Lithofacies definition based on cut-offs in Indicator Kriging mapping, case study Lower Pontian reservoir, Sava Depression

K. Novak Zelenika

ORIGINAL SCIENTIFIC PAPER

Mapping of the lithofacies is very important for getting insight to sedimentary environments, shapes and boundaries of hydrocarbon reservoirs especially in reservoir characterization. Indicator Kriging technique is most often used for lithofacies mapping. It is based on indicator transformed input data, depending on presence or absence of the certain lithofacies. Indicator transformation of the input data is performed based on cut-offs into values 0 or 1.

Turbidites were dominant clastic transport mechanism in the Croatian part of the Pannonian Basin System during the Early Pontian. Most of transported detritus had been eroded in the Eastern Alps and re-deposited several times before the suspended materials entered the Sava Depression. Due to long transport only medium and fine grained sands and silts (Tb - Td Bouma sequences) reached the Sava Depression. When turbiditic currents were not active, typical calm deep water sediment was deposited.

It was presented how to use core and log data to define proper cut-offs for describing different lithofacies. Obtained results are probability maps and with a proper cut-offs definition some of them can show turbiditic channel and material transport direction.

Key words: lithofacies, turbidites, Indicator Kriging, Upper Miocene, Sava Depression, Croatia

1. INTRODUCTION

The Late Pannonian and Early Pontian periods belong to the 2nd transtensional phase.[10], when thermal subsidence generally re-opened many depressional areas along the entire Pannonian Basin System, created depositional spaces for the accommodation of a huge volume of sandy material. During these periods the main sandstone hydrocarbon reservoirs were deposited.[17]

Sedimentation area in time of the Pannonian Basin System extension in Croatia were marginal parts of the Medvednica, Papuk, Psunj Mt. and the lowest parts of the Sava, Drava, Slavonia-Srijem and Mura Depressions.[9,18] It is still questionable how many surfaces and which mountains in Northern Croatia were uplifted representing land which gave material for sedimentation. The highest like Medvednica and Papuk must have been the islands in the sedimentation area. But it is still an open question if the lower moun-

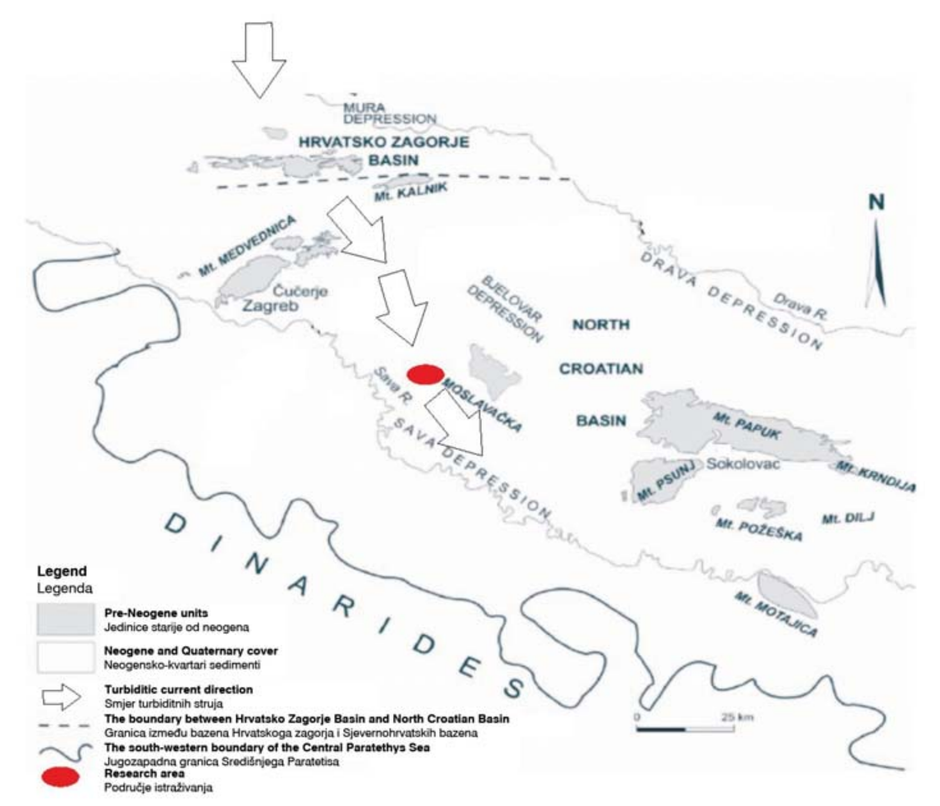

Fig. 1. Turbiditic currents and detritus transport direction during Early Pontian (adjusted from ref.[1])

Sl. 1. Smjer donosa materijala turbiditnim strujama u vrijeme ranog ponta (prilagođeno iz[1]) tains, like Moslavačka gora or Krndija, were islands or under water highs during extension, especially when extension was the strongest.

Turbidites were dominant clastic transport mechanism in the Croatian part of the Pannonian Basin System (CPBS) during the Late Pannonian and Early Pontian.[14,15,18] Although, there are some theories that local mountains, which were uplifted above lake level during the Early Pontian, gave some material, it was proven that most of transported detritus had been eroded in the Eastern Alps, deposited in the Vienna Basin and from that point, turbiditic material had been re-deposited several times before the suspended materials entered the Sava Depression (Figure 1). In Late Pannonian few long regional tectonic channels dominated inside the Sava Depression[19] and they were the place of sandy detritus deposition, but during Early Pontian some additional faulting and strike-slip reactivation was possible. The main direction of turbiditic currents in the Late Pannonian and Early Pontian was northwest-southeast[20], and the strongest deposition in the deepest part of the lake resulted with the largest material thicknesses. Due to long transport by turbidity currents (from the Eastern Alps) it was logically to conclude that only the medium and fine grained sands as well as silts (Tb - Td lithofacies) reached the Sava Depression. In the calm period, when turbiditic currents were not active, typical calm deep water sediment, calcite rich mud (marl after litification) was deposited.

Lithostratigrphicaly, Lower Pontian (7.1-6.3 Ma; time scale according to ref.[4]) sediments of the Sava Depression (Figure 2) are represented with sandstone and marl interlayering, but except pure channel sandstones and basinal marls, there are transitional lithofacies like marly sandstones and sandy marls.

In reservoir characterization, mapping of the lithofacies is important for getting insight to sedimentary environments, shapes and boundaries of hydrocarbon reservoirs. Indicator Kriging is a technique which is most often used for lithofacies mapping. It is based on indicator transformation of the input data (based on different cut-offs) into 0 or 1(ref.[12]), depending on presence or absence of the certain lithofacies. Obtained maps show probabilities that mapped variable is lower than the cut-off, and with a proper cut-off selection it is possible to map turbiditic channel or to observe material transport direction. It is also possible to draw conclusion about lithofacies changes according to porosity values.

2. BASIC ABOUT INDICATOR KRIGING MAPPING

Basics about Indicator Kriging mapping were described in refs.[2,3,5,6,8,12] Indicator Kriging is used for creating the maps with only two values, so called "two-type map", i.e. for binary mapping, where the conditional probability is evaluated so that the mapped variable could be described with one of two possible values.[3,8,16] The basic of Indicator Kriging is indicator transformation, which

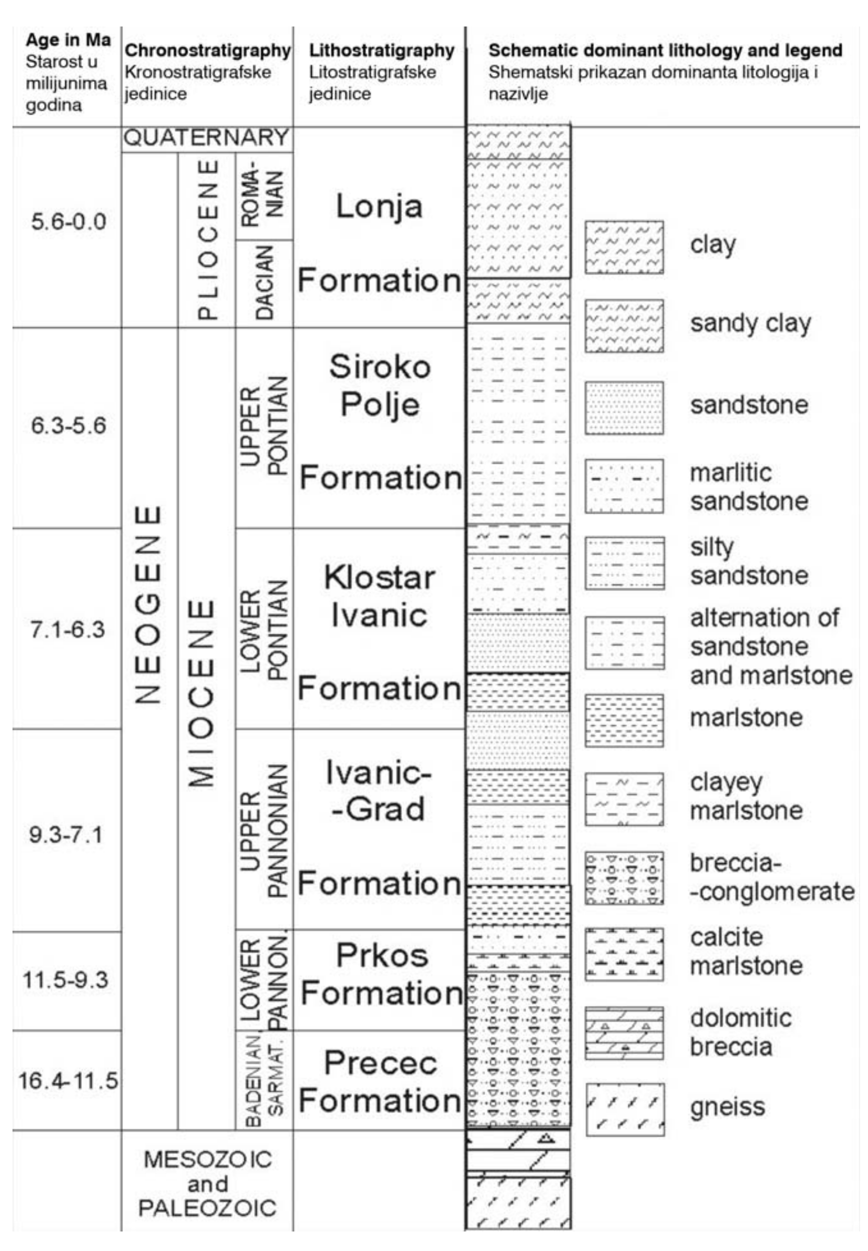

Fig. 2. Chronostratigraphy, lithostratigraphy and lithology of the Sava Depression
Sl. 2. Kronostratigrafija, litostratigrafia i litiologjia Savske depresije

means that measured data are transformed in indicator values (using cut-off values) into variable 0 and 1. Indicator variable in every measured location will be calculated for some geological variable (e.g. porosity) using cut-off value by the term:

$$I(x) = \begin{cases} 1 \text{ if } Z(x) \leq v_{cutoff} \\ 0 \text{ if } Z(x) > v_{cutoff} \end{cases} \quad (1)$$

where are:

$I(x)$ indicator variable

$Z(x)$ originally measured value

V_{cutoff} cut-off value

Maps obtained by Indicator Kriging are probability maps, which show probability that the mapped variable is lower (or higher) than certain cut-off value, defined as important for the interpretation. For example indicator maps can show probability that thickness is lower than 100 m or porosity lower than 19% etc.

3. LITHOFACIES DEFINITION BASED ON CORE EXAMINATION

Definition of the different lithofacies was based on cores examination.[13] Upper Pannonian and Lower Pontian cores were examined. Mineral composition of the Upper Pannonian and Lower Pontian reservoirs was very similar except that Upper Pannonian reservoirs have more mica minerals (especially muscovite). Chlorite biotite was present in Upper Pannonian and Lower Pontian reservoirs, but Lower Pontian reservoirs also contain unchanged biotite, which was not found in Upper Pannonian reservoirs.

There were just two of the selected wells which had both, log and core data for the same interval of the Lower Pontian sandstones. Therefore clarification of the lithofacies included some elements of subjectivity based on experience. If coarse and medium grained material was dominate, core was declared as sandstone, and of course the opposite, if fine grained material was dominant it represented silt or silty (marly) sandstones. Cores of a pure marls were not found. Some of examined cores and their lithological definition is given in Figure 3.

4. INPUT DATA FOR INDICTOR KRIGING MAPPING

Input data for Indicator Kriging mapping were well log porosities measured in 20 wells of the Lower Pontian reservoir (Table 1). They represent average porosity in the reservoir on the well location. Since all of the wells used in mapping were drilled decades ago, only conventional well logs were available for porosity calculation. Log porosities were compared with core porosities from two wells (Table 1). In the analysed reservoir, porosity from wells varies between 5.5 and 23.3% (Table 1). Of course, the average porosity value of wells strongly depends on different lithofacies and their location in Upper Miocene depositional environment.

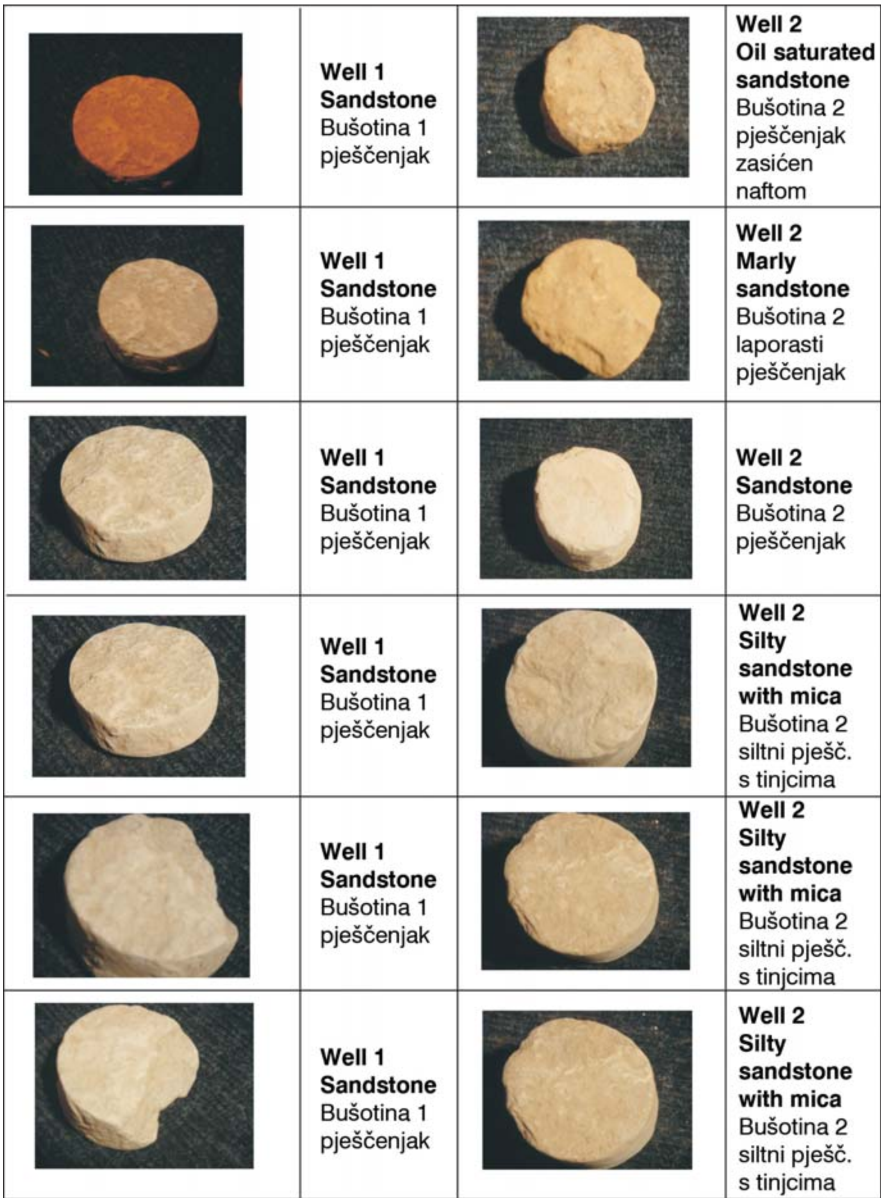

Fig. 3. Some of examined cores of the Lower Pontian reservoirs (from ref.[11])
Sl. 3. Neke od pregledanih jezgara donjopontskog ležišta (iz[11])

Table 1. Input well data (from ref.[10])

Well	Reservoir	Average log porosity (%)	Average core porosity (%)
Well 1	Lower Pontian reservoir	23.3	15.8
Well 2		22.0	21.2
Well 3		19.9	
Well 4		19.5	
Well 5		19.6	
Well 6		21.1	
Well 7		20.5	
Well 8		20.1	
Well 9		21.2	
Well 10		17.9	
Well 11		19.2	
Well 12		13.8	
Well 13		5.5	
Well 14		19.7	
Well 15		18.2	
Well 16		21.8	
Well 17		18.1	
Well 18		18.5	
Well 19		19.6	
Well 20		18.4	

5. CUT-OFFS DEFINITION

According to ref.[12] correct selection of the cut-offs is essential for Indicator Kriging mapping. In case of too many cut-offs the computation time increase drastically, but with too few cut-offs one can lose some important details of the distribution. So, recommended number of cut-offs for this kind of mapping is 5-11.

For many statistical analyses, especially for geostatistical mapping.[3,7], normal distribution is mathematical base for the proper use of descriptive statistics, which includes variance, mean, mod, median etc. Variogram, which is a basis for kriging mapping, is derived from the variance. That means that normal distribution is also condition for a variogram as a representative tool. Many of geostatistical methods, as the first step, perform normal transformation of data wherever it is possible. In ref.[13] it was proven that the best way for cut-off definition is to group the data into several classes so that they approximately follow normal distribution pattern. Figure 4 represent normally distributed porosity classes in this analysis subsequently applied as cut-offs for indicator transformation of the input data from the Lower Pontian reservoir.

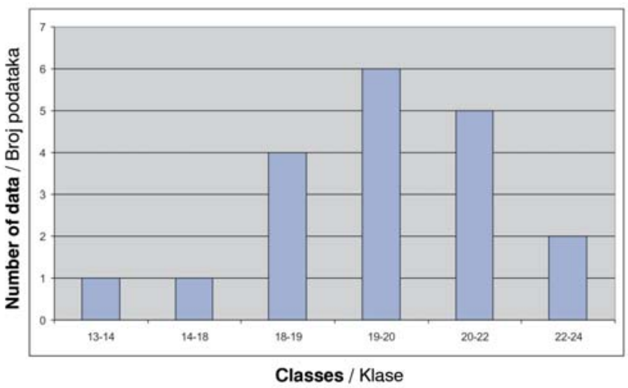

Fig. 4. Normally distributed porosity classes within the Lower Pontian reservoir (from ref.[11])

Sl. 4. Razredi poroznosti donjopontskog ležišta koji slijede normalnu distribuciju (iz[11])

6. LITHOFACIES DEFINITION BASED ON CUT-OFFS

Empirical experience shows that sandstones in this type of reservoir have porosity between 15 and 25%. Most of the well log measurements cover the main part of the reservoir, which is sandstone by lithology, but it is also the most abundant part. Since chosen wells are equally distributed on the reservoir area, it is logical that most of the well log measurements are from the sandstone. On the other hand, one well shows extremely low log porosity value (5.5%). Such low porosity directly points to marl, i.e. to Te Bouma sequence. One well has porosity value 13.8%, which indicates part of depositional environment with marls, sandy marls and marly sand intercalation i.e. Tc Bouma sequence. As there was just one measure-

Table 2. Input well data with defined Bouma sequence and minimum and maximum cut-offs

Well	Reservoir	Average log porosity (%)	Bouma sequence	Cut-offs for IK mapping
Well 1	Lower Pontian reservoir	23.3		Maximum
Well 2		22.0		
Well 3		19.9		
Well 4		19.5		
Well 5		19.6		
Well 6		21.1		
Well 7		20.5		
Well 8		20.1		
Well 9		21.2		
Well 10		17.9		
Well 11		19.2		
Well 12		13.8	Tc	Minimum
Well 13		5.5	Te	
Well 14		19.7		
Well 15		18.2		
Well 16		21.8		
Well 17		18.1		
Well 18		18.5		
Well 19		19.6		
Well 20		18.4		

ment in Tc interval and one in Te, which is not the highest porosity value in marl (also concluded by experience) and does not represent border between Te and Td lithofacies, it was not possible to define borders between Te and Td or Tc and Td intervals. For that reason it was decided to map Tc and Tb intervals with a goal of finding border between them, and to exclude the well with minimal value as outlier.[12]

Remaining lowest (13.8%) and the highest (23.3%) porosities (Table 2) defined minimum and maximum cut-off for the indicator mapping.

7. INDICATOR KRIGING MAPPING

Indicator Kriging maps show probability that the mapped variable is smaller than certain cutoff value. That means that probability map for porosity smaller than 19% also includes probability that porosity is smaller than 18%. Better lithofacies definition would be achieved with probability maps of interval 18 to 19%, but the same result can be obtained by observing and overlapping two maps (one which shows probability that the mapped variable is smaller than 18% and another which shows probability that the mapped variable is smaller than 19%). Areas of the lowest probabilities on the map for porosity smaller than 18% and areas of the highest probabilities for the porosity smaller than 19% are areas of the interval 18 to 19%.

Northwest-southeast direction can also be very well observed in porosity probability map for cutoff 19% (Figure 5). Blue on the map shows the area of the highest probability that porosities are higher than 19%, i.e. according to experience pure sandstones location. Northwest-southeast direction is also direction of the regional fault which close the reservoir on southwest. Figure 5 (probability for porosity values less than 20%) shows highest probability for the highest porosities in the deepest part of the reservoir. Yet, detail observation of probability maps for cutoff 19% and 20% (Figure 5), give possibility for reconstruct direction of material transport. Depositional channel, whose direction is northwest-southeast, can be observed in Figure 5 for cut-off 19%, but if the cutoff value is increased only for 1%, depositional channel cannot be so well observed. However, higher porosity values on western part of the reservoir are obvious. Since turbititic channel is the best seen in probability map for 19% of porosity it could be assumed that this value is actually border between Tc and Tb sequence.

8. CONCLUSION

During the Late Pannonian and the Early Pontian in the Croatian part of the Pannonian Basin System the second transtension prevailed. Miner down lifted fault areas inside the Sava Depressions represented suitable places for sediments accumulations. Detritus had been brought by turbidites from the Eastern Alps, several times redeposited, until it finally reached the Sava Depression. Due to the long distance transport (several hundred kilometers), turbidites have incomplete Bouma sequence (Tb-Td).

Although normality is not the condition for Indicator Kriging mapping, definition of classes that approximately follow normal distribution (made in this research) is useful, because it makes possible to calculate the descriptive statistics of such data and improve interpretation of indicator maps.

Porosity interpretation on the probability map lower than 19% in Lower Pontian reservoir showed that the coarsest material in this part of the Sava Depression mostly came from north (as it was interpreted in ref.[20] Part of this material was deposited in local synclines. During Early Pontian material was transported to the regional fault, where part of middle grained material was deposited, and another part was transported parallel with the fault toward SE.

The Indicator Kriging maps proved heterogeneity of the reservoirs by existence of different lithofacies starting with sandstones in the central part of the channel to marly sandstones, sandy marls and marls. Borders between parts of the reservoir with higher and lower porosity were better defined. Indicator maps also show probabilities of the lithofacies at the certain location. It is very important to try to map certain cut-offs which are borders between different lithofacies. In this case turbiditic channel and material transport direction could be observed in maps. In the study area border between

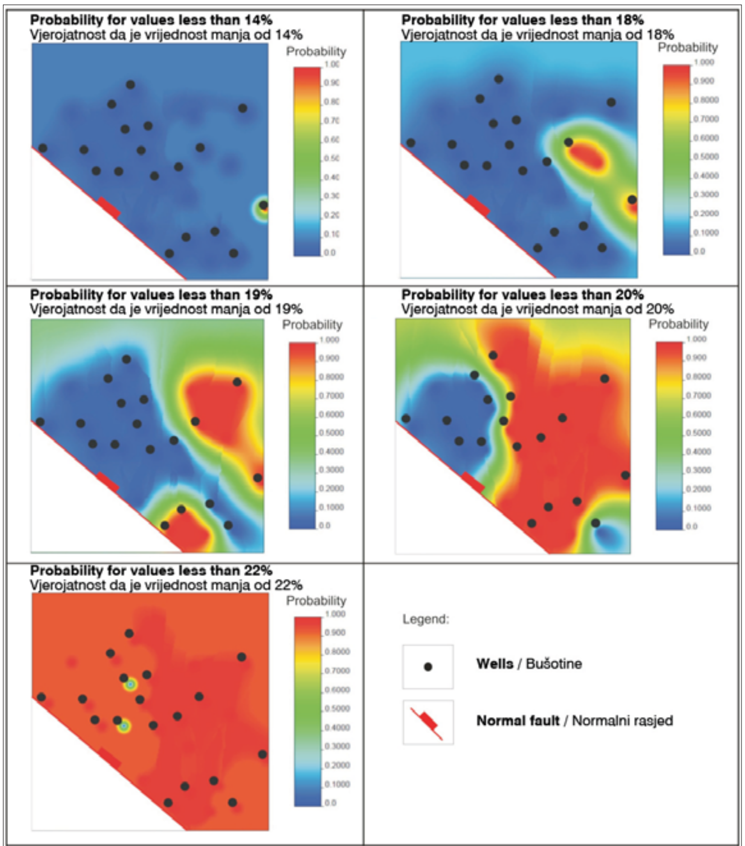

Fig. 5. Probability maps for porosity cut-offs (from ref.[12])
Sl. 5. Karte vjerojatnosti za granične vrijednosti poroznosti (iz[12])

Tb and Tc Bouma sequence could represent 19% porosity.

9. REFERENCES

1. Ćorić, S., Pavelić, D., Rögl, F., Mandić, O., Vrbac, S., Avanić, R., Jerković, L. & Vranjković, A. (2009): Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys), Geologia Croatica, 62, 1, 31-43.
2. Deutsch, C.V. (2002): Geostatistical Reservoir Modeling. Oxford University Press, New York, 376 p.
3. Deutsch, C.V. & Journel, A.G. (1997): GSLIB: Geostatistical Software Library and User's Guide, 2nd edn. Oxford University Press, New York, 369 p.
4. Haq, B.U. & Eysinga, F.W.B. (1998): Geological Time Table, Fifth Edition (Wall Chart). Elsevier Science, Amsterdam.
5. Hohn, M.E. (1988): Geostatistics and petroleum geology. Van Nostrand Reinhold, New York, 264 p.
6. Hohn, M.E. & McDowel, R.R. (1994): Geostatistical Analysis of oil production and potential using indicator kriging. In: Stochastic Modelling and Geostatistics. Prociples, Methods and Case Studies (Eds. Yarus, J.M., Chambers, R.), AAPG Computer Applications in Geology, 3, 121-130.
7. Isaaks, E. & Srivastava, R. (1989): An Introduction to Applied Geostatistics. Oxford University Press Inc., New York, 580 p.
8. Journel, A. G. (1983): Non-parametric estimation of spatial distribution. Mathematical Geology, 15, 3, 445-468.
9. Malvić, T. (2003): Naftnogeološki odnosi i vjerojatnost pronalaska novih zaliha ugljikovodika u bjelovarskoj uleknini (Oil-Geological Relations and Probability of Discovering New Hydrocarbon Reserves in the Bjelovar Sag). University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, 123 p.
10. Malvić T. & Velić J. (2011): 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 (Ed. Schattner, U.), 215-238, InTech, Rijeka.
11. Novak Zelenika, K. (2012): Cut-offs definition in Indicator Kriging mapping, case study Lower Pontian reservoir in the Sava Depression. In: Geomathematics as geoscience Conference book (Eds. Malvić, T., Geiger, J., Cvetković, M.), 127-134, Croatian Geological Society, Zagreb.
12. Novak Zelenika, K., Malvić, T. & Geiger, J. (2010): Kartiranje gornjomiocenskih pješčenjačkih facijesa metodom indikatorskog kriginga, Nafta, 61, 5, 225-233.
13. Novak Zelenika, K., Velić, J., Malvić, T. & Cvetković, M. (2011): Geological Variables Fitting in Normal Distribution and Application in Indicator Geostatistical Methods. In: IAMG 2011 Conference proceedings (Eds. Marschallinger, R., Zobl, F.), 245-251, IAMG, Salzburg.
14. Rögl, F. (1996): Stratigraphic Correlation of the Paratethys Oligocene and Miocene, Mitteilungen Ges. Geol. Bergbaustudenten Österreich, 41, 65-73.
15. Rögl, F. (1998): Palaeographic Consideration for Mediterranean and Paratethys Seaways (Oligocene to Miocene), Ann. Naturhist. Mus. Wien, 99A, 279-310.
16. Solow, R. (1986): Mapping by simple indicator kriging, Mathematical Geology, 18, 3, 335-352.
17. Velić J. (2007): Geologija ležišta nafte i plina. Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb.
18. Vrbanac, B. (1996): Paleostrukturne i sedimentološke analize gornjopanonskih naslaga formacije Ivanić grad u Savskoj Depresiji Palaeostructural and sedimentological analyses of Late Pannonian sediments of Ivanić Grad formation in the Sava depression . Unpub. PhD Thesis, Faculty of Natural Sciences, University of Zagreb, 121 p.
19. Vrbanac (2002): Facies and facies architecture of the Ivanić Grad Formation (Upper Pannonian) - Sava Depression, NW Croatia, Geologia Croatica, 55, 1, 57-77.
20. Vrbanac, B., Velić, J. & Malvić, T. (2010): Sedimentation of deep-water turbidites in main and marginal basins in the SW part of the Pannonian Basin, Geologica Carpathica, 61, 1, 55-69.

❖

Author:

Kristina Novak Zelenika, INA- Oil Industry Plc. Exploration and Production of Oil and Gas, Sector for Geology and Reservoir Management, Šubićeva 29, 10000 Zagreb, e-mail: kristina.novakzelenika@ina.hr