Cokriging geostatistical mapping and importance of quality of seismic attribute(s)

T. Malvić, M. Barišić and I. Futivić

ORIGINAL SCIENTIFIC PAPER

Multi-component seismic provides a new way of looking at reservoirs properties. Application for seismic based both on P and S waves (PS signal) is constructed on the difference in reflectivity of these waves' types. One of the most important property of S-waves is their relative insensitivity to saturation (P-waves are very sensitive).

The 3D seismic was acquired and interpreted in the Molve field. The reliability of each seismic attribute was not enough to interpret gas zones, porosity and water saturation. The reason was complex reservoir geology, represented by even 4 lithofacies: lithofacies IV (mostly retrograde metamorphosed gneisses; Palaeozoic and older), lithofacies III (metaquartzites of Permian and Triassic ages), lithofacies II (mostly dolomites of Jurassic and Triassic age) and lithofacies I (Miocene limestones). It is why seismic attribute and reservoir parameter couldn't be correlated. It is why new type of multi-attribute was created for each of four reservoir lithofacies. Such multi-attribute was much more easily correlated by petrophysical variables. Based on Kalkomey's approach, the probability that calculated correlation was false had been estimated at 0.15.

Moreover, there was established correlation between attribute and porosity, especially in reservoir lithofacies III, consisting of quartzite, schist and greywacke. It is why the porosity was interpolated using geostatistical method of cokriging, i.e. using secondary seismic variable. Also, multi-attribute analysis makes the best reservoir visualization in limestone lithology of lithofacies II. It could be expected that in several years new multi-component seismic data could be recorded for the most important Croatian hydrocarbon fields. The Molve is one of the most important. New seismic data will improve the quality of interpreted attributes, and make possible to establish clear correlation between seismic and petrophysics in all lithostratigraphic units of such heterogeneous reservoir.

Key words: attributes, interpolation, cokriging, Molve, three-component (3C) seismic

1. Introduction

The Molve field was discovered in 1974 and it is the most important gas field in Croatian part of Pannonian basin, located in northwest part of Drava depression (Figure 1). Seismic interpretation, as well as reservoir modelling, is made with main goal to established reliable reservoir characterization model. Molve reservoir was initially overpressured (initial pressure was about 40-50% higher than hydrostatic), with high temperature, in intensively faulted zone with significant secondary porosity.[1]

Chronostratigraphic analysis enabled distinction of four main lithofacies.[1,2]

- Lithofacies I - Miocene limestone biomicrites and biocalcirudites;
- Lithofacies II - fractured Jurassic-Triassic dolomites, shale, filites;

Fig. 1. Location map
Sl. 1. Položajna karta

- Lithofacies III – Permian and Triassic metaquartzites with micas intrusion on southern part of the field and
- Lithofacies IV - Cambrian-Pre-Cambrian retrograde gneisses.

The Molve field encompasses the largest gas-condensate reservoir in Croatia. Interpretation of zones saturated by gas, water or porosity in complex lithological framework (like in the Molve field) includes knowing of geology, reservoir characteristics and rock physics. It can be done using multicomponent seismic survey and processing. Multicomponent methods have applications especially in heterogeneous reservoirs like in the Molve field. Analysis of the S-wave anisotropy can be very important interpretation tool.

Seismic interpretation was made continuously from discovery of the Molve field, and the latest data are based on 3D seismic information. It offered very detail insight in field structure (Figure 2), but also in lithological transitions as well as fluids saturation and their contacts. The total seismic information was represented through several attributes. However, reliability of single attribute was not enough for interpretation of zones saturated with gas, water or calculation of porosity. The reason was complex geology, when seismic attribute and reservoir variables couldn't be correlated. New type of multi-attribute was created for each lithofacies, and such attribute was much more easily correlated by petrophysical variables. Some calculation based on Kalkomey's approach9 indicated that established correlation could be false only in 15% events, what is promising result.

The most reliable correlation between seismic attribute and porosity was calculated for lithofacies III, which had been interpolated using cokriging method.

Generally, the Molve field was very detailed mapped regarding strata depth, reservoir thickness and porosity distribution. The most advance interpolation modelling was done on porosity maps, finally reaching very reliable maps for all four lithofacies. Maps are obtained by kriging and stochastic Gaussian approach,[11] but in lithofacies III it was possible to apply cokriging method.

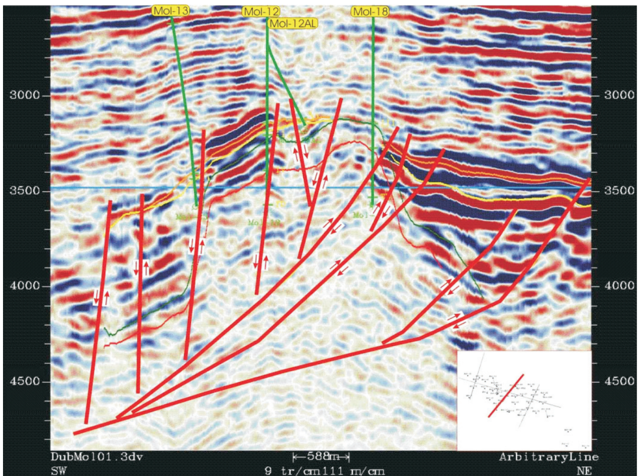

Fig. 2. The Molve structure shown on seismic line striking NE-SW
Sl. 2. Struktura Molve prikazana na seizmičkom profilu pružanja SI-JZ

2. Mathematical fundamentals of cokriging

Cokriging, like basic Kriging method, also includes several interpolation techniques.[6,7,8] That method includes two variables, primary as well as secondary that describes behavior of primary (and also these two variables are in strong correlation). Also, secondary variable had being interpreted on much greater number of locations.

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

Where:

$\sum_{i=1}^{n} \lambda_i \cdot z_i$ - *any kriging equation (e.g. see Eq. 2)*

$\sum_{j=1}^{m} \chi_j \cdot s_j$ *secondary kriging equation, applicable to the second variable*

Simple kriging matrix equation, as the simplest kriging technique, is:

$$\begin{bmatrix} \gamma(Z_1-Z_1) & \gamma(Z_1-Z_2) & \dots & \gamma(Z_1-Z_n) \\ \gamma(Z_2-Z_1) & \gamma(Z_2-Z_2) & \dots & \gamma(Z_2-Z_n) \\ & & \dots & \\ \gamma(Z_n-Z_1) & \gamma(Z_n-Z_2) & \dots & \gamma(Z_n-Z_n) \end{bmatrix} \cdot \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \\ \lambda_n \end{bmatrix} = \begin{bmatrix} \gamma(Z_1-Z) \\ \gamma(Z_2-Z) \\ \\ \gamma(Z_n-Z) \end{bmatrix} \tag{2}$$

Where are:

γ	*the variogram values;*
$Z_1 \dots Z_n$	*known measured values at points (hard data);*
Z	*the point at which new values are estimated from hard data.*

Furthermore, when this estimation is performed at the control point (so called hard-data), the error can also be calculated at the point as:

$$\varepsilon = (Z_{real} - Z_{estimated}) \tag{3}$$

If in measured data was not possible observed any drift (e.g. very clear similarity in data values regarding geographical locations), and the sum of all weighting coefficients is 1, unbiasedness of estimation is achieved. The difference between all the measured and estimated values is called the **estimation error** or **kriging variance** and it is expressed as:

$$\sigma^2 = \frac{\sum_{i=1}^{n} (Z_{real} - Z_{estimated})_i^2}{n} \tag{4}$$

In an ideal case, kriging tries to calculate the optimal weighting coefficients that will lead to the minimal estimation error. Such coefficients, which lead to an estimation of unbiasedness with minimal variance, are calculated by solving of the matrix equations system.

Another numerical validation method is called **cross-validation**. It is a numerically relatively simple and widely used technique for evaluation of estimation quality. It is based on removing the value measured on selected location and estimating a new value on the same lace considering the remaining existing data.[5] The procedure is repeated for all the wells and at the end the mean square error (MSE) of the estimation is calculated. The disadvantage of the method could be its particular insensitivity to the number of analysed wells. This procedure is sometimes known also as jack-knifing but generally these are two different approaches.[3,12]

$$MSEmethod = \frac{1}{n}\sum_{i=1}^{n}(meas.val - est.val.)_i^2 \qquad (5)$$

Where are:

MSEmethod mean square error of the selected method estimate

meas.val. measured value of the selected variable on the well «i»

est.val. estimated value of the selected variable on the well «i»

3. Cokriging mapping in the Molve field

In the Molve field lithofacies III was mapped by cokriging. Seismic attributes (amplitude, frequency and phase) had been interpreted. Such interpretation was been able to done in all lithofacies except in the oldest lithofacies IV due to insufficient number of data. Amplitude was selected as the most descriptive attribute for porosity values. It is why different derivation of amplitude had been correlated by porosities averaged at the well location in reservoir part called as lithofacies III (Table 1).

Table 1. Correlation among porosity and amplitude attributes (16 data pairs

	Amplitude	Reflection strength	Dip of reflect. strength
Porosity	0.47	0.51	-0.14

The maximal correlation was calculated between porosity and reflection strength. Correlation significance was checked using t-test. Calculated value is t=2.22, and $t_{critical}$=1.76 (for α=5%). It means that calculated correlation is statistically significant. In geological sense, the reflection strength can describe variation in porosities. It is why reflection strength is selected as secondary spatial variable. Furthermore, the secondary variable is sampled at much more grid nodes than primary (2 500 vs. 16 nodes). It is why anisotropic experimental variogram is modelled from secondary variable data (Figure 3). This model is defined by:

- Azimuth of primary axis 120°;
- Lag-spacing about 350 m;
- Primary range 4 000 m (spherical theoretical model without nugget);
- Secondary range 2 900 m (spherical theoretical model without nugget).

The number of variogram data pairs was extremely high and it represents benefit of introducing of secondary variable. The ranges could be determined extremely precise (in any interpretation can vary only a few percent).

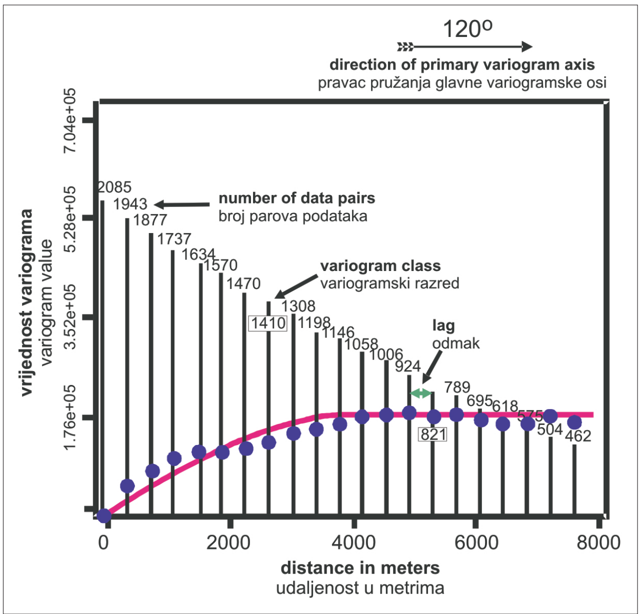

Fig. 3. Experimental variograms on primary axis in lithofacies III
Sl. 3. Eksperimentalni variogrami na primarnoj osi u litofacijesu III

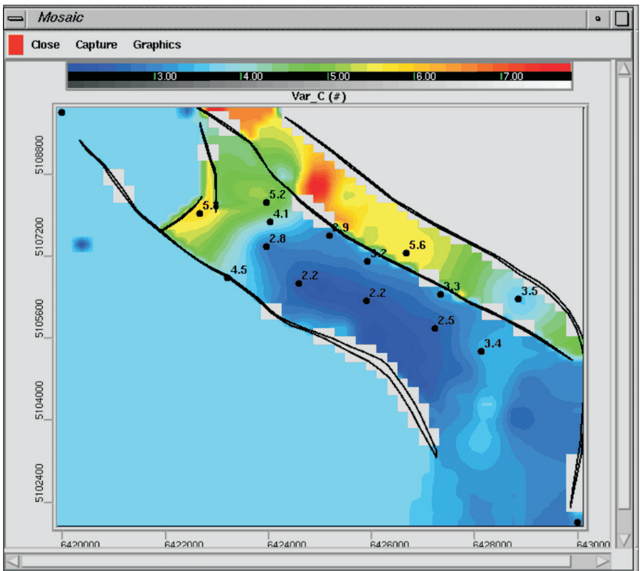

Figure 4: Porosity interpolation obtained by Ordinary Cokriging in lithofacies III (colour porosity scale is on the top – 0.002 on the left / blue ; 0.008 on the right / red)
Sl. 4. Interpolacija poroznosti dobivena običnim kokrigingom u litofacijesu III (skala poroznosti u boji je na vrhu - 0,002 dij. jed. na lijevo / plavo ; 0,008 dij. jed. na desno / crveno)

The relevant porosity map, obtain by Ordinary Cokriging technique, is shown on Figure 4.

The numerical quality of interpolation was checked using cross-validation, and the obtained value is

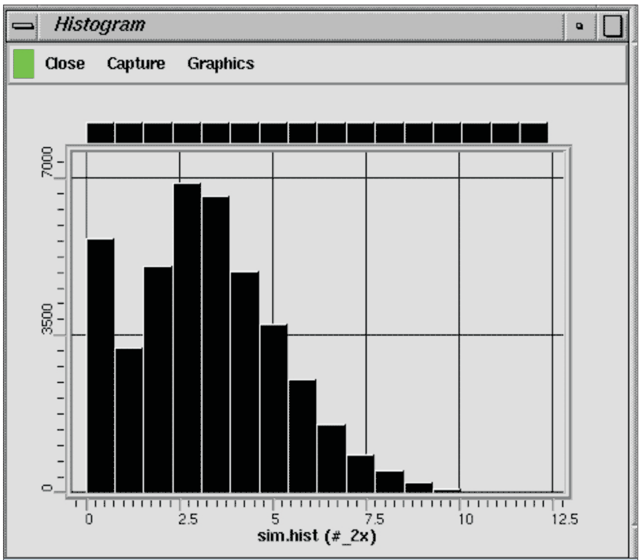

Fig. 5. Histogram of simulated data in lithofacies III
Sl. 5. Histogram simuliranih podataka u litofacijesu III

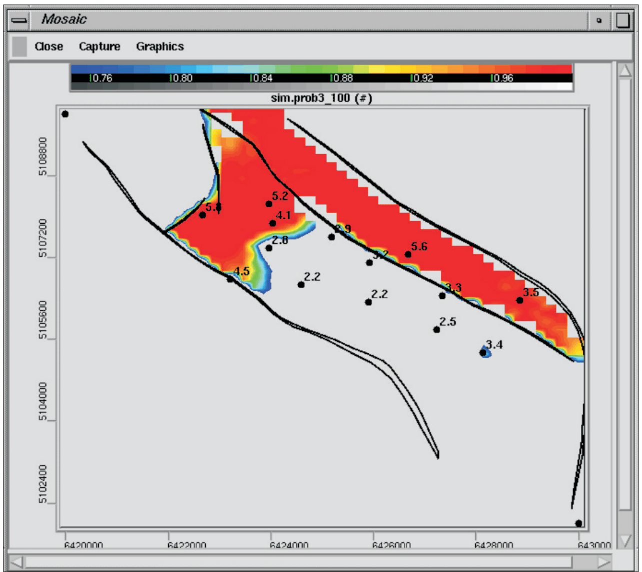

Fig. 6. Probability maps that porosity is equal or larger from 3% in lithofacies III (colour probability scale is on the top – 0.75 on the left / blue ; 1.00 on the right / red)
Sl. 6. Karta vjerojatnosti da je poroznost jednaka ili veća od 3 % u litofacijesu III (skala vjerojatnosti u boji je na vrhu - 0,75 na lijevo / plavo ; 1,00 na desno / crveno)

$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(x_{measured} - x_{estimated}\right) = 1.28$. It is the lowest possible value that could be reached by available data in analysed lithofacies.

Some additional information about reservoir is gained using stochastical Gaussian simulations. There were performed 100 realizations, but this approach was based on the kriging solution as the zero-realization, because stochastics analysis had been done only for primary variable (porosity). The analysed new porosity dataset was derived from a set of 100 realizations. Calculated histogram of simulation data (original dataset was too small for calculation of reliable histogram) is shown on Figure 5.

Statistical values derived from histogram are defined by average porosity of 0.031 9, standard deviation of 1.99 and maximal value of 0.122 7. There are several useful maps that could be derived from a stochastical set of 100 realizations. Here is presented the map (Figure 6) where porosity values are shown only in cells where value could be minimum 0.003. Note that zones of higher porosities are mostly located along the main faults.

4. Seismic attribute analysis in the Molve field

Attribute analysis can reveal much information about reservoir, for example in identification of different lithotypes, porosities and gas saturation.

Multi-attribute is quotient of normalized amplitude and frequency and their product with phase within every lithofacies.[14] For correlating seismic attributes and reservoir parameters under such complex sedimentation and tectonics it should be taken into consideration the actual lithological complexity. After creating multi-attribute it was possible to reach good correlation between attributes and reservoir characteristics in lithofacies III. Such correlation was successful for each lithotypes. Probability of false correlation[9] between porosity and seismic attribute was estimated as low as 0.15.

Lithofacies I is defined by two main genetic and production units - biomicrites with poorer and biocalcirudites with very good reservoir properties.

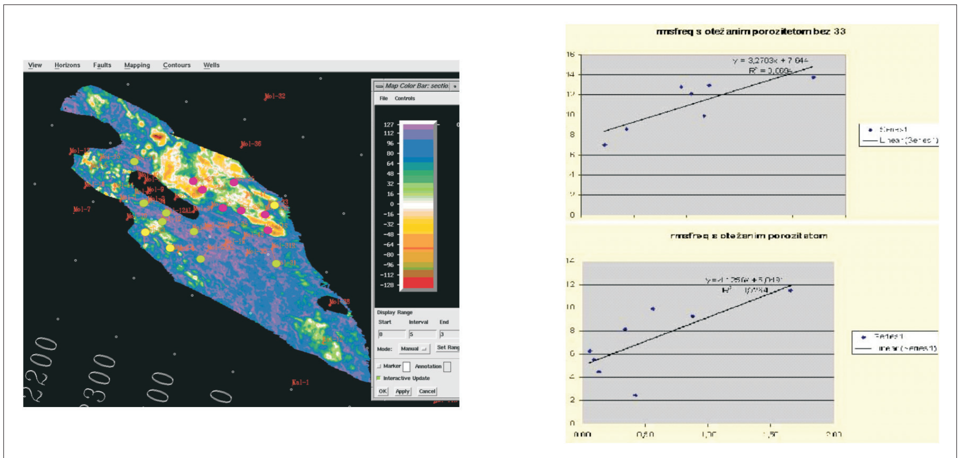

Fig. 7. Correlation between multi-attribute and net pore volume in lithofacies I [13]
Sl. 7. Korelacija između složenoga atributa i efektivne debljine x poroznost u litofacijesu I [13]

There are good correlations between multi-attribute and product of net pore volume for both of these lithotypes (Figure 7).

Lithofacies II includes pure dolomites on the northern part and shaly dolomite on southern part of the field (Figure 8). Coefficient of determination (R2) between multi-attribute and net pore volume was 0.65.

Lithofacies III mostly included the metaquartzites as dominant lithotype (areas with significant mica content, as impermeable regions, were excluded from analysis; Figure 9). The coefficient of determination (R2) between multi-attribute and net pore volume was 0.72.

Lithofacies IV included too small number of data for reliable analysis.

There is no doubt that quality of seismic attribute and any their synthetic attribute (created from two or more single attributes) is "key-tool" for establishing of significance correlation between porosity (or any reservoir variable) and seismic.

It is worthy to mention that transversal waves are more and more the valuable source of seismic signal that is eventually converted in attributes. Moreover, from the end of the 1980s interest in the P-wave as a source of S-waves energy starts to grow. This came partly from vertical seismic profiles (VSP) measurements. Figure 10 shows a VSP example where P-waves are converted directly to S-wave reflections (PS-waves). Such waves have nearly equal amplitude as P-wave.

The most projects, where multi-component seismic had been applied[4,5] using S-waves as the source of seismic signals, had been performed in reservoirs in clastic rocks where change in compressibility is the main property of seismic time-lapse proves. But similar analysis can be done in carbonate reservoir rocks, where S-waves anisotropy can be useful tool for measuring of changes in hardness. Such method can be applied in any heterogeneous reservoir, like such described in the Molve field, hopefully to reach the better attribute analysis.

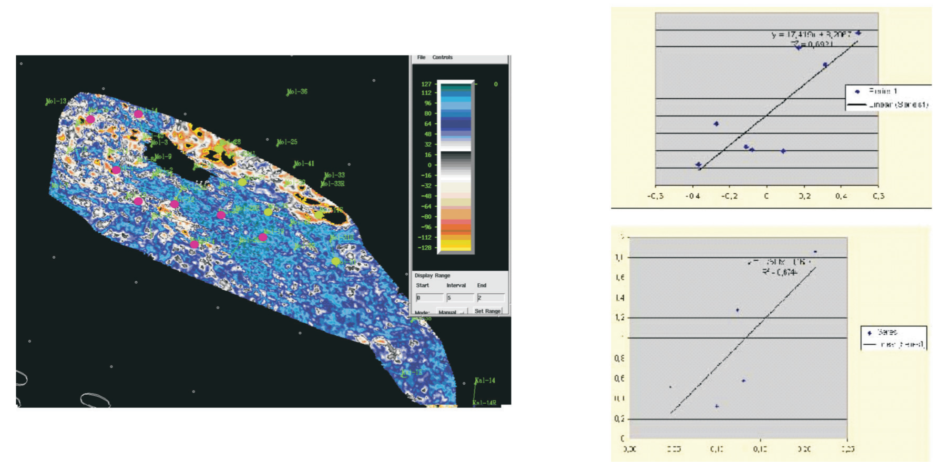

Fig. 8. Correlation between multi-attribute and net pore volume in lithofacies II [13]
Sl. 8. Korelacija između složenoga atributa i efektivne debljine x poroznost u litofacijesu II [13]

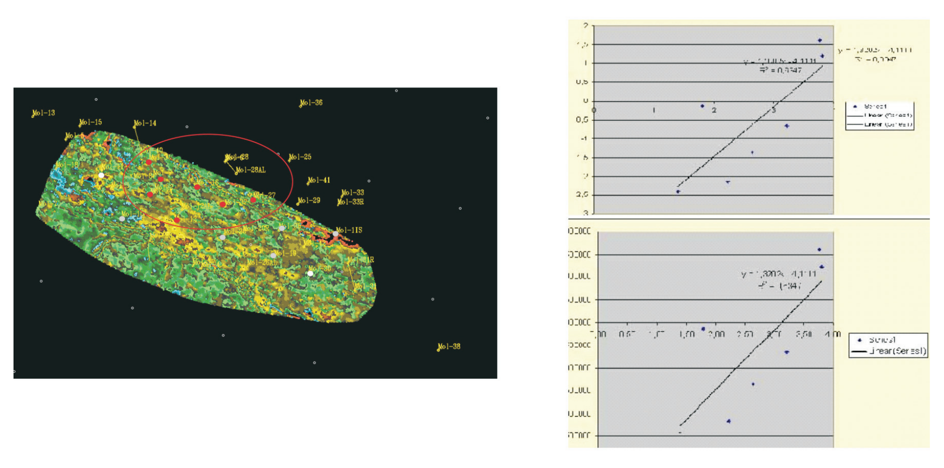

Fig. 9. Correlation between multi-attribute and net pore volume in lithofacies III [13]
Sl. 9. Korelacija između složenoga atributa i efektivne debljine x poroznost u litofacijesu III [13]

5. Conclusion

Full wave imaging of high quality, using transversal (S) waves, should improve resolution and more efficient noise suppression. Such high-quality seismic and consequently more confident attribute analyses should improve our knowledge of reservoir in any sense and allowed to use cokriging interpolation for entire reservoir sequence. Also, the S-waves insensitivity to fluid effects, can very successful help in discrimination of lithologies.

Quality of existing seismic data and their good processing made possible to apply Ordinary Kriging in lithofacies III of the Molve field. Defining of secondary variable, sampled on much grater number of location than primary, had offered the possibility to define very reliable anisotropic variogram model. Such by Ordinary Kriging technique had been interpolated very precise porosity map in lithofacies III inside the field borders defined by main faults.

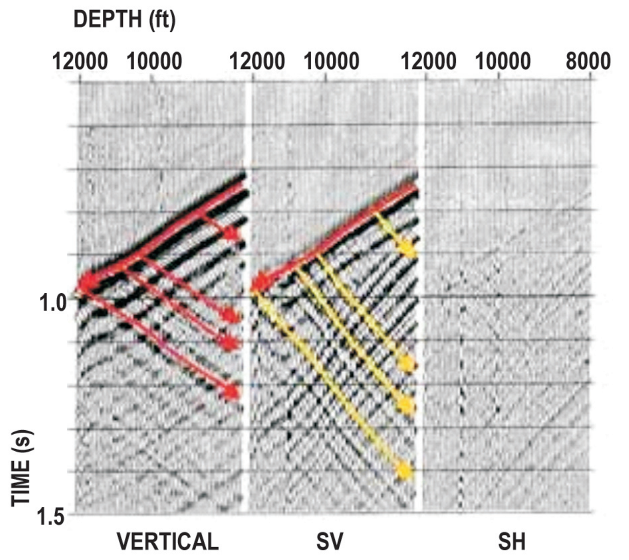

Fig. 10. P-waves are converted directly to S-wave reflections (SV events in yellow) and have nearly equal amplitude[10]
Sl. 10. P-valovi izravno konvertirani u reflekse S-valova (SV događaji označenim žutim) imaju gotovo jednaku amplitudu kao izvorni refleksi P-valova[10]

The supplemental statistical values of porosity had been calculated using sequential Gaussian approach in lithofacies III. The average porosity had been estimated on 0.031 9.

Of course, defining of multi-attribute (what depends on more quality of seismic signal) would probably result in establishing the correlation between porosity and attributes also in other lithofacies in the Molve field. It would largely improve mapping of the porosity and generally of the reservoir variables, because visualization of such attribute makes possible recognition of the zones characterised by better reservoir properties or areas that including residual gas accumulations.

Acknowledgments

The presented results are partially based on data previously publicly published activities of Reservoir Engineering & Field Development as well as Exploration Department as parts of INA-Oil Industry Plc. We gratefully reprint some results from papers given in references.

6. References

1. Barić, G., Mesić, I., Jungwirth, M. & Spanić, D. (1990) Plinsko i plinsko kondenzatna polja Molve, Kalinovac i Stari Gradac [Gas and gas condensate fields Molve, Kalinovac and Stari Gradac], Nafta, 41, 2, 71 – 89
2. Dalić, N., Malvić, T. & Velić, J. (2005): Različiti udjeli u povećanju iscrpka iz paleozojsko-mezozojskih litofacijesa na poljima Molve i Kalinovac [Different portions in increment of total recovery obtained from Paleozoic-Mesozoic lithofacies at the fields Molve and Kalinovac], 3. hrvatski geološki kongres, Opatija, Croatia, 29. IX.-1. X. 2005., p. 31-32
3. Davis, B.M. (1987) Uses and Abuses of Cross-Validation in Geostatistics, Mathematical Geology, 19, 3, 241 - 248
4. Davis, T.L. (2006) Multicomponent seismic characterization and monitoring of the CO_2 flood at Weyburn Field, Saskatchewan, Canada, Nafta, 57, 11, 451 - 455
5. Gaiser, J. E. and Strudley A. (2005) Acquisition and application of multicomponent vector wavefields: are they practical?, First Break, 23, 61 - 67
6. Hohn, M.E. (1988) Geostatistics and Petroleum Geology, Van Nostrand Reinhold, New York.
7. Isaaks, E. and Srivastava, R. (1989) An Introduction to Applied Geostatistics, Oxford University Press, New York.
8. Journel, A.G. and Huijbregts, C.J. (1978) Mining Geostatistics. Academic Press, Orlando.
9. Kalkomey, C.T. (1997) Potential risk when using seismic attributes as predictors of reservoir properties, The Leading Edge, March, 247 - 251
10. Iverson, W.P., Fahmy, B.A. and Smithson, S.B. (1989) VPVS from mode-converted P-SV reflections, Geophysics, 54, 843 - 852.
11. Malvić, T. (2005) Results of geostatistical porosity mapping in Western Drava Depression fields (Molve, Kalinovac, Stari Gradac), Nafta, 56, 12, 465 - 476
12. Malvić, T. and Bastaić, B. (2008) Reducing variogram uncertainties using the jack-knifing method, a case study of the Stari Gradac-Barcs Nyugat field, Bulletin of Hungarian Geological Society (Földtani Kozlony), 138, 2, 165 - 174
13. Sladović, Ž., and Futivić, I.: Multiattribute Analyses in Gas Field Development (Molve Field Study), EAGE/SEG International Conference and Exhibition, St. Petersburg, Russia, 16-19. October 2006, Abstract number A021 (Field & Reservoir Studies)
14. Sladović Z., Futivić I. and Durn T. New approach to attribute analysis on Bačkovica gas field, 3rd Croatian Geological Congress, Opatija, Croatia, 28.9.-2.10. 2005, poster

❖

Authors:

Tomislav Malvić DSc, Graduate in Geology, INA-Naftaplin, Reservoir Engineering and Field Development Department, Advisor, tomislav.malvic@ina.hr, University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Institute for Geology and Geological Engineering, visiting lecturer

Miroslav Barišić, Graduate in Geology, retired (ex. INA-Naftaplin, Exploration Dept.), miroslav.barisic2@zg.t-com.hr

Igor Futivić, Graduate in Geology, INA-Naftaplin, Reservoir Engineering and Field Development Department, Head of Unit for field stimulation, igor.futivic@ina.hr