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Indicator Kriging porosity maps of Upper Miocene sandstones, Sava Depression, Northern Croatia

Indikatorsko krigiranje poroznosti zgornjemiocenskih peščenjakov v Posavski kadunji v severni Hrvaški

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Abstract

There are geologically and geostatistically analysed two, presently, the most interesting Upper Miocene sandstone Croatian hydrocarbon reservoirs in the Sava Depression regarding injection of carbon-dioxide. The intention is increasing oil recovery and, simultaneously, keeps part of injected CO_2 permanently in depleted reservoirs. Lithologically, both reservoirs are dominantly fine to medium-grained sandstones, with very restricted pelitic content, where silt, clay and marl fractions are increased only in laterally marginal parts. Lithostratigraphically (informally) those two reservoirs are named as "Gamma 3" (older, here analysed as reservoir "A") and "Gamma 4" (younger, here as reservoir "B"), both belonging to the Iva Member, i.e. the Ivanić Grad Formation. Indicator Kriging had been used to map probabilities to obtain different porosities that indicated on different lithofacies.

Key words: sandstones, Indicator Kriging, porosity, Upper Miocene, Sava Depression, Croatia

Izvleček

V dveh na Hrvaškem sedaj najobetavnejših zgornjemiocenskih rezervoarjih ogljikovodikov so geološko in geostatistično preiskali možnost vtiskanja ogljikovega dioksida. Cilj je bil povečati izkoristek črpanja nafte, hkrati pa v izpraznjenih rezervoarjih trajno uskladiščiti del vtisnjenega CO_2. Litološko sta oba rezervoarja v pretežno drobno do srednjezrnatih peščenjakih z zelo podrejenim pelitskim deležem, pri čemer so meljaste, glinene in laporne frakcije znatneje zastopane le bočno v obrobnih delih. Na osnovi litostratigrafije so rezervoarja neformalno poimenovali "Gama 3" (starejši, označen kot rezervoar "A") in "Gama 4" (mlajši, označeni kot rezervoar "B"). Oba pripadata členu Iva, tj. Ivanićgradski formaciji. Za kartiranje verjetnosti nastopanja različnih poroznosti, ki indicirajo različne litofaciese, so uporabili metodo indikatorskega krigiranja.

Ključne besede: peščenjaki, indikatorsko krigiranje, poroznost, zgornji miocen, Posavska kadunja, Hrvaška

Introduction

In Croatia, the projects for CO_2 transport and storage can be successfully applied in order to (a) increase oil recovery from "mature" sandstone reservoirs and on a commercial basis, (b) permanent store CO_2 with the purpose of greenhouse gas (abbr. GHG) emission reduction. The CO_2 generated from combustion of fossil fuels or produced during production of oil or natural gas is injected into hydrocarbon reservoirs with the aim of increasing oil recovery for more then 30 years, where recovery could be averagely increased for 10–14 %[1, 2]. Currently several dozen of the Enhanced Oil Recovery (abbr. EOR) projects are operating worldwide[3–5].

The CO_2 trapping in the subsurface depends on reservoir pressure, temperature and properties of cap rock. Reservoirs suitable for application of the EOR methods could be described by the following characteristics[6–8]: (a) oil viscosity < 12 mPa s, (b) oil density 825–865 kg/m^3, (c) residual oil saturation, Sor > 25 %, (d) initial reservoir pressure > 100 bar. In addition CO_2 mineral trapping can increase volume of trapped gas for few percentages[9]. Generally, sediments deeper than 800 m provide natural reservoir pressure sufficient to keep the CO_2 in supercritical state. The quality of cap rocks is very important factor for fluid storage into subsurface reservoirs[10].

Assessment of applicability of CO_2 injection into Croatian oil fields was conducted in the '70s and '80s of the last century, mostly through a pilot project on limited part of the Ivanić Field[11–13]. Its results led to a decision on implementation of the EOR project, but also initiated further geological modelling of sandstone reservoirs possibly and partially saturated with CO_2. In the case of the Ivanić Field considered are medium to fine-grained sandstone reservoirs, more than 10 m thick, and still in production as oil reservoirs (but largely exhausted). The age is Upper Pannonian. There is planned to inject 400 000 m^3/d of CO_2 collected onto gas-processing plant Molve. The results could be twofold: (a) enhanced oil recovery and (b) reducing of CO_2 emission[14, 15].

A model of injected gas behaviour is based on an analysis of several geological variables, including fluid properties and chemical reactions. However, it is important to understand distribution of porosity and permeability, as probably two important variables, within the reservoir. Geostatistical methods for reservoir mapping could be divided into deterministical and stochastical ones. Deterministical provide "the most probable" solution from available data, sometimes described like in Kriging based simulation as the median or "zero-realisation" when it is later applied in simulation. The most probable means that there are also other possibilities in representation of surface, which are "located" in uncertainty range typical for input dataset. It resulted in set of equiprobable realisations where selection of representative ones is based on several techniques, but no one of them favour any realisation as more probable.

This study shows applications of Indicator Kriging (abbr. IK) probability maps, as deterministical method, in estimation of porosity and permeability. Such data are derived from Upper Miocene sandstone reservoirs into the Ivanić Field, planned for injection of CO_2. Presented models are the first of such estimation made for those sandstones and consequently this is the first application of indicator transformation into analyses of CO_2 target reservoirs in Croatia.

Geological description of the study area within the Sava Depression

During Late Pannonian and Early Pontian many depressional areas along the entire Pannonian Basin System were re-extended due to the thermal subsidence as result of 2nd transtensional phase[16–18]. Depositional spaces for the accommodation of a huge volume of sandy material were created, and the main sandstone hydrocarbon reservoirs were deposited[19]. Turbidites were dominant clastic transport mechanism in the Croatian part of the Pannonian Basin System (abbr. CPBS) during that time, originated from the Eastern Alps and transported through the Vienna Basin, the Styrian Basin and the Mura Depression, more to the east in several re-deposition phases, when it eventually entered into the Sava Depression[4, 17, 20–22]. Due to long transport only the medium and fine-grained sands and silts reached the depression, where in the calm periods, when turbiditic currents were not active, typical calm deep-water calcite rich mad (later marls) were deposited. However, the CPBS was characterised with several prominent, even present-day, mountains that existed during entire Miocene like uplifted palaeorelief. Probably some of them were isolated islands in the Central Paratethys and, later, the Lake Pannon and, eventually, the Sava Lake, giving small part of sandy and silty detritus into dominant turbiditic and basin deposits[6, 23]. Study area is located in the northwestern part of the Sava Depression (Figure 1). Present-day the Ivanić Field is asymmetrical brachianticline, with longer axis of northwest-southeast strike, slightly pronounced top in the southern part, and series of NW-SE faults extended along the western part (Figure 2).

Lithologically, reservoir rocks are mostly medium and fine-grained sandstones, i.e. lithoarenites, in vertical alternation with marls (Figure 3). Sandstone and marl layers are not always laterally continuous, i.e. rather they pinch out or could be eroded. As results, some sandstones deposited in separate events could be in direct contact, i.e. amalgamated.

The reservoir "series" (i.e. set of connected depositional events) were classified as Upper Pannonian (9.3–7.1 Ma[16]). Reservoirs are elongated along NW-SE direction and represented fast gravitationally dropped sediment, into "strike-slip" area as depositional minimum. Such areas were characteristic for the entire CPBS during Upper Miocene[17], and typical sedimentation model for such sediments in the western Sava Depression had been described for the Kloštar Field[24, 25]. It assumed that the coarsest

Figure 1: *Location map of the Ivanić Field[12].*

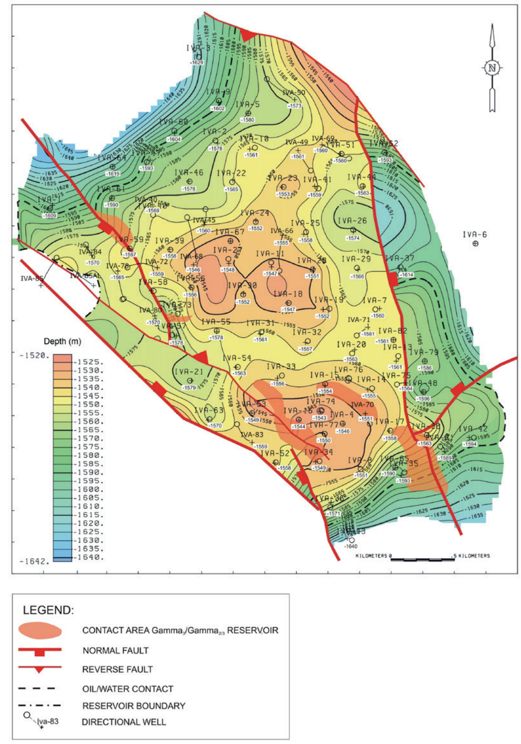


Figure 2: *Structural top map of the reservoir „A" based onto archive maps[12].*

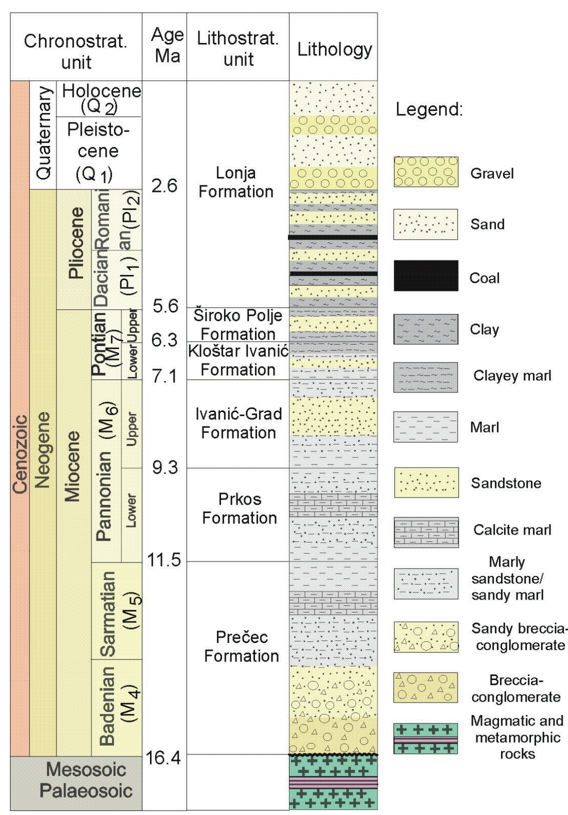


Figure 3: *Schematic geological (lithological, lithostratigraphical and chronostratigraphical) section of the Ivanić Field.*

material had been deposited in the central part of palaeostructure, i.e. main channel(s). Laterally, toward structure borders, depositional lithofacies gradually were replaced with basinal marls.

Basics about applied mapping methods

Deterministical interpolation methods are still commonly used for reservoir characterization and modelling in Croatia[2, 26–30]. However, in several cases stochastical methods are also applied[12] as standard part of geomathematics as it is understood in Croatia[31].

In general, deterministic models for the same input data give always the same results if the analytical method is the same. There are many deterministic interpolation methods, but Kriging is commonly used in geosciences, dealing very well with clustered data and numerical outliers. The goal of the method is to determine spatial relationships between the measured data and the point where value is estimating and it is why a mapping is preceded by variogram (sometimes covariance or madogram) analysis. So, the point's mutual distances, not values, are crucial for interpolation. Moreover, the Kriging is marked with Kriging variance that could be calculated as regional or local. In each case the goal is minimised such variance, i.e. differences between expected and estimated values[32].

Linearity of Kriging estimation could be expresed by Equation 1. It means that value of regionalised variable at selected location (Z_k) is estimated from all surrounding and spatially dependence values (Z_i), using appropriate weighting coefficient (λ_i).

$$Z_k = \sum_{i=1}^{n} \lambda_i \times Z_i \qquad (1)$$

Where are:
Z_k – kriged value,
Z_i – value at location "i",
λ – weighted coefficient.

Such estimation also implies that values Z_i will have normal (Gaussian) distribution. It is conseqeunce of the central limit theorem where is implied that any variable with large number of indenpendent events obtains Gaussian distribution, whatever is probability density function of events[33]. The weighting coefficients in the Kriging are calculated using matrix eqautions[34, 35].

One of the most frequently used Kriging method for facies identification is the Indicator Kriging, i.e. usage of porosity cutoffs. It does not require stationarity assumption of 1st or 2nd degree, or multivariate normality, and is very robust in respect to outliers. In fact, statistics is represented only with variograms, and the originally continuous distribution is discretized using cutoffs, knowing know that at a particular location the value lies in a particular interval.

Indicator approach is used for mapping of two categorical (discrete) values or indicator variable, shown by 0 and 1. Intention is showing two different lithotypes or lithofacies, very often by using the cut-off values for porosity as a geological variable suitable for distinguishing clastic lithofacies[36]. The input values are transformed into indicator ones by using the cut-offs that determine presence or absence of lithofacies. Such method is described with following Equation 2:

$$I(x)_k = \begin{cases} 1 & \text{if} \quad z(x) \le \nu \\ 0 & \text{if} \quad z(x) > \nu \end{cases} \qquad (2)$$

Where are:
$I(x)$ – indicator variable,
$z(x)$ – measured value,
ν – cut-off.

Calculation of the Indicator Kriging, as each Kriging technique, requires variogram analysis. The special in this technique is that variograms need to be calculating for each cut-off and standardised with sill onto 1. Moreover, recommended number of cut-offs is between 5 and 11, what requires sufficient number of measurements[36]. Indicator maps correspond to continuous assessment of iso-probability lines with values in the interval [0, 1]. Mathematically such maps show the probability of the event $\{z(x) < \nu k\}$.

Input datasets

Input datasets consisted of 16 wells with porosity and permeability values of the reservoirs "A" and "B" (Table 1 and 2). Porosities were calculated from the log analyses and cored intervals. Permeabilities were obtained by unsteady state method at a constant oil/water viscosity ratio and applying a constant differential pressure across the core samples. After correction for overburden pressure, depth correlation of log analyses and coring data was performed.

Several cut-offs were defined for probability mapping:

— In reservoir "A":
< 15 %, 15–19 %, 19–22 %, 22–24 % and > 24 % for porosity, and < 40 × 10^{-3} μm², 40–50 × 10^{-3} μm², 50–60 × 10^{-3} μm², 60–70 × 10^{-3} μm², 70–80 × 10^{-3} μm² and > 80 × 10^{-3} μm² for permeability.

— In reservoir "B":
< 10 %, 10–15 %, 15–20 %, 20–23 % and > 23 %, and < 1 × 10^{-3} μm², 1–5 × 10^{-3} μm², 5–20 × 10^{-3} μm², 35–75 × 10^{-3} μm² and > 75 × 10^{-3} μm².

Histograms are shown in Figure 4.

Indicator Kriging porosity subsurface maps and correlation between porosity and permeability

Petrophysical parameters were mapped by the Indicator Kriging and obtained are probability maps for certain interval. Porosity intervals 19–22 % for reservoir "A" (Map 1) and 20–23 % for reservoir "B" (Map 2) are chosen as the best representing for extension of medium-grained reservoir sandstones. For reservoir "A" is also derived E-type map that shows the most probable values of porosity (Map 3). Correlation between porosity and permeability was calculated using Pearson's correlation coefficient, and coefficient of determination. The value for the reservoir "A" reservoir is R = 0.76 and R^2 = 0.57 retrospectively (Figure 5) and for reservoir "B" 0.89 and 0.79 (Figure 6).

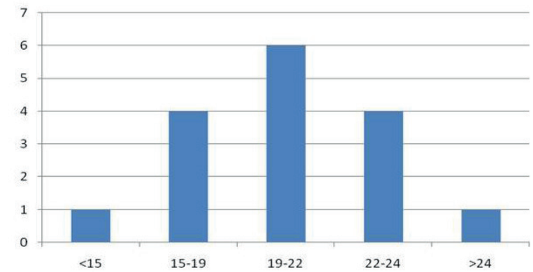
The both values are qualitatively "high" and can described stronger linear dependence between two analysed variables, especially for reservoir "B". Furthermore, both reservoirs are result of deeper lake sedimentary processes. Later, area was subdued to compaction. However, there were not existed processes that could

Table 1: *Input dataset for the reservoir "A"*

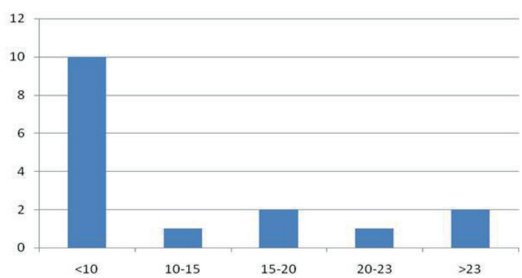
Well	Porosity (%)	Horizontal permeability (10^{-3} μm²)
Well 1	21.03	LIQUIDATED
Well 2	18.68	56.22
Well 3	22.65	76.40
Well 4	18.23	39.90
Well 5	20.20	LIQUIDATED
Well 6	14.32	41.40
Well 7	21.32	52.40
Well 8	18.93	48.09
Well 9	22.03	70.68
Well 10	17.27	60.14
Well 11	24.21	81.01
Well 12	23.13	62.50
Well 13	20.95	49.74
Well 14	22.08	67.20
Well 15	19.80	60.93
Well 16	21.12	58.11

Table 2: *Input dataset for the reservoir "B" reservoir*

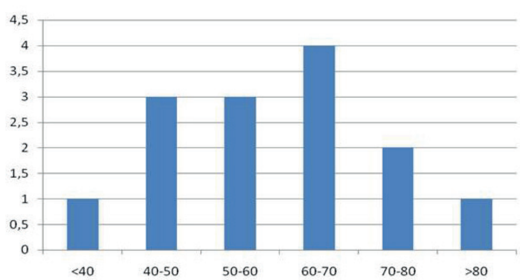
Well	Porosity (%)	Horizontal permeability (10^{-3} μm²)
Well 1	1.90	LIQUIDATED
Well 2	0.81	1.39
Well 3	5.10	4.07
Well 4	19.78	32.85
Well 5	0.00	LIQUIDATED
Well 6	0.00	0.91
Well 7	0.00	1.39
Well 8	0.00	1.20
Well 9	8.62	10.39
Well 10	23.76	77.38
Well 11	1.99	2.54
Well 12	23.13	34.36
Well 13	12.07	15.83
Well 14	19.09	29.40
Well 15	0.00	1.63
Well 16	21.27	36.37



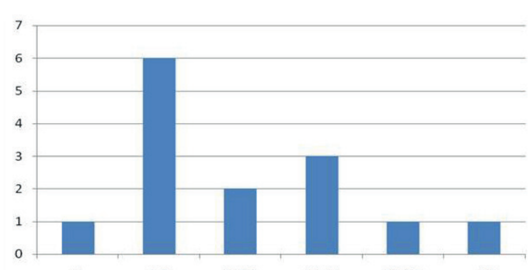
Histogram of number of data in cut-off defined classes of "Gamma 3" porosity
X axis: porosity (%), Y axis: number of data)



Histogram of number of data in cut-off defined classes of "Gamma 4" porosity
(X axis: porosity (%), Y axis: number of data)

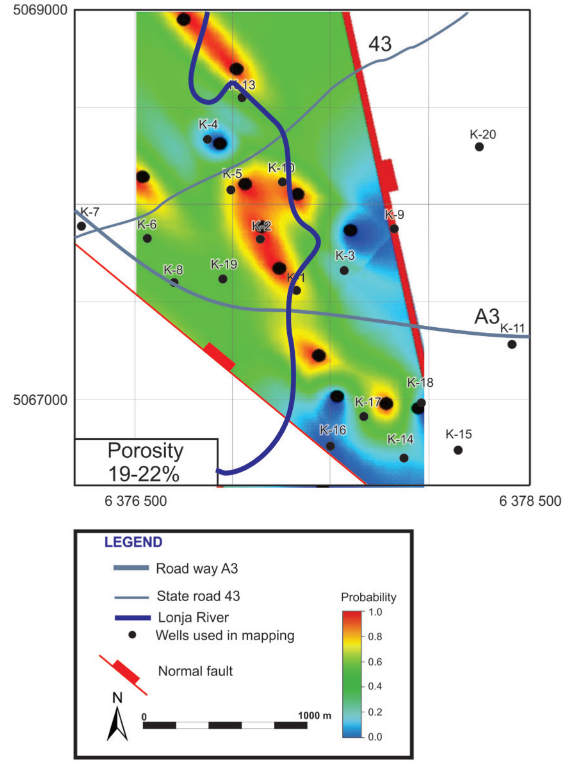


Histogram of number of data in cut-off defined classes of "Gamma 3" porosity
(X axis: permeability (10^{-3} μm^2), Y axis: number of data)

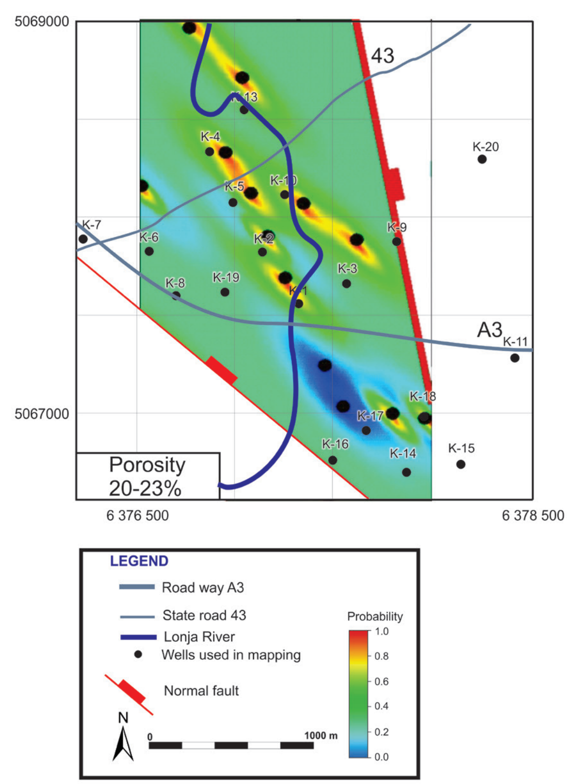


Histogram of number of data in cut-off defined classes of "Gamma 4" porosity
(X axis: permeability (10^{-3} μm^2), Y axis: number of data)

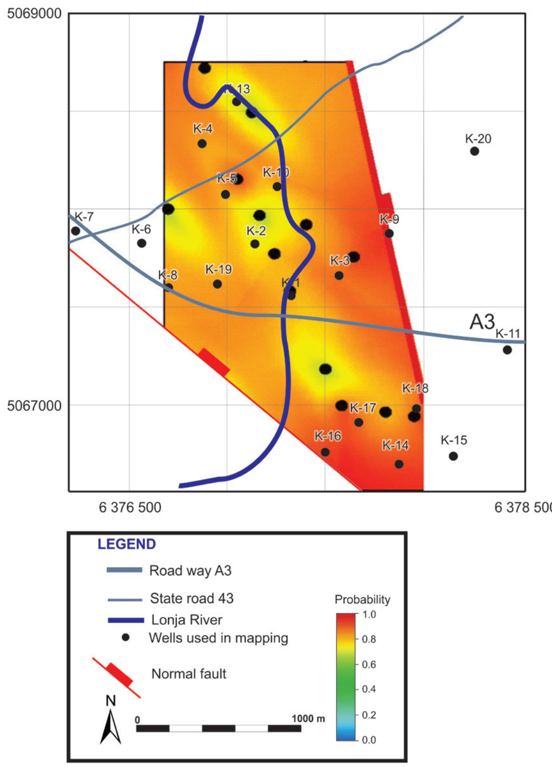
Figure 4: *Histograms of defined classes for the reservoirs "A" and "B" porosity and permeability.*



Map 1: *Probability map for the porosity interval* 19–22 % *of reservoir "A".*



Map 2: *Probability map for the porosity interval* 20–23 % *of reservoir "B".*



Map 3: *Indicator Kriging E-type map of reservoir "A" porosity, based on the equation of Ordinary Kriging.*

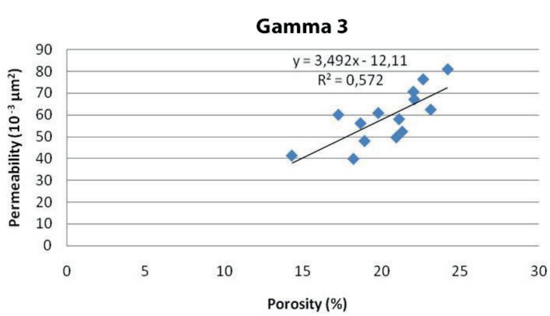


Figure 5: *Porosity and permeability regression line for reservoir "A".*

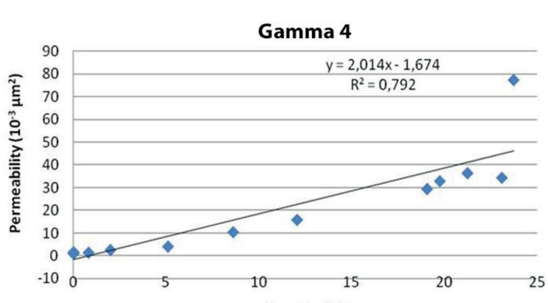


Figure 6: *Porosity and permeability regression line for reservoir "A".*

result in secondary porosity (tectonic caused fracturing) or filling pores with dissolved materials. So, the primary porosity played main role in fluid distribution, what is favourable for linear relation between porosity and permeability. The larger correlation between porosity and permeability in reservoir "B" is probably reflection of generally narrow range of both values in analysed lithological sequence, what is consequence of more uniform depositional environment.

Results and conclusions

Analysed sandstone reservoirs were created in brackish, lacustric depositional environments of the Lake Pannon. The mineral content is represented with quartz, dolomite rock fragments, micas, K-feldspars and cement. The texture is medium to fine-grained with porosity mostly between 15 % and 25 % and average permeability between 50 and 60 × 10^{-3} μm^2. Those values can be considered as typical for the Upper Miocene sandstones in the Sava Depression. Depositional environment included periodically active regional turbidites during Late Pannonian and Early Pontian stages.

However, here are marked intervals between 19 % and 23 % as the most representative for describing depositional area of typical channel, medium-grained sandstone lithofacies. Those are the best lithology for fluid flow and injection into analysed reservoirs. For this purpose those intervals are mapped into two reservoirs planned for CO_2 injection. The results (Maps 1 and 2) shows areas where such turbiditic lithofacies could be certainly followed. However, the maps are biased with elongated "bull-eyes" effect, what is not favourable feature for interpretation. It could be override using approximately omnidirectional variogram model, with larger ranges, but it was not observed in data itself. So, presented Indicator Kriging probability maps are considered as the most representative and useful for planning pilot injection.

The last Map 3 is direct porosity map of the reservoir "A", but interpolated using Ordinary and Indicator Kriging algorithms simultaneously.

It was possible using algorithm that indicator probability maps considered as the "weights" for the more precise application of the Ordinary Kriging.
Interestingly, not each "bull-eye" shape was characterised with maximal probabilities or direct porosity estimated values. It is directed reflection of palaeo-depths of each such "micro" strike-slip on the bottom of the Ivanić Structure during Upper Pannonian, where some of them were deeper and "collected" the coarser detritus (mostly on the east and southeast) then other ones.

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