Peer-reviewed version available at *Geosciences* **2019**, *9*, 36; doi:10.3390/geosciences9010036

Article

Kriging with small number of data supported by jack-knifing, case study in the Sava Depression (Northern Croatia)

Tomislav Malvić [1,*], Josip Ivšinović [2], Josipa Velić [3] and Rajna Rajić [1]

[1] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering (Full Professors); tomislav.malvic@rgn.hr , rajna.rajic@rgn.hr
[2] INA Plc., Zagreb (MS in Petr. Eng.); josip.ivsinovic@ina.hr
[2] University of Zagreb (Prof. Emerita); josipa.velic@rgn.hr
* Correspondence: tomislav.malvic@rgn.hr; Tel.: +385-1-5535758

Abstract: Presented is semivariogram and the Ordinary Kriging analyses of porosity data from the Sava Depression (Northern Croatia), as part of the Croatian part of the Pannonian Basin System. Data are taken from hydrocarbon reservoirs of the Lower Pontian (Upper Miocene) age, which belongs to the Kloštar-Ivanić Formation. Original datasets had been jack-knifed with purpose to "artificially" increased data and calculate the more reliable semivariograms. The results showed that such improvements can assist in the interpolation of more reliable maps. The both sets, made by original and jack-knifed data, need to be compared using geological recognition of non-allowed shapes ("bull-eyes", "butterfly effects") as well as cross-validation results. That comparison made possible to select the most appropriate porosity interpolation.

Keywords: Ordinary Kriging, variogram, jack-knifing, Upper Miocene, Northern Croatia, porosity

1. Introduction

The hydrocarbon reservoirs in the Sava Depression (Northern Croatia) are in the secondary or tertiary recovery phase. The most of the are supported by water injection. Here are analyzed two fields from mention depression with still significant production of hydrocarbons from selected reservoirs. Those are field "A", reservoir "L" and the field "B", reservoir "K", hydrodynamic unit "K1".

This analyses in the continuation and based of many previous works published for the volume of the Sava Depression as well as the entire Croatian part of the Pannonian Basin System (abbr. CPBS). The works [1] and [2] presented injection and separation of reservoir fluids in these fields. The costs of such processes are given in [2, 3]. Statistical and mapping represented continuation of previous regional works, especially in the Sava Depression. So, [4] presented using of descriptive statistics (porosity vs. depth) and tests (t, F-tests) and Pearson correlation for interpretation of influence of increasing of depth on decreasing of porosity in the Bjelovar Subdepression (the Kloštar-Ivanić Formation, Pepelana and Poljana Members). [5] pointed out the Kriging as the most appropriate method for porosity interpolation in the Sava Depression. [6], for the data from the Stari Gradac-Barcs Nygat Field (the Drava Depression), for the first time in Croatian geology, applied the jack-knifing in the variogram modelling of the reservoir variables. In the same field, [7] for the first time applied stochastically improved probability of success calculation. [8] described the most often applied Kriging techniques – Simple, Ordinary and Indicator – and is given optimal Lagrange value in the Ordinary Kriging for the CPBS. [9] gave sequential Gaussian simulation (abbr. SGS) results for the Kloštar Field in the Sava Depression. [10] analyzed lithofacies from logs, porosity maps, and made indicator transformation and maps (the Kloštar Field, Sava Depression). In the same field, [11]

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

analyzed reservoir porosity, depth and thickness using 100 realizations of the SGS. [12] applied geostatistics for the most detail geological model of the Kloštar Field and typical depositional model of the Upper Miocene sandstone reservoirs in the Sava Depression. [13] described the four main application of geostatistics and recommended for the CPBS such interpolation for the datasets with 20 or more points. [14] recommended the Ordinary Kriging as the most appropriate technique for the sandstone reservoirs in the Sava Depression. [15] applied the sequential indicator simulations for porosity mapping (the CPBS), using reservoir thickness maps as the secondary source of information. [16] applied stochastically improved probability model of geological risk as new approach for clastic reservoirs in the CPBS. [17] used the Ordinary and Indicator Kriging as well as the SGS for CO2 sequestration in the oil reservoirs. Deterministical method for geological risk has been adapted for sequestration purpose. [18] mapped the Bjelovar Subdepression using the Ordinary Kriging and digitalized set of older maps. [19] analyzed data from the Šandrovac Field (the Drava Depression) comparing the Ordinary Kriging, Inverse Distance Weighting and Nearest Neighborhood. [20] used the Universal Kriging, for the first time in the Bjelovar Subdepression and proven as the best interpolation method in the CPBS if regional trend is visible. [21] described application of stochastic simulation for Lower Pontian reservoir in general (the CBPS). [22] presented the problem of selection appropriate mapping method for the dataset with small number of data (i.e., Nearest Neighborhood vs. Inverse Distance Weighting).

All these works have been analyzed before presented study. The problem of relatively small number of data is characteristic for almost each particular structure (field) in the Sava Depression. Such data cannot be additionally collected (most due to expenses), so the statistically available methods (jack-knifing) for increasing of "artificial" data are analyzed. For the fields "A" (reservoir "L") and "B" (reservoir "K"/HD "K1") two variables are collected (porosity, injected water) and mapped with several methods (Nearest Neighborhood, Inverse Distance Weighting, Kriging). Both fields are located in the Sava Depression, about 90 km south-eastern from the capital Zagreb (Figure 1) and close to the highway A3 (5 km) and regional railroad (4 km).

The smaller location maps of analyzed fields has been presented at Figure 2 (the field "A" with blue and "B" with red borders). The both fields are on the hilly terrain. "A" is elongated structure with strike NW-SE and altitude 113-216 m, crossed by numerous landslides, and partially forested. Similarly, the altitude of field "B" is 120-231 m. The hills are steep, locally forested.

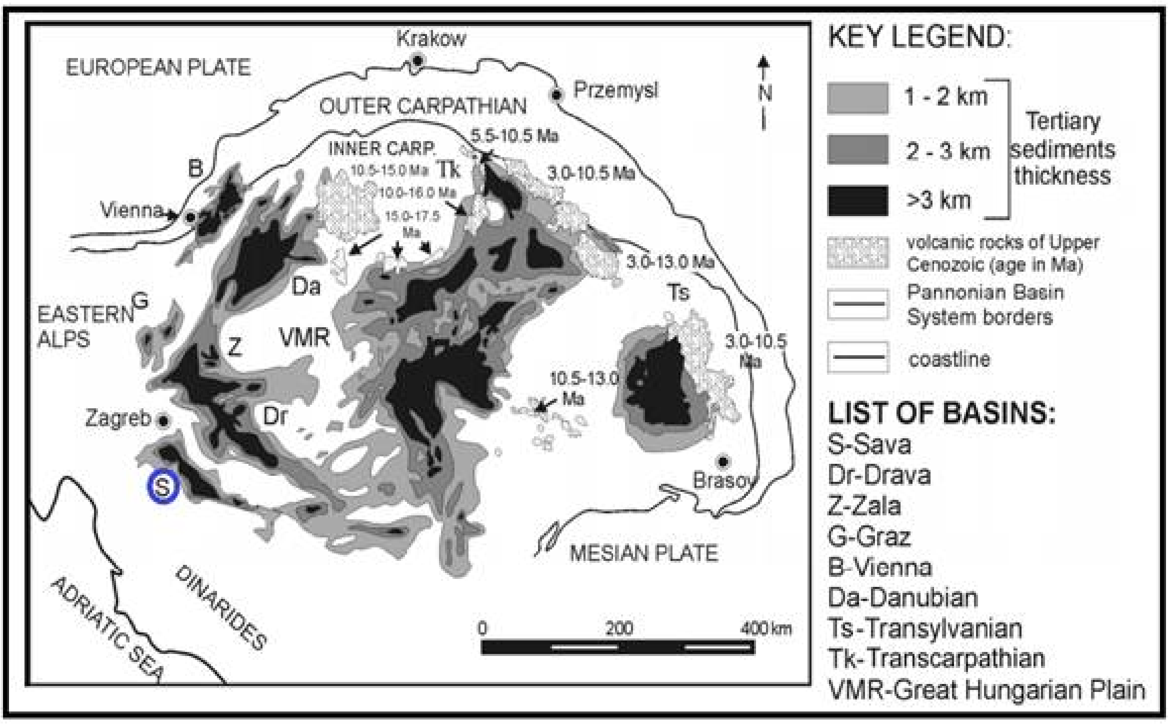
Figure 1. Regional geological units of the 2nd order (depressions in the CPBS) and location of the fields „A“ and „B“ in the Sava Depression (from [23])

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

Figure 2. Satellite maps of the fields „A“ and „B“ (taken from Google). The figure represents area boxed on Figure 1.

2. Geological history of the Sava Depression and analyzed structures

Here is given the short review of geological history for typical sandstone, Neogene hydrocarbon reservoir in the CPBS, and particularly Sava Depression, i.e. type that had been analyzed in this paper. The CPBS is located at the very south-western part of the PBS. Marginal location, regional position of the rock of the pre-Neogene basement and Neogene and Quaternary tectonics are reason for the present-day structures and their elongation northwest – southeast. The entire area is divided in the four depressions – Sava, Drava, Mura and Slavonia-Srijem (Figures 1 and 3).



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

Figure 3. Regional geological units of the 1st order in the Pannonian Basin System (abbr. PBS) (modified from MALVIĆ 2012b, ROYDEN, 1988)

Croatian depressions were situated always at the margins of the PBS. Consequently, those areas were covered by shallow marine environments of the Paratethys during Badenian and Sarmatian (16.4 – 11.5 Ma). It was reduced in the Pannonian Lake in the Lower Pannonian (11.5 – 9.3 Ma), and disintegrated during the Upper Pannonian (9.3 – 7.1 Ma) and Pontian (7.1 – 5.7 Ma) in several lakes. They were during Pliocene again connected in the smaller Slavonian Lake (PAVELIĆ & KOVAČIĆ, 2018) and eventually finished as continental facies (in Upper Romanian) that prevailing today (Holocene). The main stages of the geological evolution are shown on Figure 4.

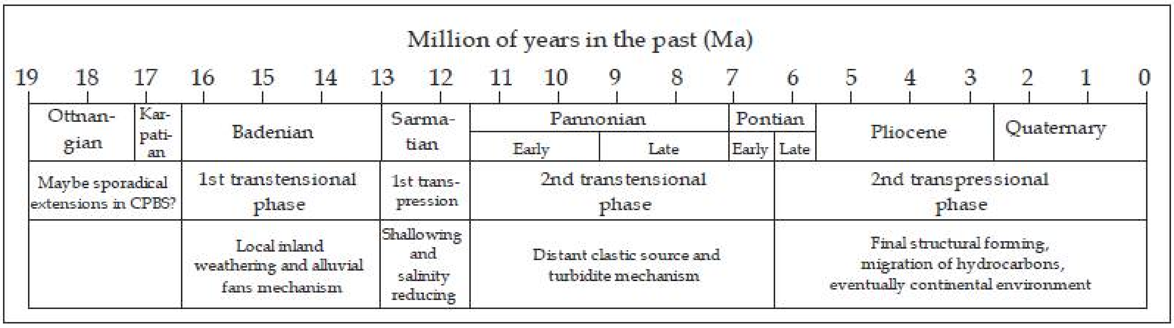


Figure 4. Timescale of the main tectonical and depositional events during Neogene and Quaternary in the CPBS [25]

In the entire CPBS, from Badenian until Upper Pontian (Middle to Upper Miocene), firstly carbonate, later clastic environments dominated. During Lower Pontian (Figure 5) the clastic reservoirs, analyzed here, had been deposited in the Sava Depression. In was time when huge volumes of sand and silt were transported by turbidites. In the meantime, during “calm” periods, different carbonate-rich mud was deposited. Such alterations of clastic is typical for “high” and “low” energy environments in the CPBS and had been presented, e.g., in [26].

 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

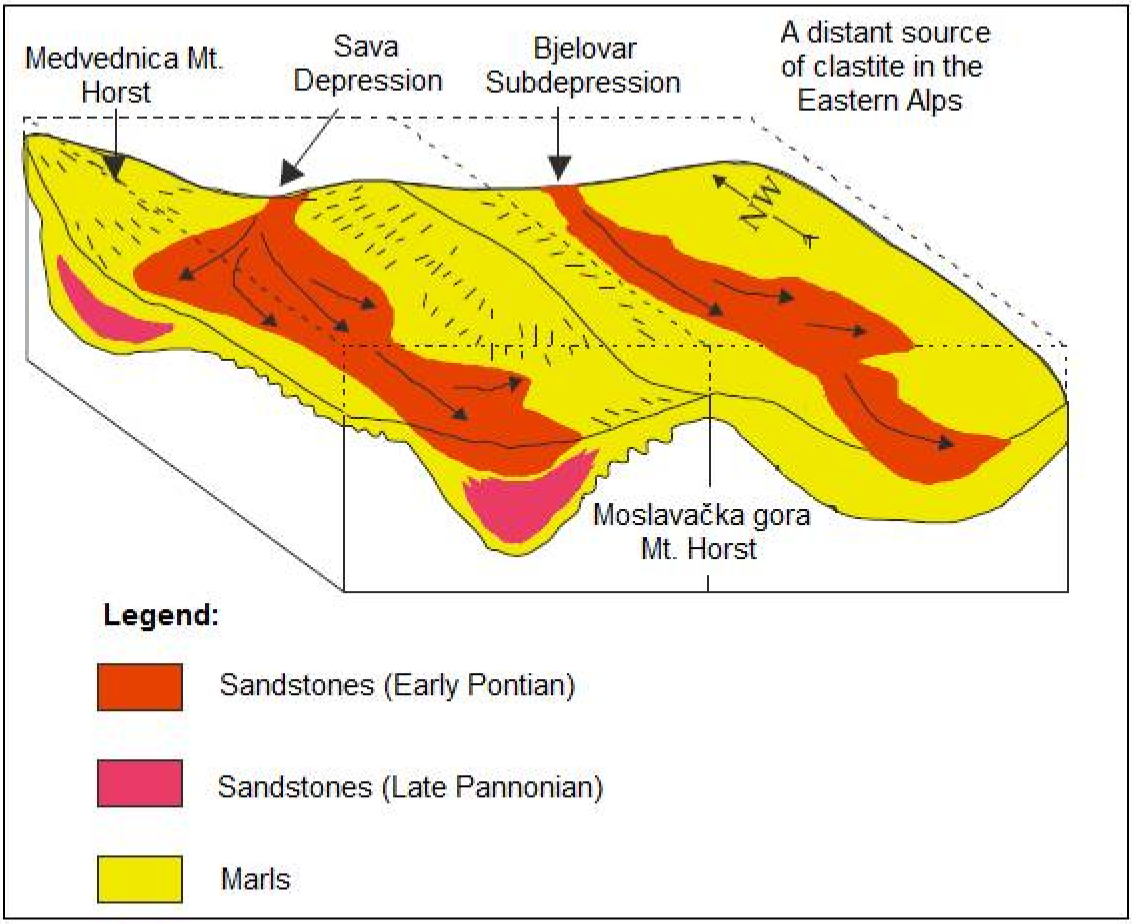
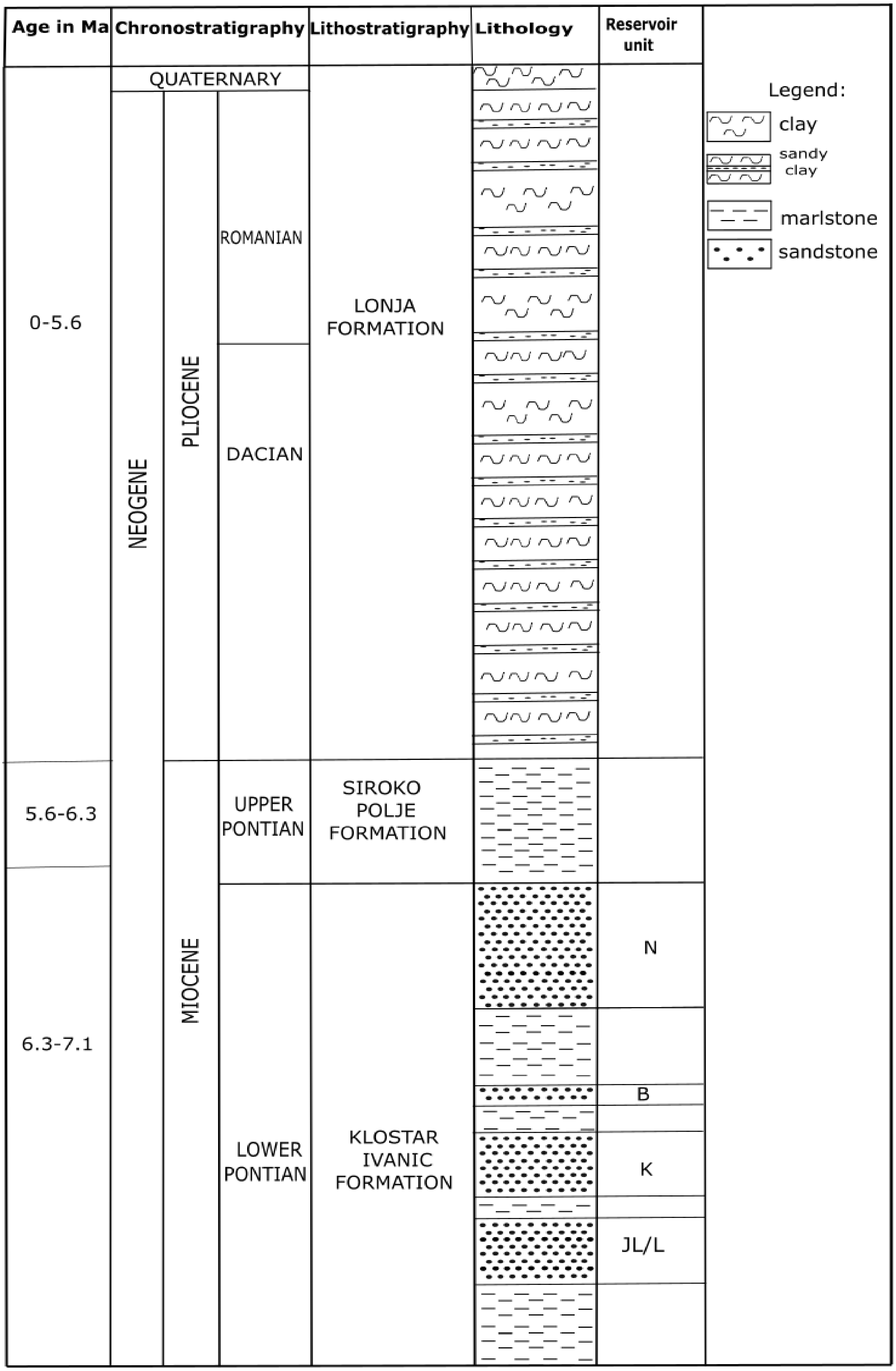


Figure 5. Schematic view on regional lacustrine environments at the border of the Sava and Drava Depressions. The huge amount of pelitic (marlstone) and turbiditic (sandstone, siltstone) clastics had been deposited. Taken from [25, 26, 27].

Consequently, more than 95 % sandstone reservoirs in the CPBS are of turbidite origin, and Upper Pannonian or Lower Pontian age. Such sandstones include several lithofacies. In the central part those are "pure", medium-grained sandstones, which gradually change into silty or clayey sandstones and siltstones on structural margins. Such heterogeneity was important for secondary migration as well as current recovery and production regime. The analyzed fields "A" and "B" are located in the western part of the Sava Depression, where currently water injection supports the production. The typical geological column has been drawn based on geological data from drilling and logging (Figure 6). The most of wells reached the rocks of the Kloštar-Ivanić Formation (Lower Pontian), because the reservoirs are discovered in that sediments. The formation is typical alteration of marlstones and sandstones, where analyzed reservoirs belong to the Pepelana Member. The marlstones are hard, grey to brown, and isolators for sandstone reservoirs (Figures 7 and 8).

Peer-reviewed version available at *Geosciences* **2019**, *9*, 36; doi:10.3390/geosciences9010036

135



136
137 **Figure 6.** Typical geological column for the fields "A" and "B". The formal and informal
138 lithostratigraphic units are listed.

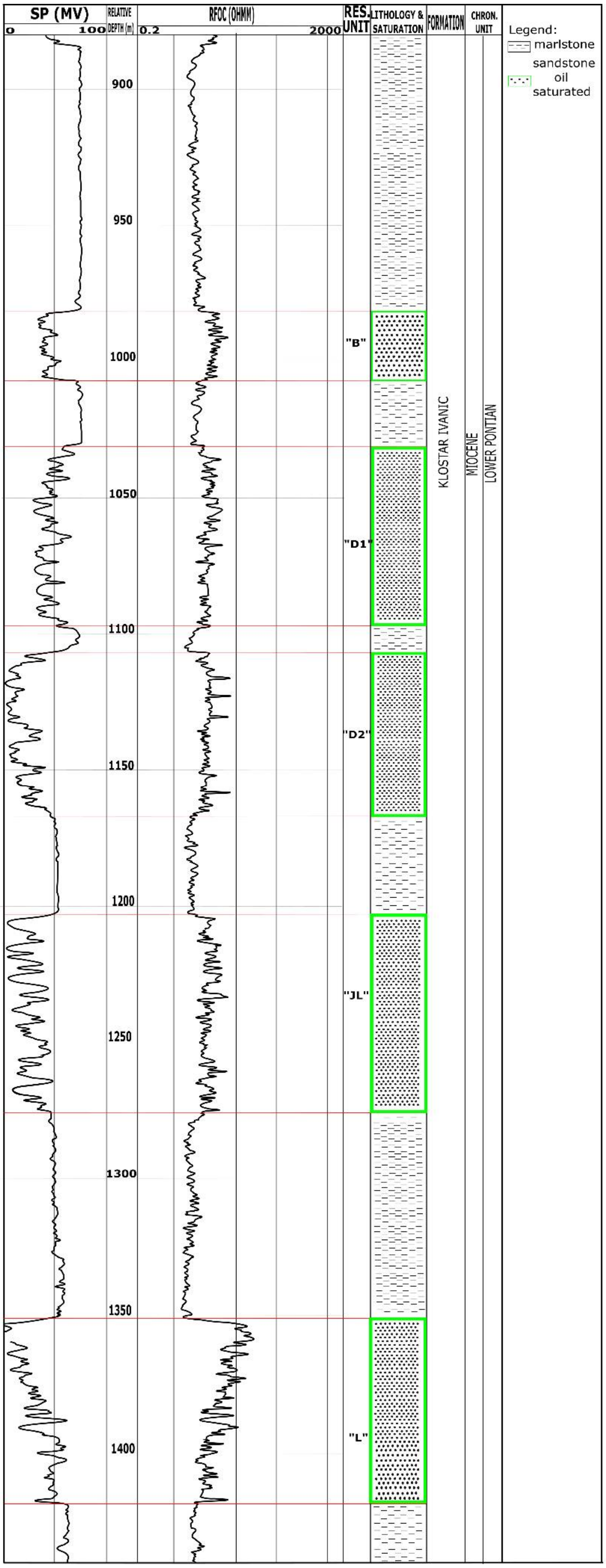


Figure 7. The composite log-lithological column in the field "A" (from archive of INA Plc. and re-drawn)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

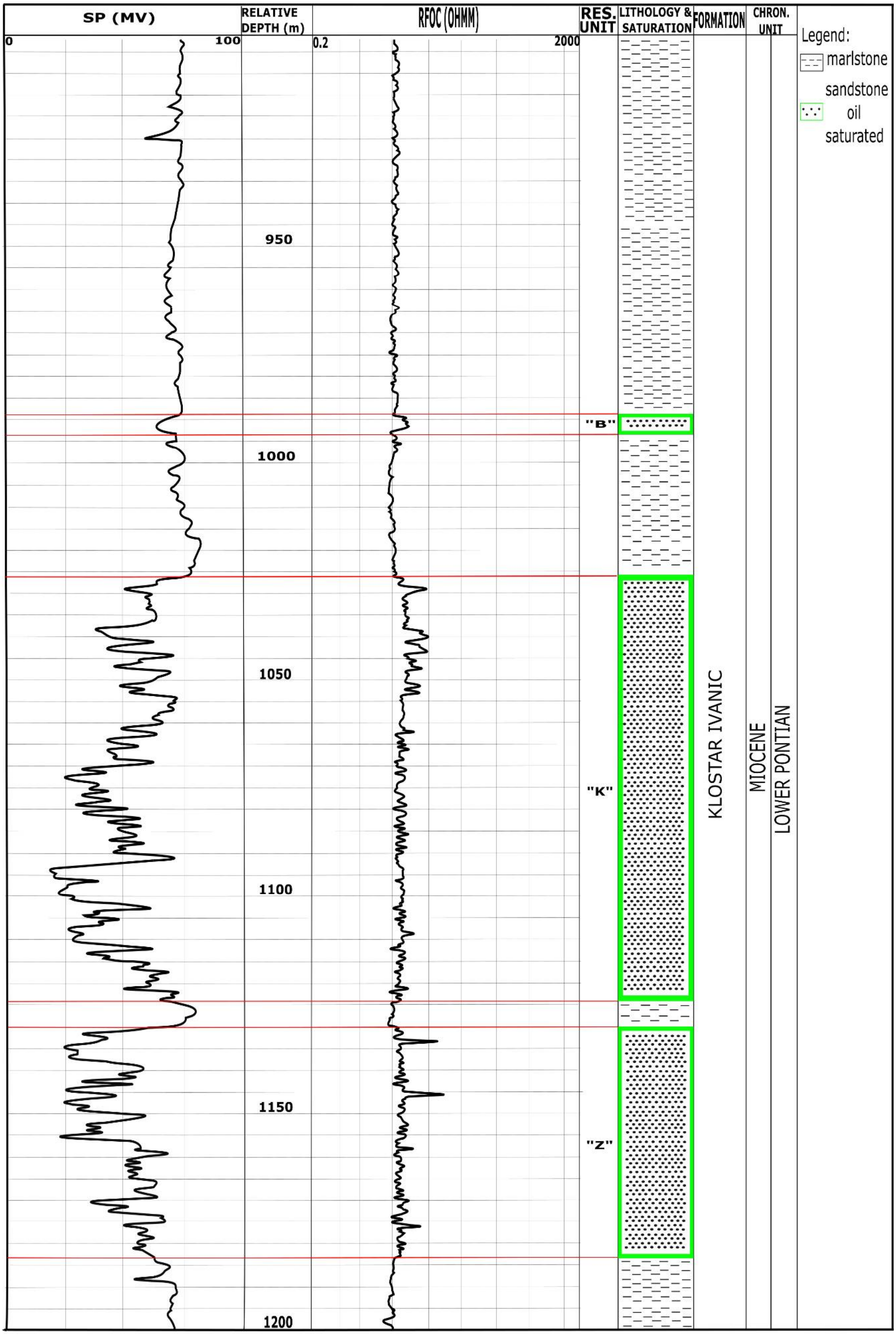


Figure 8. The composite log-lithological column in the field "A" (from archive of INA Plc. and re-drawn)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

3. Results

Exploration drilling in the analyzed fields dated in the 1960's. Consequently, the subsurface mapping has been done for each particular reservoir. Such maps are regularly updated.

3.1. The field "A", reservoir "L"

3.1.1. Reservoir type

According to classification [27] the reservoirs in the field "A" are of bedding type, capped by isolators, and margined with lithological and/or tectonical screens. The reservoir rocks are rhythmically interbedded with thin marls or sandy marls. The entire reservoir is single hydrodynamic units. Sandstones are enriched by mica minerals and dominant quartz detritus.

3.1.2. Granulometry, porosity, saturation and permeability of sandstones

Granulometry has been calculated from cores and CaCO3 usnig calcimetry analysis (Table 1). Based on 619 data from cores taken in 10 wells porosity varied 22.3 – 24.7 %. Porosity estimated from logs showed slightly different values: 16.7 – 20.1 % in gas saturated and 15.6 – 23.9 % in oil saturated part. Saturation is also calculated dually– in 42 wells from cores, and in 36 from logs. The accepted values are 59.8 -77.0 % for S_g and 57.3 – 71.6 for S_o. The permeability has been calculated from data taken in 7 wells: 8 – 27 x 10^{-3} μm^2.

Table 1. Granulometry of reservoir "L" (Md – mean grain diameter, So – coefficient of sorting, Sk – coefficient of asymmetry) (from archive of INA Plc.)

Well	Md	So	Sk	Sand (%)	Coarse silt (%)	Clay (%)	$CaCO_3$ with gran. (%)	$CaCO_3$ (%)	No. of data
2	0.095	1.697	0.831	71.5	21	7.5	30.6		3
57	0.282	1.640	1.087	63	47		26.8	22.3	3
83	0.068	1.581	0.938	53	42	5	29	25	28
91	0.074	1.558	0.935	59	38	3	31.8		23
92	0.063	1.546	1.02	54	44	2	29		6
145	0.081	2.31	0.683	59.5	37.5	3	26.5		6
153	0.066	2.135	0.786	50	47.7	2.3	26.5		11

3.1.3. Structural settings

The isopach map of reservoir "L" is given on Figure 9 with shown sections presented on Figures 10 and 11. It is clearly seen (Figure 10) that thickness of reservoirs in Kloštar-Ivanić Formation are mostly constant in central part (reservoir "N" about 150 m, "B" 20 m, "K" and "JL" 80 m, and "L" 45 m). However, analyzed "L" is example of thinning from 70 m (L-161) to only 20 m (L-153). Analyzing section SW-NE (Figure 11) thickness of the reservoir "L" is about 20 m (L-63, L-57, L-27) and gradually thicken to 39 m (L-131alfa).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

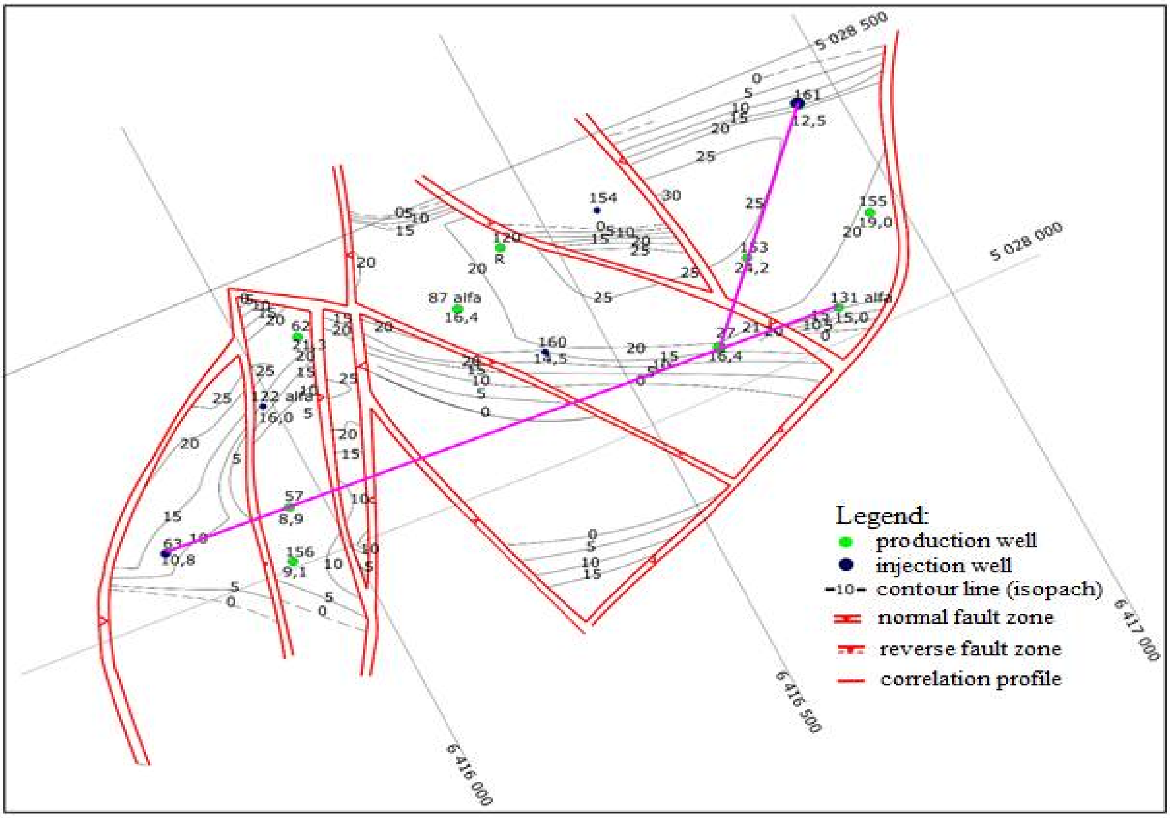


Figure 9. Isopach map of the reservoir "L", part where reservoir pressure is supported with water injection (from archive of INA Plc. and re-drawn)

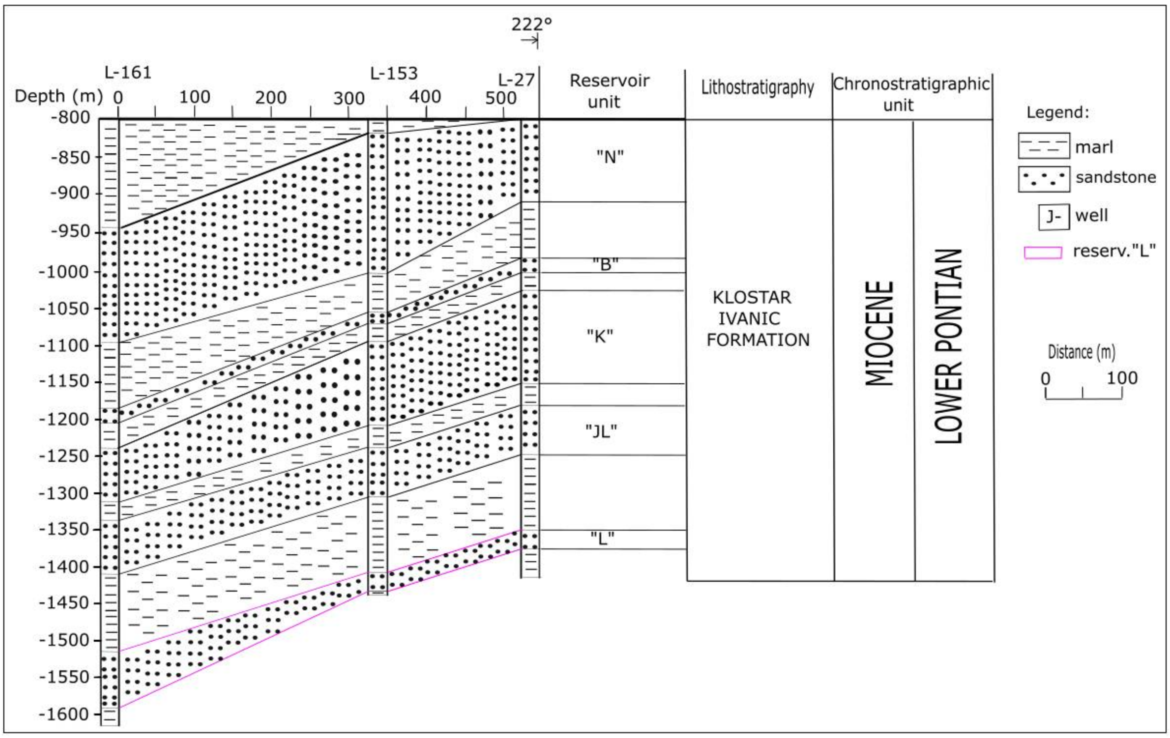


Figure 10. Correlation section through wells L-161 – L-153 – L-27

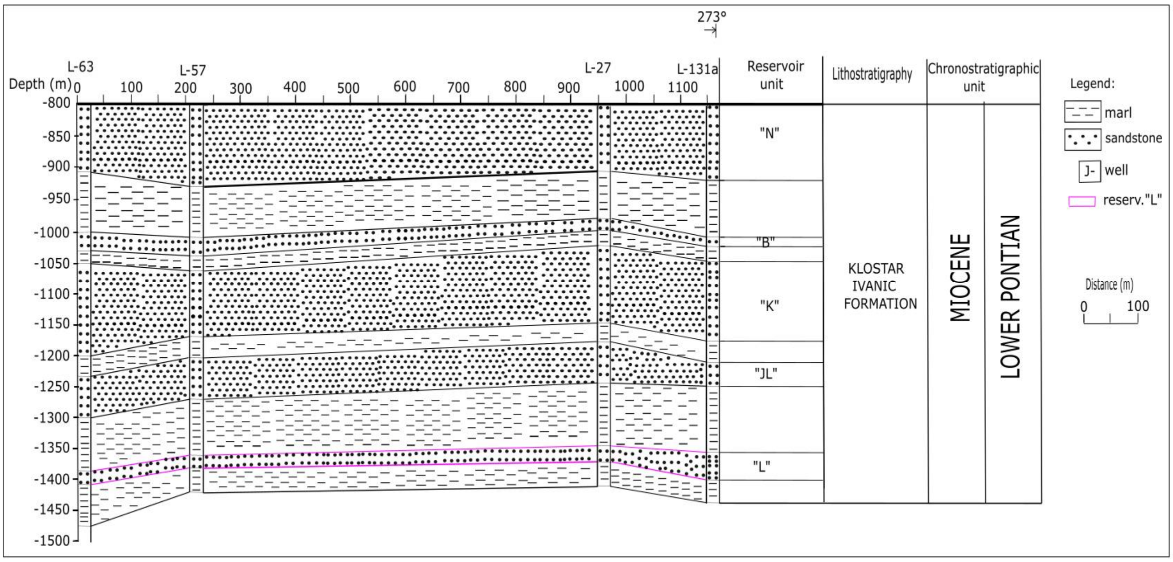


Figure 11. Correlation section through wells L-163 – L-57 – L-27 – L-131alfa

3.1.4. Variogram analysis and Ordinary Kriging of porosity

Porosity data were available in 25 wells (Figure 12). In the past, porosity maps have not been properly interpolated for entire reservoir, i.e. often has been replaced with average for the single tectonic block.

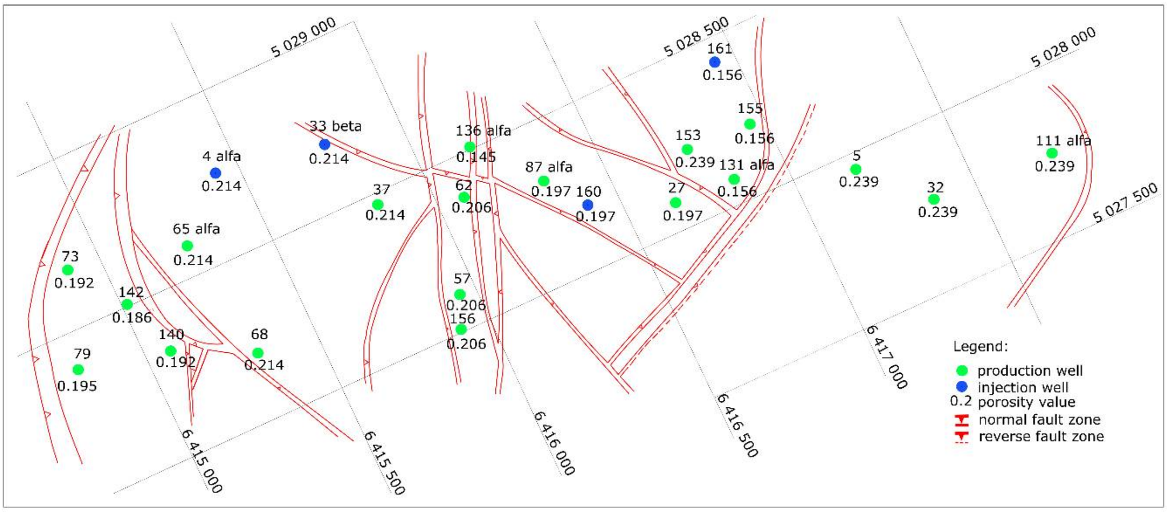


Figure 12. Porosity data available for reservoir "L" (from archive of INA Plc. and re-drawn)

The Kriging has been proven as the most appropriate method for interpolation of sandstone Upper Miocene reservoir variables in the CPBS (e.g., [5, 10, 12, 20]). Consequently, the experimental semivariogram for porosity had been calculated (Figure 13).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

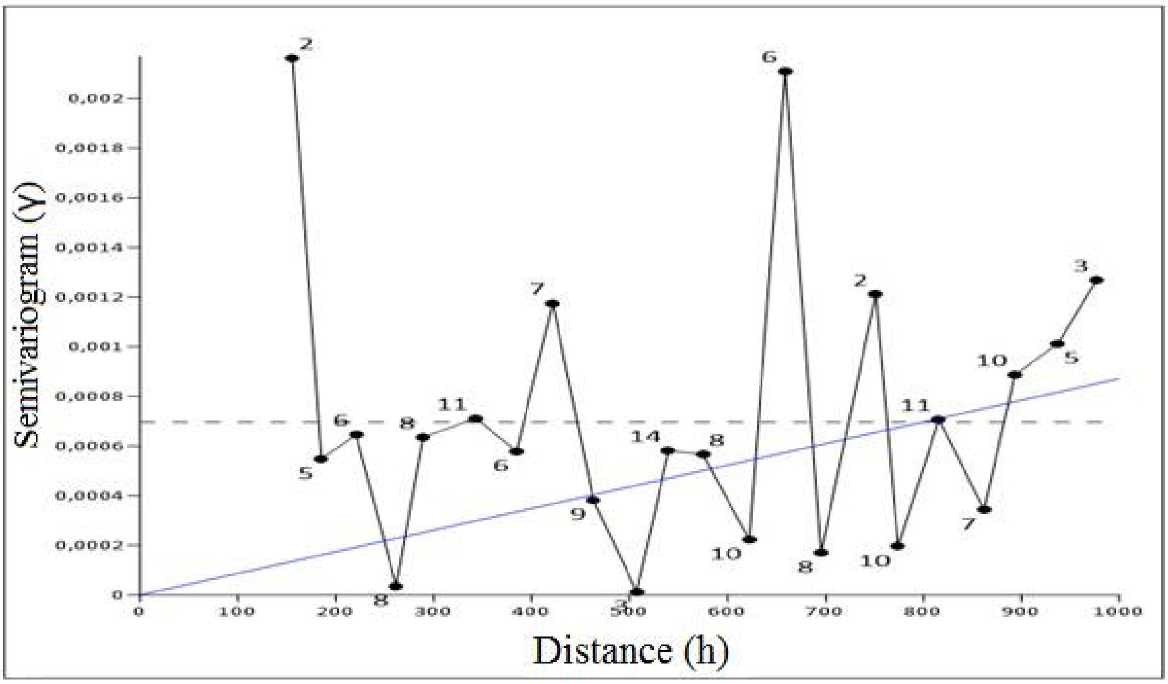


Figure 13. Experimental semivariogram, reservoir "L", porosity

Unfortunately, the semivariogram is characterized with large oscillations and low number of data pairs per class. So, approximation had been possible done only with the simplest – linear model. The Ordinary Kriging map is shown on Figure 14.

The cross-validation (porosity expressed as parts of units, not as percentages, are used in this type of calculations) for the Kriged map is 0.000676. However, variogram model is obviously characterized with large uncertainties (estimation of nugget, number of data pairs). It is why that has been decided to apply jack-knifing statistical method with purpose to artificially increase number of data. Jack-knifing has been previously applied or described in the CPBS [6, 29]. Basically, this method has similar algorithm as cross-validation, where data or group of data has been "deleted" and estimation is done from the rest. Such re-sampling method is characterized with standard error (e.g., [30, 31, 32]) and can be used as one of the improvements in the basic Kriging techniques or data intended to interpolate using the Kriging (e.g., digital terrain model, DTM, data, like in [33]). In this study it had been applied for each variogram class (step), which was calculated several times. The final value was the approximation of each calculation set for the same class (lag). Consequently, the number of data pairs included in calculation of class has been much larger. The "jack-knifed" semivariogram for the same reservoir porosity is given on Figure 15. Oscillations are largely decreased in several points, and experimental semivariogram is approximated with exponential theoretical model, significantly decreasing the range.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

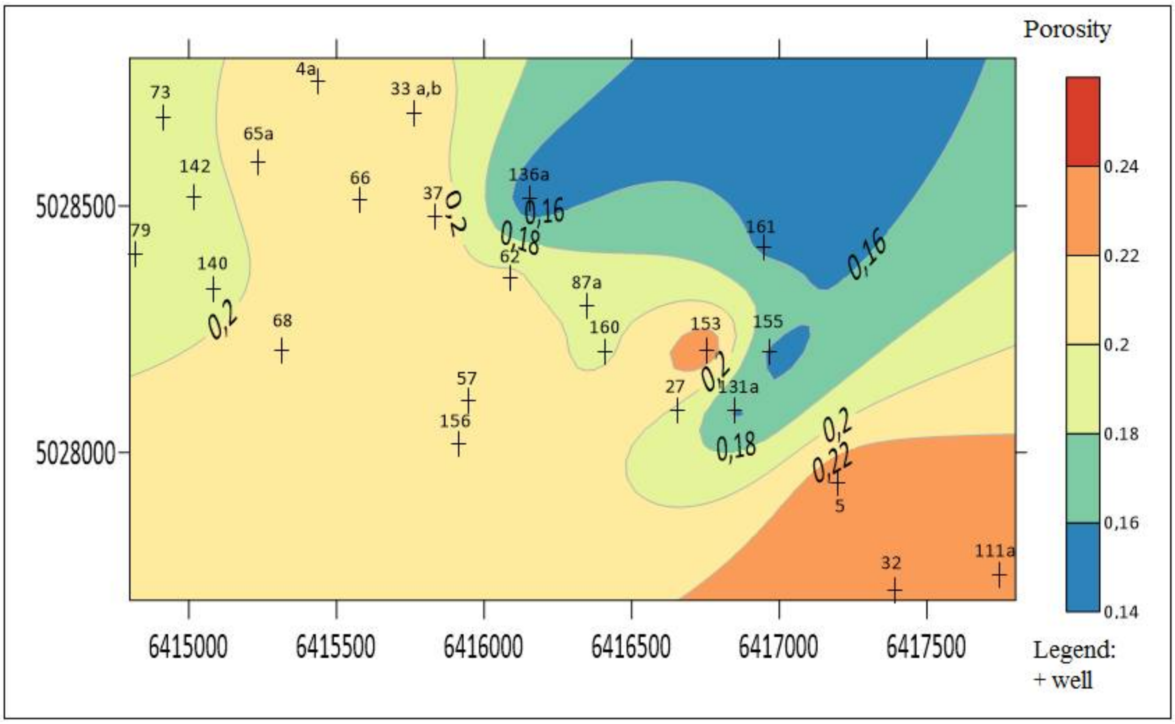


Figure 14. Porosity map for reservoir "L" interpolated by the Ordinary Kriging

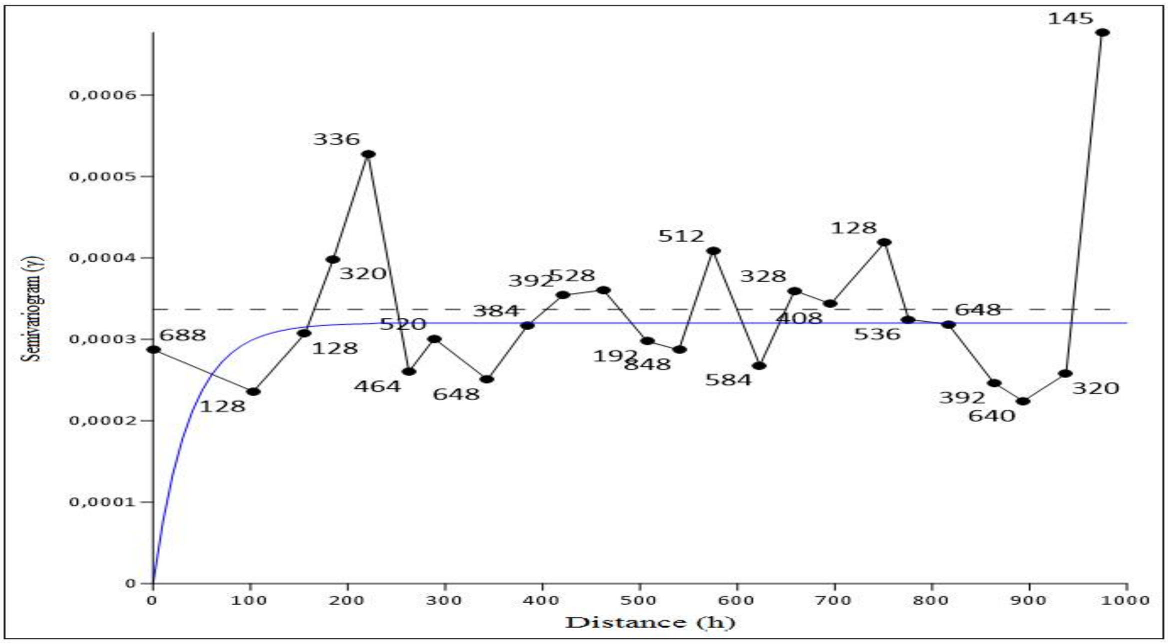


Figure 15. Experimental semivariogram, reservoir "L", porosity, after jack-knifing

Using the new one semivariogram the new porosity map has been interpolated (Figure 16). Due to much smaller range, the new porosity map is characterized with numerous "bull-eyes" shapes.

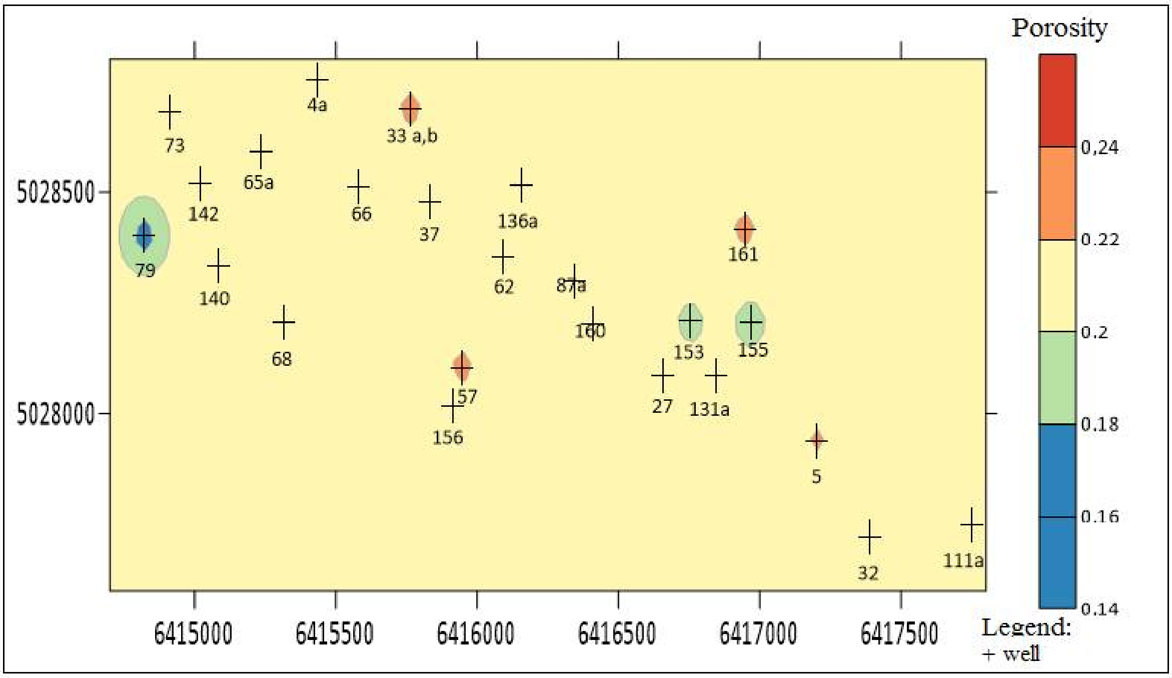


Figure 16. Porosity map for reservoir "L" interpolated by the Ordinary Kriging with jack-knifed semivariogram

3.2. The field "B", reservoir "K", hydrodynamic unit "K1"

3.2.1. Reservoir type

According to [27] the reservoirs in the field "B" are of bedding type, capped by isolators, and margined with lithological and/or tectonical screens. In that brachianticline, with strike northwest – southeast, sandstones reservoirs are enriched by mica minerals and quartz and occasionally interbedded with marls and (shallower) sandy marls. The reservoir "K" is divided in several tectonic blocks, where each of them is mostly separated hydrodynamic unit (abbr. HD). It is why here is analyzed the largest one such unit – HD "K1".

3.2.2. Granulometry, porosity, saturation and permeability of sandstones

Granulometry is shown in Table 2. Porosity is calculated for cores in 3 wells (27.2 – 31.5 %) and logs in 36 wells (18.2 – 22.3 % in gas saturated and 18.3 – 24.9 % in oil saturated part). Saturation has been determined using laboratory in 32 wells and from logs in 36 wells. S_g is 69.3 – 79.5 % and S_o 52.8 – 71.6 %. Permeability (in 3 wells) is 29.6 – 121.2 x 10^{-3} μm^2.

Table 2. Granulometry of reservoir "K" (Md – mean grain diameter, So – coefficient of sorting, Sk – coefficient of asymmetry) (from archive of INA Plc.)

Well	Md	So	Sk	Sand (%)	Coarse silt (%)	Clay (%)	$CaCO_3$ with gran. (%)	$CaCO_3$ (%)
25	0.071	1.560	1.239	56	44	0	30.1	14
31	0.101	1.430	0.980	76	24	0	28.4	4
33	0.099	1.660	1.100	75	25	0	35.4	1
45	0.094	1.496	1.445	85	15	0	28.8	1
55	0.094	1.461	1.172	77	23	0	27.6	41
57	0.037	1.564	1.251	28	72	0	20.4	2
59	0.095	1.460	1.150	79	21	0	27.0	15
68	0.098	1.530	1.300	53	21	0	28.7	1
120	0.065	1.167	1.044	72	47	0	31.2	18

3.2.3. Structural settings

HD unit "K1" is the largest tectonic block and HD in the reservoir "K". The part where reservoir pressure is supported by water injection is given on Figure 17.

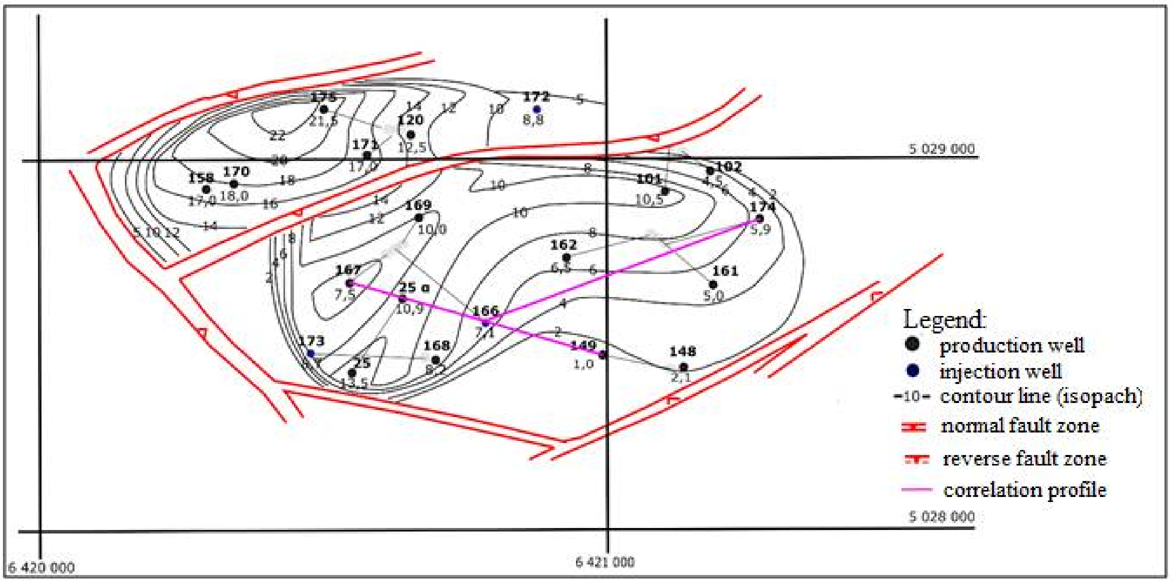


Figure 17. Isopach map of the HD unit "K1", part where reservoir pressure is supported with water injection (from archive of INA Plc.)

This reservoir has been crossed with two sections. The first has strike approx. NW-SE (Figure 18), and the second NE-SW (Figure 19). The section on Figure 18 shows that the reservoirs have similar thickness in both wells ("N" about 120 m, "K" 100 m, "Z" 40 m). Some marls pinch out, what

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

culd be reason for separation of hydrodynamic units. The next section (Figure 19) clearly shows partial structural inversion in the Kloštar-Ivanić Formation, i.e. transition from homocline (deeper) to fold (shallower).

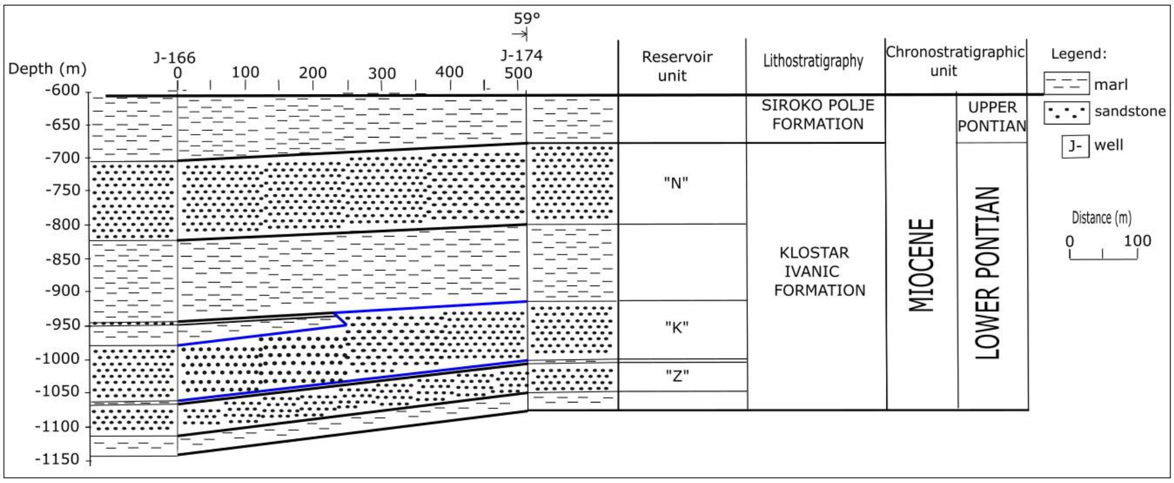


Figure 18. Correlation section through wells J-166 – J-174

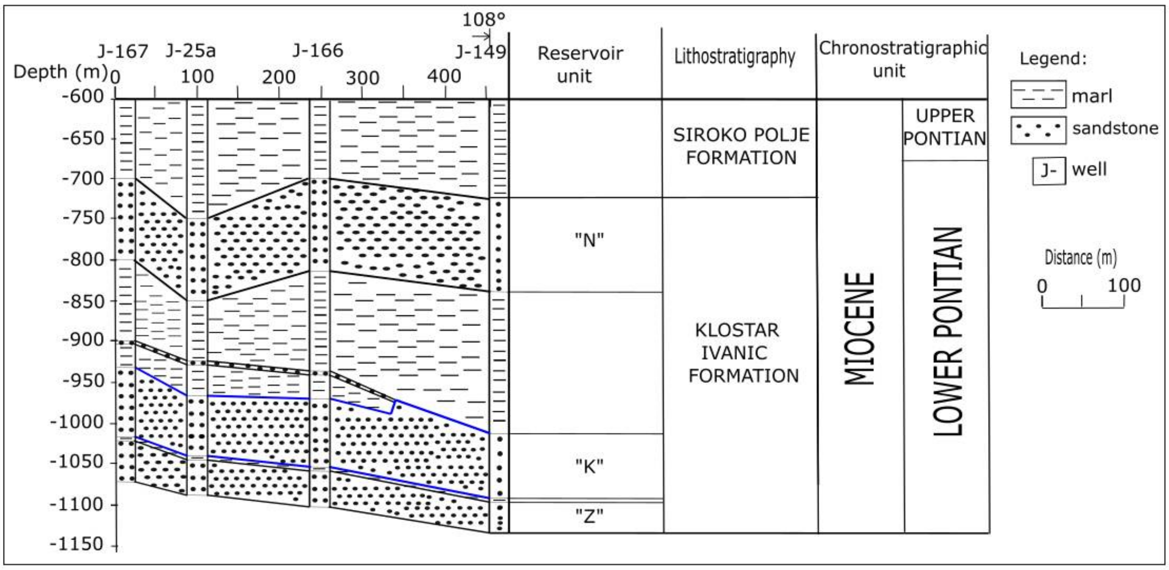


Figure 19. Correlation section through wells J-167 – J-25alfa – J-166 – J-149

3.2.4. Variogram analysis and Ordinary Kriging of porosity

Porosity data were available in 19 wells (Figure 20. The detailed porosity maps had not been interpolated up to now. It was why data were analyzed using semivariogram. The experimental one is shown on Figure 21.

 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

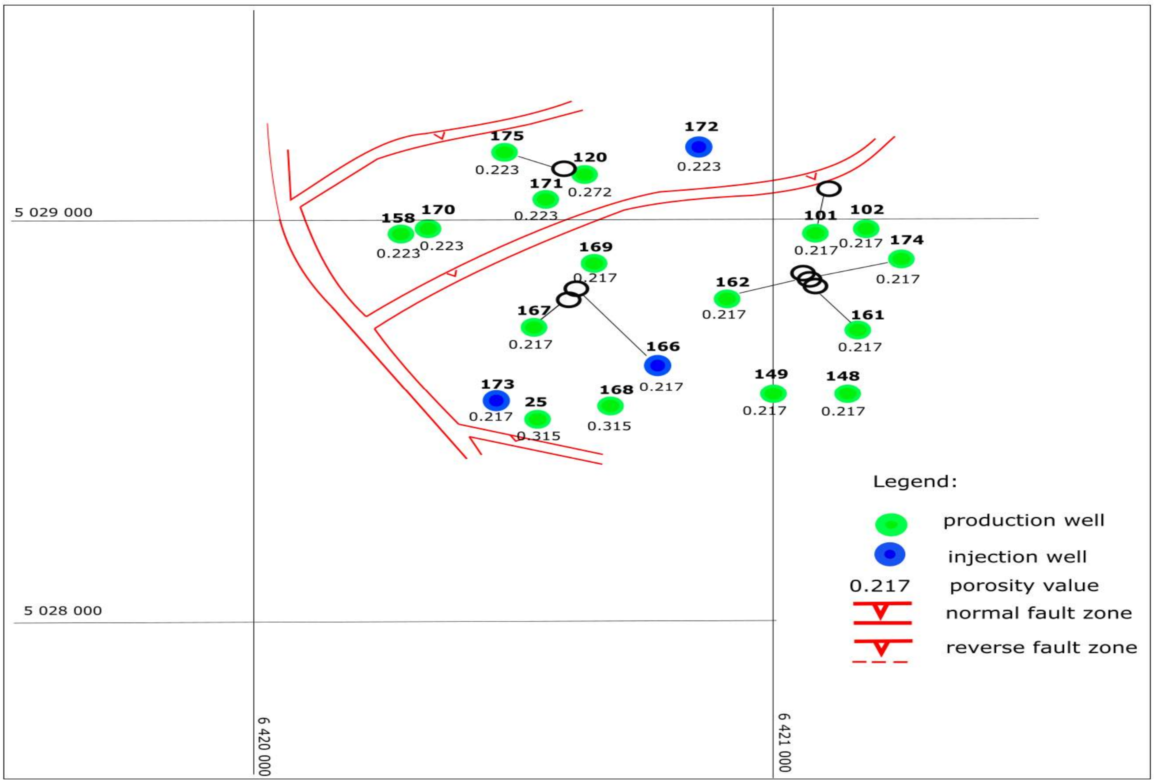


Figure 20. Porosity data available for HD "K1" (from archive of INA Plc.)

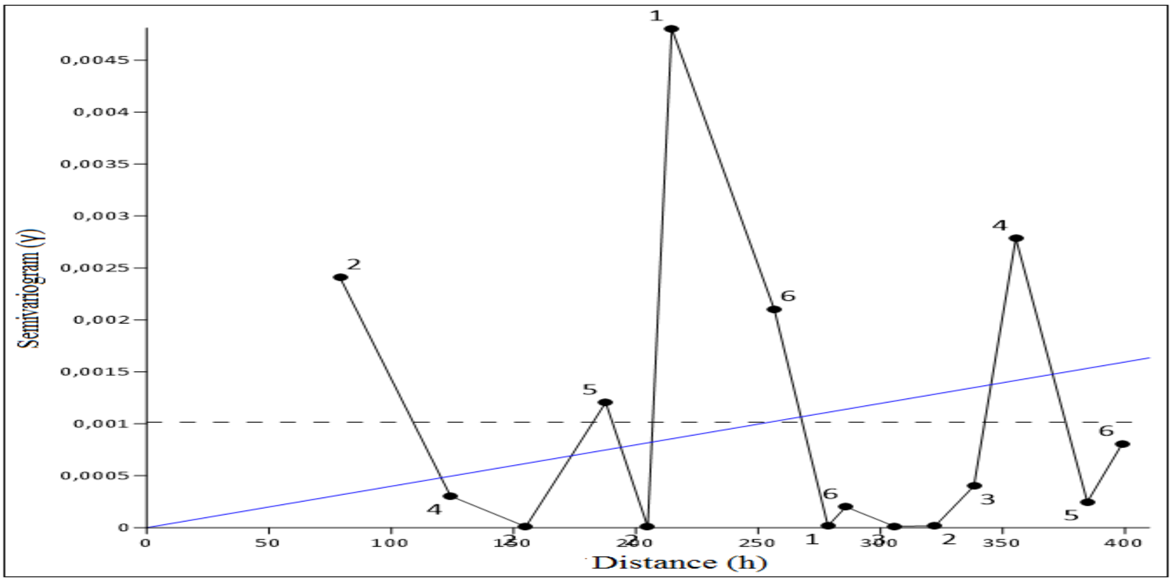


Figure 21. Experimental semivariogram, reservoir/HD "K1", porosity

Due to large uncertainties and small number of data pairs, semivariogram is approximated with the simple linear model. Unfortunately, such model did not allow to estimate nugget, and certain range. Such semivariogram is applied in the Ordinary Kriging and resulting map is shown on Figure 22. The cross-validation is 0.0013197.

Again, the new semivariogram had been calculated with "artificial" dataset obtained by jack-knifing. The new experimental model is given on Figure 23. This one could be approximated with the Gaussian theoretical model and the resulting Kriging map is shown on Figure 24. The

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at *Geosciences* **2019**, *9*, 36; doi:10.3390/geosciences9010036

semivariogram sill is lower and range larger (based on goodness of fitting) than in previous variogram model based on original dataset (19 points). The new Kriged porosity map is shown on Figure 24 and accompanied cross-validation value is 0.0009704.

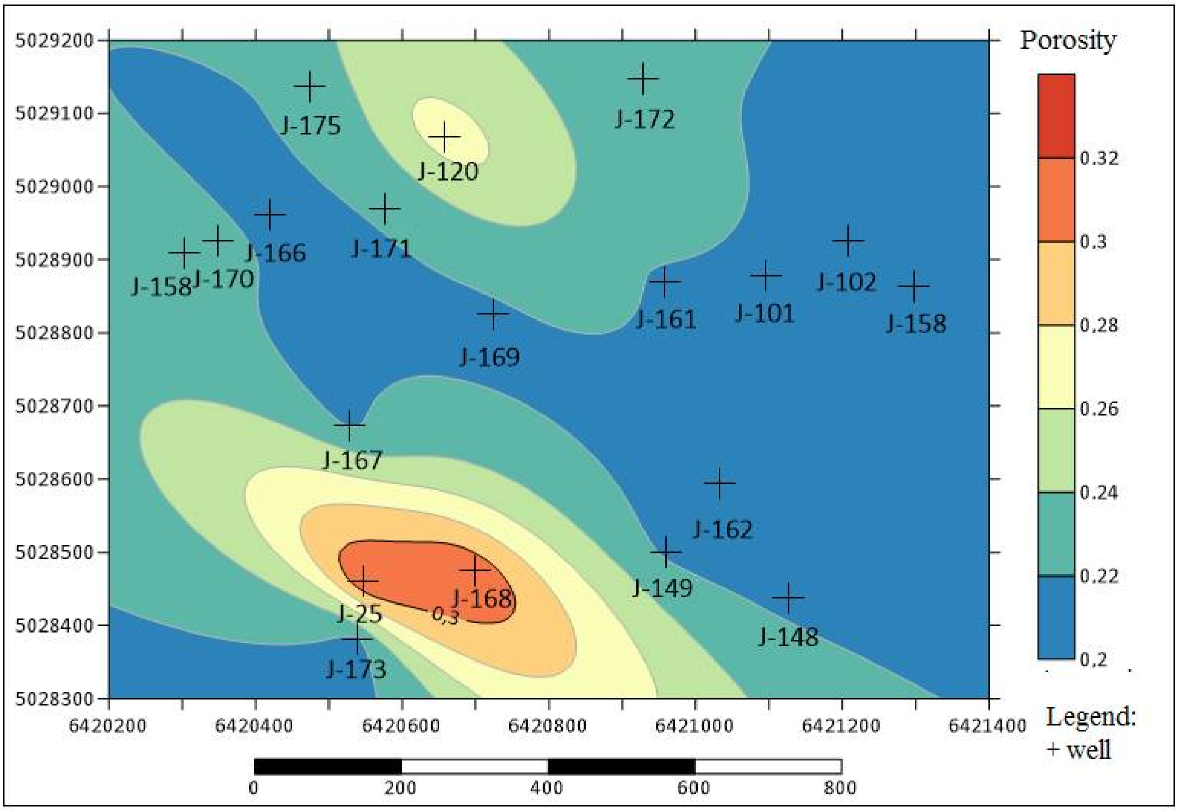


Figure 22. Porosity map for reservoir/HD "K1" interpolated by the Ordinary Kriging

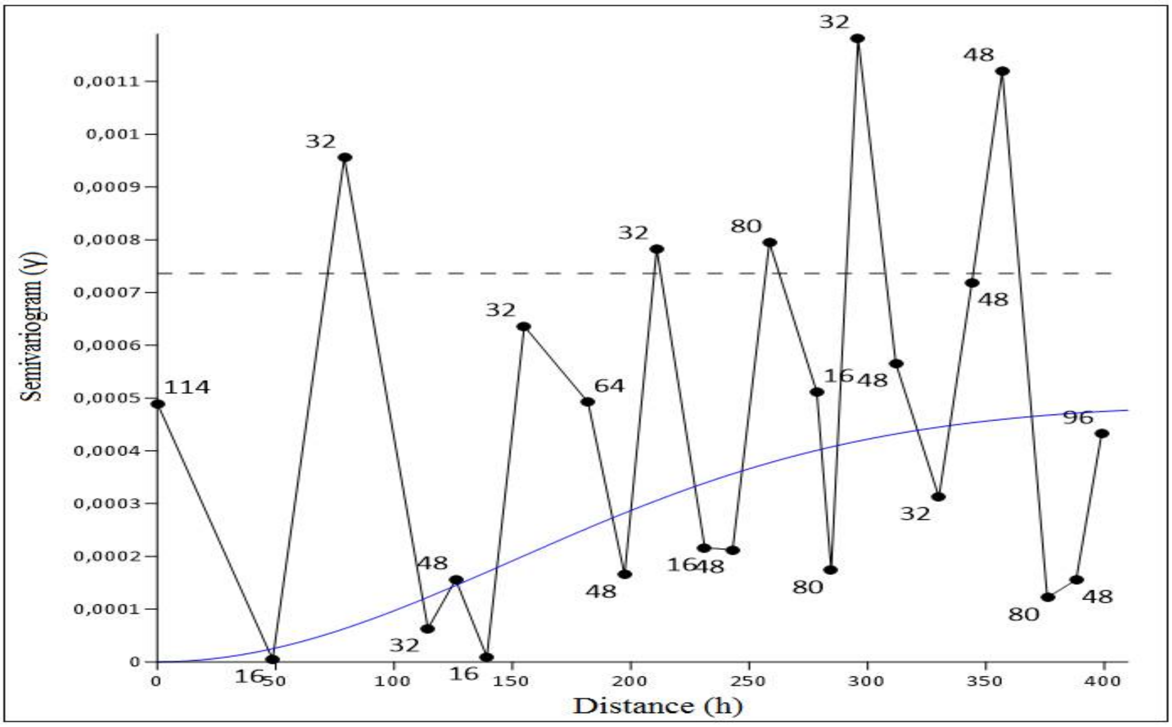


Figure 23. Experimental semivariogram, reservoir/HD "K1", porosity, after jack-knifing

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 29 November 2018 doi:10.20944/preprints201811.0614.v1

Peer-reviewed version available at Geosciences 2019, 9, 36; doi:10.3390/geosciences9010036

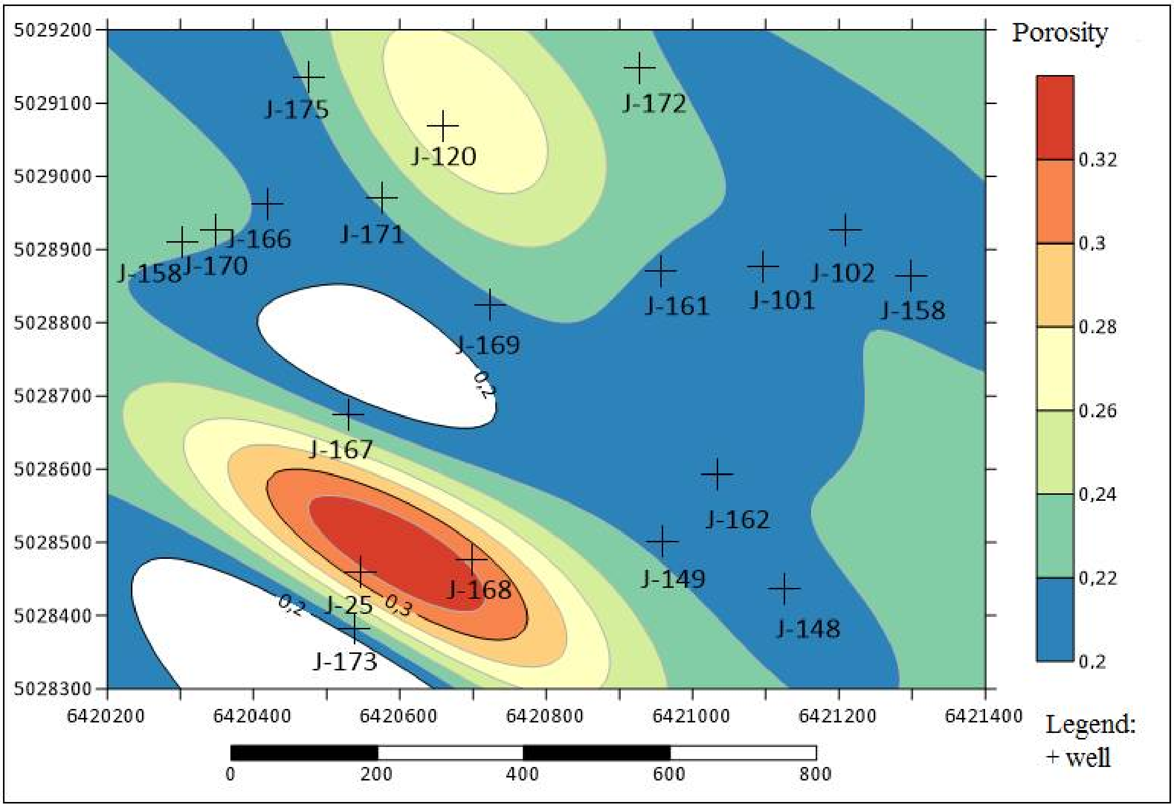


Figure 24. Porosity map for reservoir/HD "K1" interpolated by the Ordinary Kriging with jack-knifed semivariogram (the blank areas contain values less than 0.2)

4. Discussion and conclusion

Presented analysis is the first of such kind in the Sava Depression (Northern Croatia). It represented the continuation of previous geostatistical analyses done in that depression and entire CPBS. Here is pointed out the permanent problem of small datasets what could be the crucial for subsurface mapping of different geological variables. In numerous analyzes, the new hard data hardly can be obtained, mostly due to costs of drilling or seismic. Consequently, any statistical method that could increase reliability of existing datasets and their analytical results is more than welcome. The jack-knifing is one of such method. Previously, it was successfully applied in the (adjacent) Drava Depression, and here, for the first time, in the Sava Depression. That could be very appropriate for datasets of 15-30 points, where basic, descriptive statistics is more or less representative (variance and mean), and the Gaussian distribution can be assumed.

In both cases the original semivariogram results were very uncertain, with large oscillations, small number of data pairs per class and unknown nugget. Consequently, the linear model was only acceptable theoretical model to use. It was why much larger number of artificial data had been calculated using jack-knifing. As results, the new semivariograms could be approximated more reliable and with mathematically advanced theoretical models (exponential and Gaussian).

The hypothesis that new Kriged maps interpolated from "jack-knifed" semivariograms are more reliable was eventually check (a) visually (maps without the "bull-eyes" or "butterfly" effects are better) and (b) numerically using cross-validation. The results are given in Table 3 and pointed out that:

(1) When experimental semivariograms are described with large uncertainties it is recommended the calculated jack-knifed data and repeat the variogram modelling and the Kriging interpolation.

(2) Any map from the set of "old" or "new" data/semivariograms need to be firstly visually checked. If the effects like "bull-eyeing" or "butterfly shapes" are numerous the map needs to be eliminated.
(3) If both Kriged maps (based on original and jack-knifed datasets) are visually (geologically) acceptable the selection can be done based on cross-validation values.
(4) For the small data sets (less than 15) it is also recommended to interpolate with Inverse Distance Weighting and compare both OK and IDW results.

Table 3. Comparison of cross-validation values for the Ordinary Kriging (abbr. OK) maps based on original and jack-knifed semivariograms (abbr. IDW is for Inverse Distance Weighting)

Field/ reservoir	OK (original semivariogram)	OK (jack-knifed semivariogram)	Recommendation
"A"/"L"	0.000676 (linear)	0.000420 (exponential)	OK with original semivariogram or IDW. The effect of "bull-eyes" eliminated the jack-knifed approach.
"B"/"K1"	0.001320 (linear)	0.000970 (Gaussian)	OK with jack-knifed semivariogram

Presented test of the jack-knifing had been done for the sandstone reservoir porosity. The selected fields ("A", "B") and reservoirs ("L", "K1") represents typical Upper Miocene sandstones in the Sava Depression, with portion of sandy detritus 50 – 72 % and porosity 14.5 – 23.9 % ("A"), i.e., 21.7 – 31.5 % ("B"). It is why those conclusions could be applied in any other such reservoirs of the same depression (the Kloštar-Ivanić Formation).

Author Contributions: Tomislav Malvić led the research and selected the fields for analyses. **Josip Ivšinović** made the jack-knifing analyses, interpolated maps and collected data. **Josipa Velić** organized the regional geology presentation and visualization. **Rajna Rajić** checked the mathematical consistency of applied equations and methods.

Funding: This research (analyses) was partially supported with the project "Mathematical methods in geology III" (led by T. Malvić). Funds were given from the University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, for the 2018 year.

Acknowledgments: In this paper data from technical documentation of INA Plc. Had been used and presented in some maps and tables. Such data were collected for currently performed doctoral researching of Mr. Josip Ivšinović.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

[1] Ivšinović, J.; Dekanić, I. The basics of model for marginal testing of costs for disposal of extracted formation water. *Rudarsko-geološko-naftni zbornik (The Mining-Geology-Petroleum Engineering Bulletin)* **2015**, *30*, 2, 85-100.

[2] Ivšinović, J. The analysis of water injection systems in sandstone hydrocarbon reservoirs, case study from the western part of the Sava Depression. *Rudarsko-geološko-naftni zbornik (The Mining-Geology-Petroleum Engineering Bulletin)* **2017**, *32*, 17-24.

[3] Ivšinović, J. Statistical analysis of the costs of separating the produced formation water from a sandstone reservoir of Sava Depression. Proceedings of the 1nd Croatian scientific congress from geomathematics and terminology in geology, Zagreb, Croatia, 29 October 2016, Malvić, T. (ed.); Velić, J. (ed.), University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering; pp. 69-74.

[4] Malvić, T.; Velić, J.; Peh, Z. Qualitative-Quantitative Analyses of the Influence of Depth and Lithological Composition on Lower Pontian Sandstone Porosity in the Central Part of Bjelovar Sag (Croatia). *Geologia Croatica* **2015**, *58*, 73-85.

[5] Malvić, T. Production of a porosity Map by Kriging in Sandstone Reservoirs, Case study from the Sava Depression, *Kartografija i geoinformacije* **2008**, *9*, 12-19.

[6] Malvić, T.; Bastaić, B. Reducing variogram uncertainties using the "jack-knifing" method, a case study of the Stari Gradac – Barcs-Nyugat field. *Bulletin of Hungarian Geological Society* **2008**, *138*, 165-174.

[7] Malvić, T. Stochastical approach in deterministic calculation of geological risk - theory and example. *Nafta* **2009**, *60*, 658-662.

[8] Malvić, T.; Balić, D. Linearnost i Lagrangeov linearni multiplikator u jednadžbama običnoga kriginga (Linearity and Lagrange Linear Multiplicator in the Equations of Ordinary Kriging). *Nafta* **2009**, *60*, 31-43.

[9] Novak Zelenika, K.; Malvić, T. Procjena sekvencijskim Gaussovim simulacijama ležišnih varijabli pješčenjačkog donjopontskoga ležišta nafte, polje Kloštar, Savska depresija, Hrvatska (Estimations by sequential Gaussian simulations of reservoir variables in Early Pontian oil reservoir, Kloštar Field, Sava Depression, Croatia). Proceedings of the 4. Croatian Geological Congress with international participation, Šibenik, Croatia, 14-15 October 2010, Horvat, M (ed.), Croatian Geological Institute, pp. 263-264.

[10] Novak Zelenika, K.; Malvić, T.; Geiger, J. Mapping of the Late Miocene sandstone facies using indicator kriging. *Nafta* **2010**, *61*, 225-233.

[11] Novak Zelenika, K.; Malvić, T. Stochastic simulations of dependent geological variables in sandstone reservoirs of Neogene age: A case study of Kloštar Field, Sava Depression. *Geologia Croatica* **2011**, *64 (2)*, 173–183.

[12] Novak Zelenika, K. Deterministički i stohastički geološki modeli gornjomiocenskih pješčenjačkih ležišta u naftno-plinskom polju Kloštar (Deterministic and stochastic geological models of Upeer Miocene sandstone reservoirs at the Kloštar oil and gas Field), Doctoral thesis, University of Zagreb, Faculty of Mining, Geology and Petroleum, 2012.

[13] Malvić, T. History of geostatistical analyses performed in the Croatian part of the Pannonian Basin System. *Nafta* **2012**, *63*, 223-235.

[14] Husanović, E.; Malvić, T. Review of deterministic geostatistical mapping methods in Croatian hydrocarbon reservoirs and advantages of such approach. *Nafta* **2014**, *65*, 57-63. [27] Brod, I.O. Geological Terminology in Classification of Oil and Gas Accumulation, *AAPG Bulletin* **1945**, *29*, 1738 – 1755.

[15] Novak Zelenika, K.; Malvić, T. Utvrđivanje sekvencijskim indikatorskim metodama slabopropusnih litofacijesa kao vrste nekonvencionalnih ležišta ugljikovodika na primjeru polja Kloštar (Determination of low permeable lithofacies, as type of unconventional hydrocarbon reservoirs, using sequential indicator methods, case study from the Kloštar Field). *Rudarsko-geološko-naftni zbornik (The Mining-Geology-Petroleum Engineering Bulletin)* **2014**, *28*, 23-38.

[16] Malvić, T.; Velić, J. Stochastically improved methodology for probability of success (POS) calculation in hydrocarbon systems. *RMZ-Materials and geoenvironment* **2015**, *62*, 149-155.

[17] Novak Mavar, K. Modeliranje površinskoga transporta i geološki aspekti skladištenja ugljikova dioksida u neogenska pješčenjačka ležišta Sjeverne Hrvatske na primjeru polja Ivanić (Surface transportation modelling and geological aspects of carbon-dioxide storage into Northern Croatian Neogene sandstone reservoirs, case study Ivanić field), Doctoral thesis, University of Zagreb, Faculty of Mining, Geology and Petroleum, 2015.

[18] Špelić, M.; Malvić, T.; Saraf, V.; Zalović, M. Remapping of depth of e-log markers between Neogene basement and Lower/Upper Pannonian border in the Bjelovar Subdepression. *Journal of Maps* **2016**, *12*, 45-52.

[19] Mesić Kiš, I. Odabir interpolacijskog algoritma primjerenog za kartiranje naftno-plinskog polja Šandrovac (Selection of interpolation algorithm appropriate for mapping of oil and gas Šandrovac Field). Proceedings of the Symposium PhD students of Science, Zagreb, Croatia, 26 February 2016, Primožić, I. (ed), Hranilović, D. (ed), University of Zagreb, Faculty of science; pp. 64-64.

[20] Mesić Kiš, I. Kartiranje i reinterpretacija geološke povijesti Bjelovarske subdepresije univerzalnim krigiranjem te novi opći metodološki algoritmi za kartiranje sličnih prostora (Mapping and reinterpretation of the geological evolution of the Bjelovar Subdepression by Universal Kriging and new general methodological algorithms for mapping in similar areas), Doctoral thesis, University of Zagreb, Faculty of science, 2017.

[21] Malvić, T. Stochastics – advantages and uncertainties for subsurface geological mapping and volumetric or probability calculations. *Materials and Geoenvironment* **2018**, *65*, 9-19.

[22] Ivšinović, J. The cost analysis of the separation of produced formation water from the hydrocarbon reservoir using the example of the Upper Miocene sandstone deposits of the Sava depression. *Rudarsko-geološko-naftni zbornik (The Mining-Geology-Petroleum Engineering Bulletin)* **2018**, *33*, 35-43.

[23] Velić, J.; Malvić, T.; Cvetković, M. Geologija i istraživanje ležišta ugljikovodika (Geology and exploration of hydrocarbon reservoirs). Publisher: University of Zagreb, Faculty of Mining, Geology and Petroleum Zagreb, Croatia, 2015, pp. 144, ISBN 978-953-6923-28-1.

[24] Pavelić, D.; Kovačić, M. Sedimentology and stratigraphy of the Neogene rift-type North Croatian Basin (Pannonian Basin System, Croatia): A review. *Marine and petroleum geology* **2018**, *91*, 455-469.

[25] Malvić, T.; Velić, J. Neogene Tectonics in Croatian Part of the Pannonian Basin and Reflectance in Hydrocarbon Accumulations. *In New Frontiers in Tectonic Research: At the Midst of Plate Convergence*, Schattner, U. (ed); Publisher: InTech, Rijeka, Croatia 2011; 215-238, ISBN 978-953-307-594-5.

[26] Malvić T. Review of Miocene shallow marine and lacustrine depositional environments in Northern Croatia. *Geological quarterly* **2012**, *56*, 493-504.

[27] Brod, I., O. Geological Terminology in Classification of Oil and Gas Accumulation. *AAPG Bulletin* **1945**, *29*, 1738 – 1755.

[28] Vrbanac B.; Velić J.; Malvić T. Sedimentation of deep-water turbidites in main and marginal basins in the SW part of the Pannonian Basin. *Geologia Carpathica* **2010**, *61*, 55–69.

[29] Malvić, T.; Vrbanac, B. Geostatistički pojmovnik (Geostatistical Glossary). *Hrvatski matematički elektronički časopis* **2013**, *23*, 7-56.

[30] Wu, C. F. J. Jackknife, Bootstrap and Other Resampling Methods in Regression Analysis. *The Annals of Statistics* **1986**, *14*, 1261-1295.

[31] Shao, J. Jackknifing in generalized linear models. *The Annals of Statistics* **1992**, *44*, 673-686.

[32] McIntosh, A. I. The Jackknife Estimation Method, Cornell University Library, 2016. Available online: https://arxiv.org/abs/1606.00497 (accessed on 20 November 2018).

[33] Wojciech, M. Kriging Method Optimization for the Process of DTM Creation Based on Huge Data Sets Obtained from MBESs. *Geosciences* **2018**, 8, 433; doi:10.3390/geosciences8120433