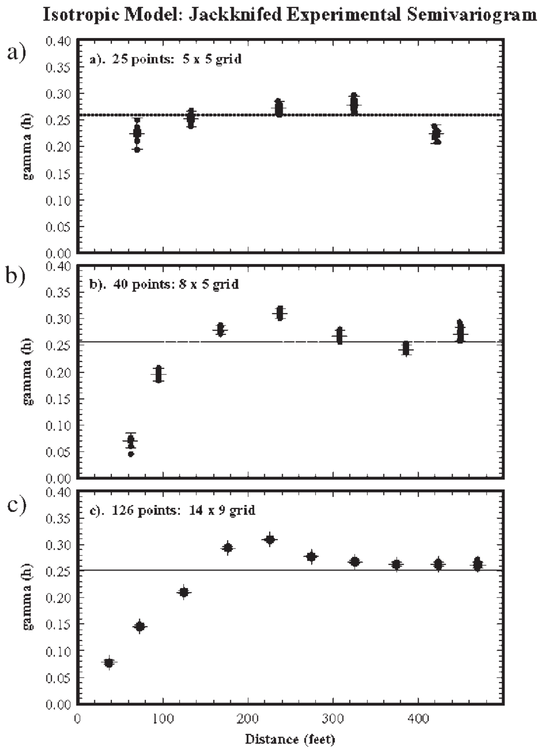

Figure 8. Substantial amount of data allows clearly defined experimental semivariogram (from WINGLE 1997)

8. ábra. *Kellő mennyiségű adatpont a tapasztalati félvariogramot jól meghatározza (WINGLE 1997 nyomán)* be clearly defined. But WINGLE (1997) stated that *"if the experimental 'jack-knifed' semivariogram of lithology at a field had the character of Figure 8c it could be argued that too much money was expended collecting data and the semivariogram could have been modelled adequately with fewer data*". It means that 'jack-knifed' results can also help in making conclusion on dataset size (too little, optimal, too large).

'Jack-knifed' semivariogram of the clastics lithofacies

The 'jack-knifed' semivariogram of the clastics lithofacies is shown on the *Figure 9*. The error bars are very wide and there are no any lags where bars are higher than sill. It indirectly points out that any spatial model will include large uncertainties, due to too small input dataset. In spite of very carefully selection of lag distance, the first point crossed the sill and open the question: "Is there any autocorrelation inside the clastics porosity dataset?". The axiomatic rule of porosity autocorrelation allowed to calculated semivariogram model (Figures 3, 4 and 5).

Putting the well names on the 'jack-knifed' semivariogram there is a possibility for pointing out the wells that have the major influence on qualitative shape of the error bars (*Figure 10*). These wells are outlined on porosity map shown on Figure 11.

Presented 'jack-knifed' semivariogram (Figure 9) suggests that 15 data points are not enough to correctly define the reliable experimental semivariogram. The data are not even sufficient to conclude if the well's pattern (*Figure 11*) is tight enough to be within the range of the local variance, as indicated by the fact that the upper limit of the uncertainty bars associated with several sample lags falls significantly above the total variance (the sill). This suggests that further data collection is required.

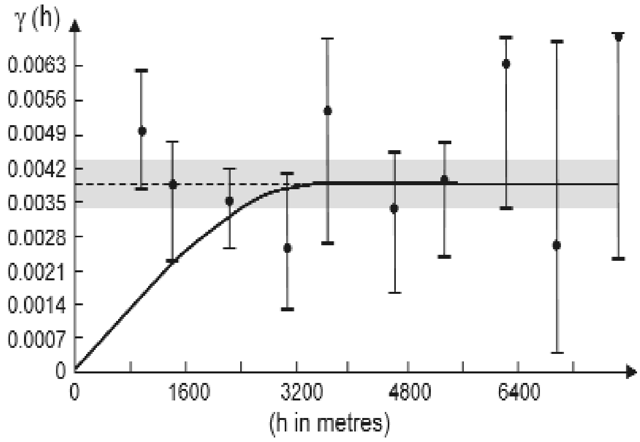

Figure 9. 'Jack-knifed' semivariogram of the clastics lithofacies

9. ábra. *A törmelékes litofáciesű képződmények jack-knife-variogramja*

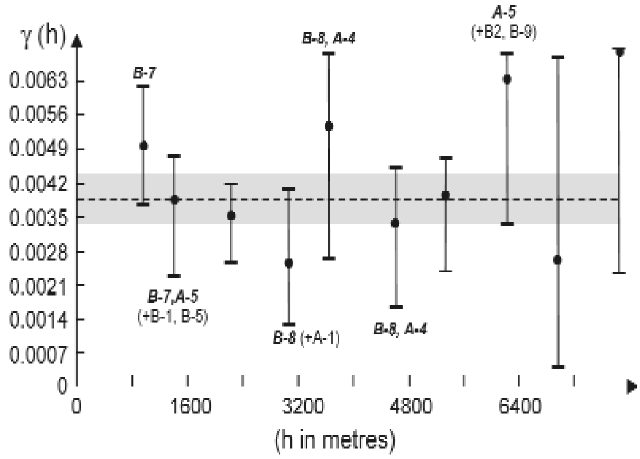

Figure 10. Wells (bold and italic) the most influenced on uncertainty range

10. ábra. *A leginkább befolyásolt fúrások (félkövér és dőlt) a bizonytalansági skálán*

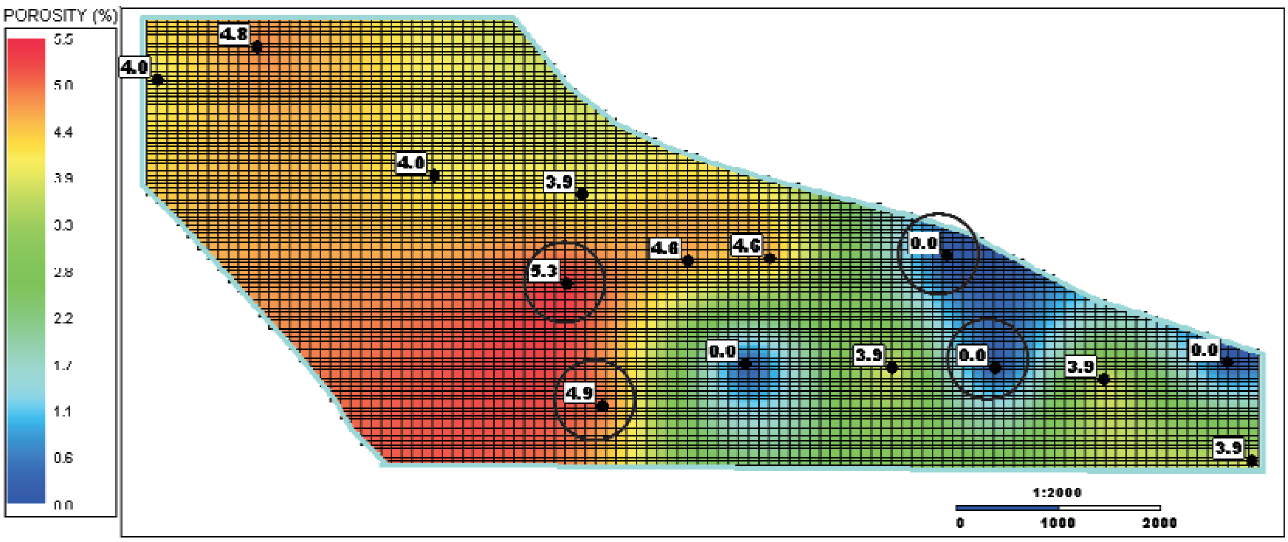

Figure 11. Locations of well data with the highest influence on 'jack-knifed' semivariogram

11. ábra. *A leginkább befolyásolt fúrások helyzete a jack-knife-variogramon*

Discussion and conclusions

It is difficult to differentiate an experimental semivariogram that represents the true nature of the site, from one that is the product of a fortunate lag selection. 'Jack-knifing' provides error-bars which gave the modeller insight look to the level of confidence which can be attributed to the modelled semivariogram. Also, because data points are being removed from the data set to calculate the experimental semivariogram, the variance, and therefore the sill, will generally increase slightly.

The practice of 'jack-knifing' variogram estimator to improve model selection is not widely practised, although this simple method has many advantages. The 'jack-knifing' should not be considered for every dataset where the experimental semivariogram is poorly behaved. 'Jack-knifing' computationally is very time-consuming job. For "n" data samples "n-1" semivariograms must be calculated.

Several representative 'jack-knifed' variograms could led us to selection of the best semivariogram model or map obtained by such semivariogram checked by methods for discrepancy measure like mean square error (MSE) or weighted squared error (WSE).

Finally, we extracted from our work several major conclusions that could be applied as recommendation in further 'jack-knifing' analysis, especially applied in the Croatian part of Pannonian Basin:

— 'Jack-knifing' could be used as empirical measure of uncertainty, which could be visually interpreted also by non-geologists.

— The experimental variogram points, characterised with uncertainties bars completely higher (lower and upper margins) than sill can be excluded from any spatial analysis.

— It means that (1) we need try to find new lag settings or (2) input dataset is definitely too small for spatial analysis.

— Stari Gradac – Barcs-Nyugat dataset is very small and consequently has high uncertainty. Each upper margin of error bars of 'jack-knifed' semivariogram points are higher than sill.

— Comparing different 'jack-knifed' semivariograms (registering missing wells in each 'jack-knifed' dataset) made possible to select the well locations that had the major influence on uncertainty range.

— That made possible to outline field' zones the most sensitive on data lacking.

— We assumed that analysed dataset would include 2 or 3 additional wells to reach optimal size for omnidirectional semivariogram modelling, but it is questionable whether present hydrocarbon production justifies new data collection (drilling or seismic acquisitions).

— The price of seismic acquisition is significantly lower than price of the well drilling. Another advantage of seismics is that the spatial distribution of collected data is much better.

— It would be very useful to check existing seismic data of the field, and to quantify uncertainties of field and equipment testing. Based on results of such quantification it would be useful to estimate the needs for new seismic model reinterpretation and possible selection of secondary variable.

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The porosity map is made using 3DField, contouring surface plotting and 3D data program that run under MsWindows. Author is Mr. Vladimir Galouchko. The program was licensed by first author and used for interpolation.

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List of equations:

Eq. 1 — Spherical theoretical semivariogram model
Eq. 2 — Jackknife estimator
Eq. 3 — Generalized jackknife

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