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Selection of the most appropriate interpolation method for sandstone reservoirs in the Kloštar oil and gas field

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ABSTRACT

The distribution of porosity data collected at the Kloštar field is analysed. This field is located in the north-western part of the Sava depression, and represents one of the most long-standing fields with respect to oil production in Croatia, where production has been ongoing for more than 50 years. Several reservoirs of very diverse lithology and stratigraphic age have been discovered. The oldest reservoirs (with minor oil reserves) occur in basement rocks of the Tertiary system (informally named the »temeljno gorje«), then in Badenian coarse-grained clastics, as well as sandstones of Pannonian and Pontian ages. Major reservoirs, with respect to size, number and volume, are located in sediments of the Upper Pannonian and Lower Pontian. These are medium-grained sandstones, mostly quartz-mica grains, mutually separated by marls. Reservoirs of Lower Pontian age occur within whole structures (anticlines) at Kloštar, while the Upper Pannonian has been developed only in the south–west part. Earlier studies on the reservoirs have included only several measured values of reservoir porosity. These values have not been mapped, but only a unique average value, characteristic for the whole reservoir was calculated. Reinterpretation of e-logs increased the number of input values to 20 points of data. Rules are determined for the distribution of porosities in the largest reservoir of the Lower Pontian named »T«. These regularities can be translated to the other sandstone reservoirs. Several interpolation methods were selected (inverse distance, nearest neighbourhood and moving average), with special emphasis on kriging. The interpolated maps are different. Based on a comparison of isoporosity, lines, shapes, and cross-validation results, kriging was evaluated as the most appropriate method for porosity interpolation.

Keywords: oil, 1st sandstone series, porosity, geostatistics, kriging, Pontian, Kloštar, Croatia

1. INTRODUCTION

The goal for estimation is to get values of a chosen variable for unsampled locations. There are different interpolation methods, and each of them includes its own mathematical rules. The goal is to achieve the interpolation that is most similar to the real geological distribution in the reservoir. In this paper the results of four methods: inverse distance weighting, nearest neighbourhood, moving average and kriging are compared. Kriging has proved to be the most appropriate linear interpolation method in the sense of least square differences. Originally this method was applied to gold deposits of South Africa by the engineer D. G. Krige, from which the name is derived (KRIGE,1951). This pioneer work was followed by strong theoretical (mathematical) development in several techniques of kriging. Today these geostatistical methods are widely used and represent a standard part of numerous methods of studies applied to reservoir rocks.

The distribution of porosity is analysed as the most important variable in the reservoir. The methods are tested using data from the »T« reservoir, which belongs to the 1st sandstone series of the Kloštar field **(Table 1)** in the Sava depression. The total number of reservoir units is 5. These are the following units (starting with the oldest): basement rocks (»temeljno gorje«), Miocene (reservoir II, III, IV, V, VI), Lower Pannonian sediments, 2nd sandstone series (reservoirs alpha, beta, gamma) and 1st sandstone series (reservoirs IK, O, P, Q, R, S, T, U, V, Y, Z) **(Table 1)**. These are the first porosity maps interpolated in Pontian reservoirs in the Kloštar field.

2. GEOGRAPHIC LOCATION AND BASIC GEOLOGY OF THE KLOŠTAR FIELD

The Kloštar field is located in the area of the Kloštar-Ivanić, Predavec, Šćapovec, Soboćani, Prkos, Gornji Šarampov and Lipovac villages, i.e. in the Kloštar, Ivanić-Grad and Brckovljani districts. It is located about 35 km east of Zagreb **(Figure 1)**. In close proximity to the south-east, lie the production oil fields of Šumečani and Bunjani. Lupoglav field lies to the northwest, and the Ivanić field is to the south. The Kloštar field covers an area of around 30 km^2, and administratively belongs to Zagreb County, and the regional geological unit of the Sava depression **(Figure 1)**. The hydrocarbon reservoirs are in lithostratigraphic units of Miocene age named the Prečec, Ivanić-Grad (Okoli sandstones) and Kloštar Ivanić (Poljana sandstones) formations. Minor oil reserves also occur in rocks of Palaeozoic age. Generally, there are twenty stratified and/or massive reservoirs proven, forming 5 units named (from the oldest) basement rocks (»temeljno gorje«), Miocene, Lower Pannonian, 2nd sandstone series and 1st sandstone series **(Table 1)**.

Figure 1: Geographic location of the Kloštar field

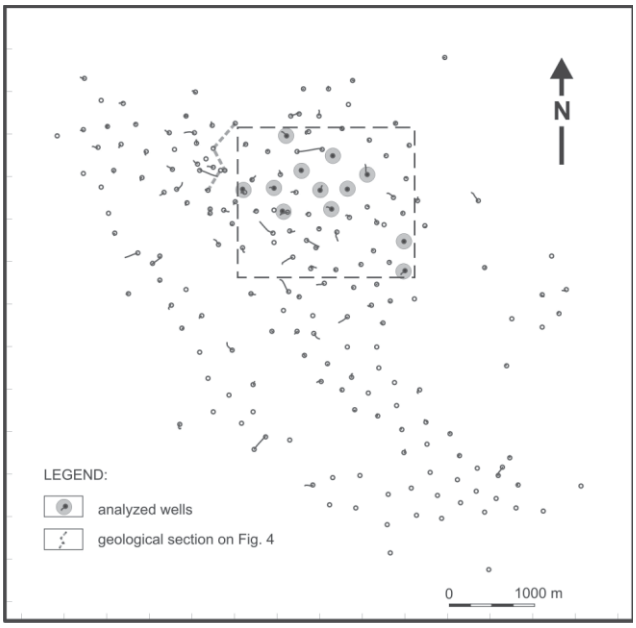

Figure 2: Schematic map of well locations at the analyzed field

The average effective thickness of particular reservoirs is 5 metres. The permeability varies between 2.4 and 179.9 x 10^{-3} μm^2. There are a total of 196 wells drilled to date. Of these, 64 are classified as measuring wells, 59 are in production, 68 are abandoned and 5 wells are used for the injection of waste water[1]. The schematic map of well locations in the Kloštar field is shown in **Figure 2**.

3. HISTORICAL EXPLORATION OF THE KLOŠTAR AREA

Geological research in the area of Kloštar began at the beginning of the 20th century. Gas traces in wells of Kloštar, Ivanić, and surrounding villages were known from ancient times. Factors indicating the presence of hydrocarbons resulted in the first well being drilled to a depth of 905 m in 1904/5. Gas was noticed at a depth of around 650 m, but oil had not been discovered. Regional gravimetric surveying of north-west Croatia between 1940–1942 included the area of the Kloštar field. Gravimetric studies then highlighted a structure called »Križ« with a Dinaridic strike (NW–SE), in which the Šumečani (discovered in 1948), Bunjani (discovered in 1952) and Lupoglav (discovered in 1971) oil fields are located.

On the north-west part of the Križ structure, in the area of Kloštar, there has been a move towards implementing new gravimetric measurement methods since 1952. Interpretation of the results facilitated the location of the first exploration well Kloštar-1 (Klo-1). A depth of 1272 m was achieved in this well. The five reservoirs, with total depth of 853–990 metres have been drilled, to particular depths as follows: A (853–865 m), P (873–875 m), Q (891.5–898.5 the m), R (914–915 m) and Y (987–990 m). An industrially significant amount of oil was discovered. The Kloštar field was put into production in 1954. On several occasions in later years, the density of the network of seismic profiles was increased, especially in the marginal parts of field, for the purpose of field contouring and definition of petroleum geology settings. Between 1954–1961 new wells were drilled, recovery was increased using water injection and the field boundaries were extended. All these achievements led to increases in the reserves, which have been monitored[2] during whole period of production. Furthermore, possible new amounts of hydrocarbons in so-called hidden traps have been estimated[3].

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[1] Report of hydrocarbon reserves of the Kloštar field, professional documentation of INA – Reservoir Engineering and Field Development Dept., 1977; Atlas of oil and gas fields, professional documentation of INA – Reservoir Engineering and Field Development Dept., 1998, Report of hydrocarbon reserves of the Kloštar field, professional documentation of INA – Reservoir Engineering and Field Development Dept., 2002; Study of Steiner et al. from professional documentation of INA, 1999

[2] Report of hydrocarbon reserves of the Kloštar field, professional documentation of INA – Reservoir Engineering and Field Development Dept., 1977; Report of hydrocarbon reserves of the Kloštar field, professional documentation of INA – Reservoir Engineering and Field Development Dept., 2002

[3] Study of Steiner et al. from professional documentation of INA, 1999

Many other regional studies have included investigation of the Kloštar field as part of explored area. Petrophysical properties of the sandstones as well as stratigraphic architecture in the western part of the Sava depression have been well defined by JÜTTNER et al. (2001), SAFTIĆ (1998) and SAFTIĆ et al. (2001). VELIĆ & SAFTIĆ (2000) published a general paper about hydrocarbons in Croatia, and finally CVETKOVIĆ (2007) applied neural networks for log analysis in the sandstone reservoirs in the Kloštar field.

4. PETROLEUM GEOLOGY SETTINGS

The Križ structure (including the Kloštar field) is located at the most north-western part of Moslavačka gora Mt. During the Lower and Middle Miocene, a large part of Moslavačka gora Mt. was uplifted above sea-level. The Križ structure has Dinaric orientation (NW–SE), and it is formed from Pre-Palaeozoic granites and gneisses (VRAGOVIĆ & MAJER, 1980; PAMIĆ et al., 1984). The main northern fault of the Sava depression was parallel with the southern margin of this structure. Despite a large number of well data, the boundaries between stratigraphic units are often not precisely defined, mostly due to the insufficient number of palaeontological samples and a large number of tectonic blocks. At favourable locations, stratigraphic boundaries are determined from available well data (cores, mud particles and logs). There are five reservoir series defined in total, starting with Palaeozoic rocks and ending with Lower Pontian sediments.

The Basement Tertiary system includes eruptives and metamorphic rocks, granites and gneisses of Palaeozoic age. This is a buried hill formed before the Tertiary (i.e. Miocene) period, by radial tectonic movements and denudation processes. The rocks are weathered and cataclised. This explains why some parts, in structurally favourable places, are confirmed as oil reservoirs.

The Middle Miocene (Badenian, Sarmatian) was deposited periclinally over the Palaeozoic magmatic-metamorphic unconformity, i.e. sedimentation was not continuous. The Middle Miocene stratigraphy is very heterogeneous. These sediments begin with coarse-grained conglomerates, conglomeratic sandstones and sandstones often intercalated with shales. They are overlain by dark-grey, sandy and bituminised marlstones, partially intercalated with light-grey, fine-grained sandstones. Miocene beds from economic hydrocarbon reservoirs at the southern and eastern parts of the Kloštar structure.

The Upper Miocene (Pannonian, Pontian) is proven and explored throughout the entire field. Lower Pannonian strata were concordantly deposited over Sarmatian bituminised marlstones. This is a clearly recognised facies of hard, white calcitic marlstones, which can be distinguished from the sediments above and below on their lithological and electro-physical properties (PLETIKAPIĆ, 1969). There are often relatively thin beds of light-grey, fine-grained sandstones that are saturated with significant oil reserves in the southern part of the field.

Upper Pannonian sediments were deposited over the entire field. These are mostly brown or dark-grey, hard calcitic marlstones. Three sandstone series (named as *alpha, beta and gamma*) are present in the south-western part and are partially saturated with hydrocarbons. This is also called the 2nd sandstone series. The *beta* reservoir includes the largest reserves and greatest production.

Lower Pontian sediments are defined as (dark) grey, compact marlstones and sandy marlstones in the south and east of the field. Sandstones, that could be clean or include small proportions of marl or clay, are dominant in the north–west.

The sandstone reservoirs are named, from the top, as G, H, I, K, L, M and N. These are mostly saturated with water, except for some sporadic traces of gas (G and H) or oil (I and K). Deeper intervals are named O, P, Q, R, S, T, U, V, Y and Z, which are the main oil reservoirs of the field. The most important intervals are T, U and V. The units O–Z form the 1st sandstone series.

The Upper Pontian sediments are concordant and occur over the entire field. The lithology is monotonous, consisting of soft sandy or clayey sediments. The proportion of sand increases upwards.

The Pliocene, i.e. Dacian and Romanian, is also known as the »Paludina« beds. These sediments mostly include clays in alternation with medium- and coarse-grained sands.

The Quaternary consists mostly of yellowish, sandy clay sediments with numerous lime concretions. The average thickness is between 10 and 15 metres.

The Kloštar structure is a faulted anticline with Dinaric strike. The geological history is very interesting, as discovered during investigation of the structural definition and palaeotectonic evolution of the western part of the Sava depression (VELIĆ, 1979; 1980; 1983). The field structure was formed in the Middle Miocene, accompanied by strong uplifting events in the Badenian and Sarmatian. At that time, an anticline was created, with dimensions of 7 x 2 km with a NW–SE orientation. Later, in the Upper Miocene, this structure was differentiated into two smaller parts: the northern which was uplifted throughout the Pontian, and the southern part which was only activated in the Upper Pontian. In the same period the particular blocks between these uplifted areas gradually subsided, especially in the Lower Pontian. The recent structural shape was tectonically created in the Pliocene and Quaternary, when the main phase of hydrocarbon migration probably occurred.

The Kloštar structure was bordered by the principal northern fault zone of the depression. The vertical displacement, at the level of marker »Tg« (basement top), is almost 1000 metres. This is why the geological setting of the field is very complex. Such a large displacement is also reflected in the fact that the reservoirs of the 1st sandstone series are dislocated in 17 blocks **(Figure 3)**.

The reservoirs of the **1st sandstone series (Table 1, Figure 4,** named as Z, Y, V, U, T, R, S, P, P, O and IK) belong to the Lower Pontian beds. The part of the 1st sandstone series that is saturated with hydrocarbons covers the north-eastern part of the field. The structure gently sinks toward the north–west. According to the classification of oil and gas reservoirs given by Brod (in AKSIN, 1967), the hydrocarbon reservoirs of the

Table 1 Schematic review of the chrono-, lithostratigraphic and reservoir units

Age				Litho-strat. units	Reservoir series	Reservoirs
CENOZOIC	MIOCENE	UPPER MIOCENE	LOWER PONTIAN	KLOŠTAR-IVANIĆ fm.	1st sandstone series	IK, O, P, Q, R, S, T, U, V, Y, Z
			UPPER PANNONIAN	IVANIĆ-GRAD fm.	2nd sandstone series	alpha, beta, gamma
			LOWER PANNONIAN	PRKOS fm.	Pre-Valencien beds	
		MIDDLE MIOCENE	BADENIAN, SARMATIAN	PREČEC fm.	Miocene	II, III, IV, V, VI
PALEOZOIC				Basement		»temeljno gorje«

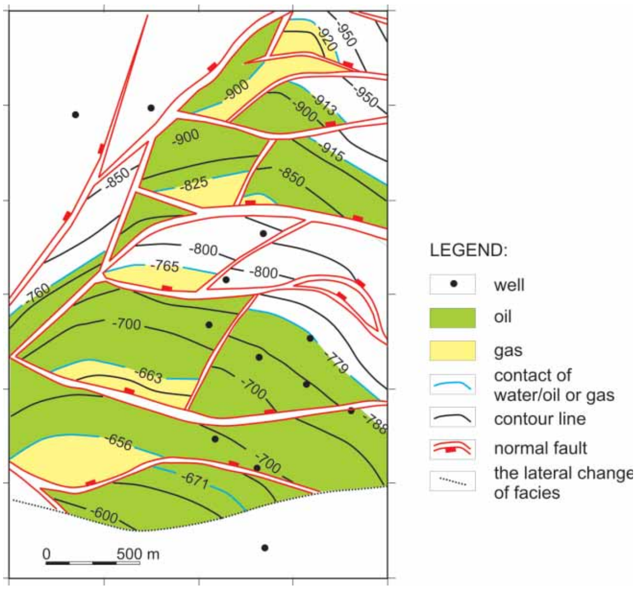

Figure 3: Structural map of »T« reservoir top (1st sandstone series). Drawn after note [3]

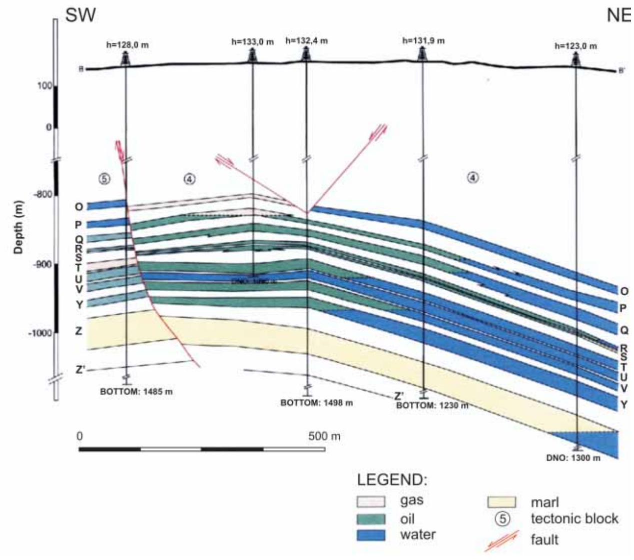

Figure 4: Schematic geological cross-section of the 1st sandstone series[4]

1st sandstone series represent a group of stratified beds delineated by tectonic and lithological barriers. The analysed **reservoir »T«**, together with reservoirs U and V, represents the most important reservoir of the 1st sandstone series. The marlstone that separates reservoirs T, U and V from each other is found in the central part. These reservoirs consist of fine- to medium-grained, weak sandstones, with a maximum thickness up to 10 metres. The marlstones gradually disappear at the east of the structure, allowing possible connection of reservoirs »T« and »U«.

The average reservoir parameters are calculated using weightening and the effective thickness of the analysed intervals. The laboratory porosity data are derived from the 51 cores from 9 wells. Due to the small number of horizontal point data (9) the average reservoir porosities are calculated as arithmetical means.

The Kloštar field is characterised by a very long production period. It has already lasted 53 years and the next 20 years of production are planned **(Figure 5)**. Therefore, emphasis is given to the interpretation of additional logs and calculation of new petrophysical values. This was done in 2007 for 20 representative wells. The average porosities for each reservoir were calculated, and this parameter was especially interpolated in sandstone reservoir »T«, as it is the largest and most typical sandstone reservoir.

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[4] Atlas of oil and gas fields, professional documentation of INA – Reservoir Engineering and Field Development Dept., 1998

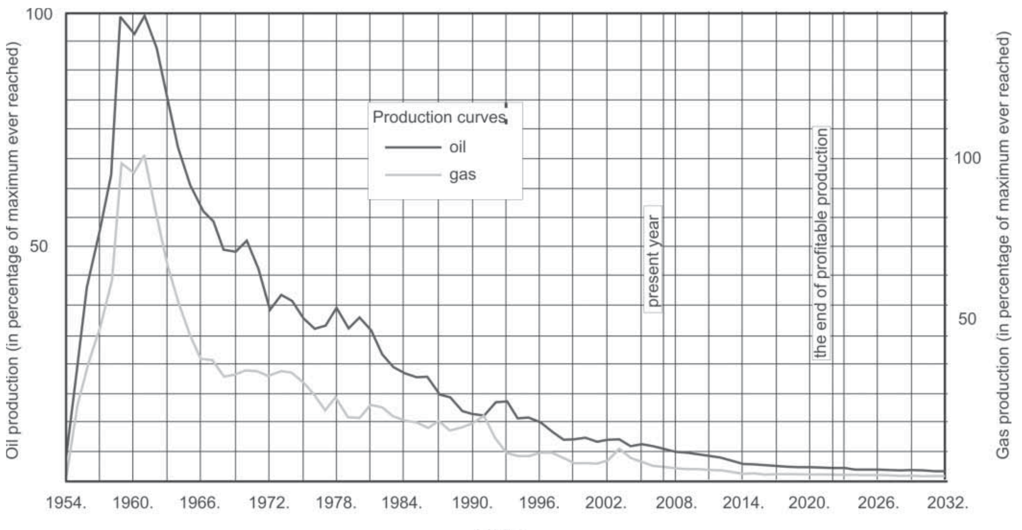

Figure 5: Production rates and dynamics (from: Atlas of oil and gas fields, professional documentation of INA-Reservoir Engineering and Field Development Dept., 1998)

5. APPLIED INTERPOLATION METHODS

The estimation, i.e. interpolation, can be done from known values of the observed primary variable (autocorrelation,) or by using one or more alternative secondary variables in the same area. A strong correlation between the primary and secondary variables is the only condition required. There are various estimation methods, i.e. different interpolation techniques. The applied program Surfer 8.0™ allows the use of twelve interpolation methods. Here, four methods are compared: inverse distance weighting, nearest neighbourhood, moving average and kriging.

The Inverse Distance Weighting method estimates values from a relatively simple mathematical expression **(Equation 1)**. The influence of each point is inversely proportional to the distance from an estimated location. The number of points included in the estimation ($z_1...z_n$), is defined by circle radii drawn around a selected location. The result is strongly dependent on the value of the *distance exponent (p)*. Most often this value is set at 2 (as here). The main reason of the popularity of a value of 2 for the distance exponent is the gently smoothing characteristic of this exponent (János Geiger, pers. comm. 2007). In the case of p=1, a simple linear interpolation can be drawn. For p=3 relatively small distances are emphasised, but from a particular distance the weightings can increase drastically. So if the operator has a mental picture of the geological lateral variation, there is the possibility of highlighting features including thin impermeable barriers, by using a large value for p.

$$z_{IU} = \frac{\frac{z_1}{d_1^p} + \frac{z_2}{d_2^p} + \ldots \frac{z_n}{d_n^p}}{\frac{1}{d_1^p} + \frac{1}{d_2^p} + \ldots \frac{1}{d_n^p}} \qquad \text{(Equation 1)}$$

Where:
z_{IU} – estimated value
$d_1...d_n$ – distances of locations 1...n to the estimated location z_{IU}
p – distance exponent
$z_1...z_n$ – real values at locations 1...n

The Nearest neighbourhood method assigns the value of the closest point to each grid node. It is not so much an interpolation method as a zonal assignment technique. This method is useful in the case of relative large zones without data (blind areas), which need to be schematically mapped. The size of the zone that needs to be »appropriate« is estimated from the defined single data, based on the type of mapped variable.

The Moving Average method calculates the values of grid nodes from averaged data measured in a particular ellipsoid or circle that surrounds each grid node. There is also a need to define the lowest number of data that can be averaged. If the numbers of data inside the defined area are lower than the minimum, the node value will not be calculated. This is not exact interpolation but rather a kind of simple method characterised by its trivial smoothing character. There are some applications when this method can also be applied to the lateral smoothing of data.

Kriging is a geostatistical method, based on calculations of spatial dependence, i.e. experimental variograms. The theory of variogram analysis is explained in numerous books and papers. Such analyses are performed at several fields in the Croatian part of the Pannonian basin system, i.e. for the significant number of core data collected in the Bjelovar subdepression (HERNITZ et. al., 2001; MALVIĆ, 2003; 2005; MALVIĆ & ĐUREKOVIĆ, 2003). Terminologically, the terms **variogram and semivariogram** (e.g. see ISAAKS & SRIVASTAVA, 1989; JOURNEL & HUIJBREGTS, 1978; HOHN, 1988; JENSEN et al., 1997; MALVIĆ, 2003) are identical, because the variogram equation can be simplified in a way whereby both sides are multiplied by '2'. The obtained function **(Equation 2)** is called a semivariogram and is written as:

$$2\gamma(h) = \frac{1}{N(h)} \times \sum_{n=1}^{N(h)} \left[z(u_n) - z(u_n + h) \right]^2 \qquad \text{(Equation 2)}$$

Where:
N(h) – number of data pairs compared at distance 'h'
$z(u_n)$ – values at location u_n
$z(u_n+h)$ – values at location u_n+h.

Almost all experimental (semi)variograms can be mathematically approximated by five theoretical models: spherical, exponential, Gaussian, linear and logarithmic (HOHN, 1988). The kriging estimation includes the following criteria:

- It needs to be unbiased,
- The difference of variances between the measured and estimated values (so called kriging variance) needs to be at the lowest possible value.

The kriging algorithm also calculates the predicted and real estimation errors. These values can be compared with measured values (or input data), and the reliability of estimation can be calculated. Kriging is described as a statistical technique called »BLUE«. The acronym BLUE means *Best Linear Unbiased Estimator*. The simple kriging formula for estimation based on »n« control points (hard-data) is given in **Equation 3:**

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

(Equation 3)

Where:
λ_i – *weighting coefficient for each location »i«*
Z_i – *surrounding known values, so called control points*
Z_k – value estimated by kriging

The Kriging method is directed to estimation of an appropriate weighting coefficient and finally a value Z_k. The set of Z_k values is obtained by applying a matrix system of linear kriging equations.

Cross-validation is a relatively simple numerical method very often applied in checking the estimation quality. It is based on moving measured values at certain locations and estimating new value at the same place. New estimations are based on the remaining measured data **(Equation 4)**. The procedure is repeated for all wells and a final value called the *Mean Square Error (MSE)* is calculated. The method's disadvantage is its insensitivity to the number of analysed wells. The famous pioneer work on cross-validation was published by DAVIS (1987). In a geological sense, the MSE value indicates an error obtained from the existing dataset using a different interpolation algorithm. For example, if the depth of strata is mapped using two methods and the same input dataset, each map will be characterised by a different MSE value **(Equation 4)**. Moreover, a lower MSE value indicates the more appropriate interpolation, i.e. the lower error obtained by n-1 data analysed sequentially. Calculation of MSE can be applied to almost all geological variables including porosity, saturation and others.

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (real\ value - estimation)_i^2$$

(Equation 4)

Where:
MSE – results obtained by cross-validation (Mean Square Error)
real value – value obtained at location »i«
estimation – value estimated at location »i«

6. RESULTS OF A COMPARISON OF INTERPOLATION METHODS

Interpolation from 20 porosity values was used as the input. This is a very limited dataset for the calculation of an experimental variogram. Therefore, directional variograms were omitted and only the omnidirectional ones (i.e. being independent of direction) were calculated. Input data were averaged log measurements collected for reservoir »T« and reinterpreted in 2007. Reinterpretation was based on the *neutron* and *density logs* (CDL – *Compensated Density Log* i CNL – *Compensated Neutron Log*). Due to a higher number of logs and better software support, the quality of the reinterpreted values is much greater than those estimated in the past. In any particular well the very dense log-porosity values were replaced by a simple average value calculated for the whole reservoir thickness. The new dataset made it possible to apply and compare several interpolation methods and results.

Results obtained by four methods are presented on different maps. Almost all, can be recognised by their very different morphologies, despite the small size of the input dataset. The direct results of the mathematical algorithms are used in each method, as described above.

The result of the inverse distance weighting method is shown in **Figure 6**. It indicates the real porosity distribution in the reservoir and is also similar to the kriging map **(Figure 7)** which is considered as the most authentic algorithm in the sense of geology and geomathematics.

However, the maps obtained by the other two methods, which are not exact interpolators, are inappropriate. These are moving average **(Figure 8)** and nearest neighbourhood **(Figure 9)** maps, where the presented isoporosity shapes cannot be meaningfully interpreted. Even if the radii of the searching ellipsoid is changed (moving average), the gradual transition among lines has not been achieved. The nearest neighbourhood result strongly emphasises the polygonal presentation. Therefore, these two methods cannot be applied to porosity interpolation in reservoirs of the 1st sandstone series.

Kriging and inverse distance weighting methods are proven as valid for porosity mapping. This also resulted from the fact that the sandstone reservoirs are a special favourable lithology for the application of geostatistical interpolation methods. This analysis also confirms that the porosity distribution in reservoir »T« of Lower Pontian age is most appropriately represented by the kriging results. The first evaluation is based on the geological meaning of isoporosity line shapes where the kriging map describes the porosity distribution in the central and eastern parts of the field particularly well.

Numerical estimation of maps is performed using a cross-validation equation. The following values were obtained for the different methods (starting with the lowest error):

1. Kriging	**366.93** **(exact interpolator)**
2. Moving average	369.26 (simple matrix smoothing)
3. Inverse distance weighting	**371.97** **(exact interpolator)**
4. Nearest neighbourhood	389.00 (zonal assignment)

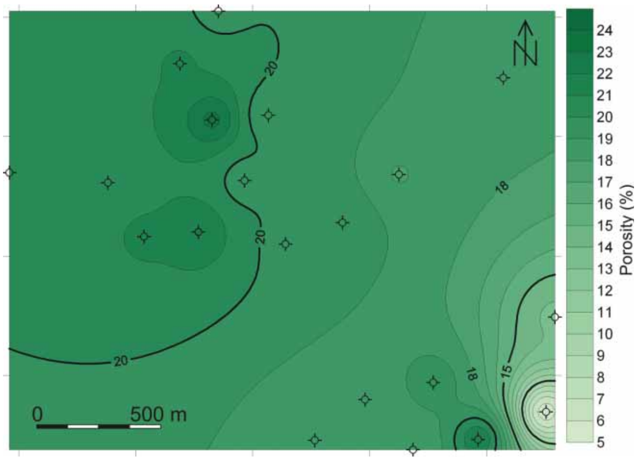

Figure 6: Porosity map interpolated by inverse distance weighting

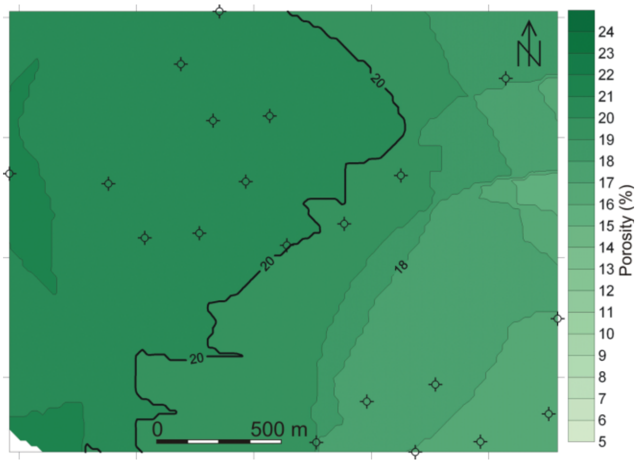

Figure 8: Porosity map interpolated by the moving average

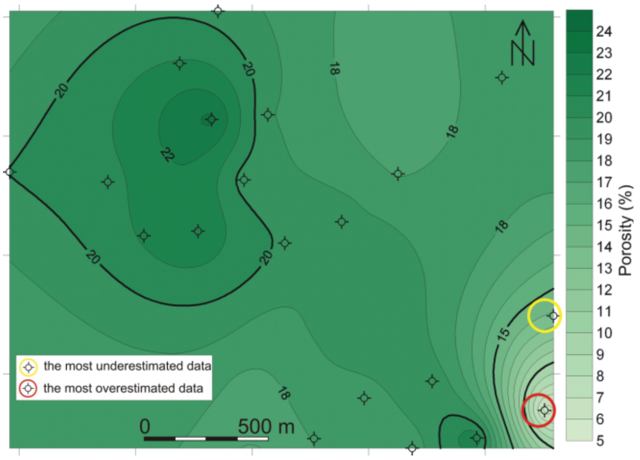

Figure 7: Porosity map interpolated by kriging (isotropic variogram model, range 1100 m)

Figure 9: Porosity map interpolated by the nearest neighbourhood

Differences are relatively small, but also show the minimum that characterises the kriging results. It is partly surprising that errors obtained by the moving average and nearest neighbourhood methods were not higher, especially when comparing by map graphics where illogical isoporosity shapes are clearly visible. It is probably a result of the relatively limited input dataset, which can not reflect the true advantage of using exact interpolators.

However, there is no doubt that the main error is connected with the inter-well area, and not for additional estimation that could be done after moving-and-estimating values at existing locations. Moreover, cross-validation results very clearly indicated estimation differences at particular wells. These are two wells located at the field margin, which is also why such results could be expected. On the relevant porosity maps these values and wells are:

- The most underestimated data is located at the well circled in yellow in **Figure 7** (measured value is 13.8; estimated 8.96),
- The most overestimated data is located at the well circled in red in **Figure 7** (measured value is 5.45; estimated 14.56).

The other two methods did not produce useful results, and the differences in cross-validation were not considered.

In fact, any »classic« interpolation methods cannot (especially in a limited dataset) represent the true nature of the inter-well area. This is the field of stochastic simulations that were not applied in this case. Moreover, the main difference between the results obtained can be explained in terms of the exact interpolator (the algorithms which honour the original values in locations being coincidental with grid points). Such interpolators are the kriging and inverse distance weighting methods. The nearest neighbourhood method is not one of estimation then assignment, and the moving average is rather a matrix-smoothing method, not an interpolator (János Geiger, 2007 pers. comm.). This is why cross-validation can be used for comparing different algorithms that have the same philosophy (i.e. exact or not exact interpolators). In such a way, this method reflects the stability of interpolation.

Alternatively, the »goodness« of interpolation may be interpreted as the scale of the data-point-error of the interpolation. That is the difference of an original data-point value and one which was estimated for the same location from the grid. Naturally, estimations try to minimize this kind of error

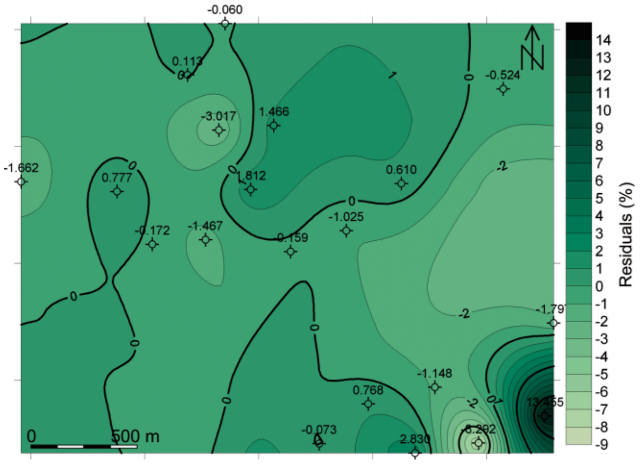

Figure 10: Residuals calculated for particular wells

and produce a Gaussian-error distribution. It includes the fact that the mean error is forced to be close to 0, while the standard deviation is about 1. However, at the well-locations these errors are different. The better the estimation, the smaller the error in a particular data point. Gridding of these point error is also worth thinking about. This is also why *residuals* are computed by the Surfer option. It gives a quantitative measure of how estimation on the grid agrees with the original data. Residual values are reported as either positive or negative values (**Figure 10**). Surfer automatically uses the *nearest neighbourhood* algorithm to calculate residuals, i.e. differences between measured and estimated values in analysed sandstone reservoir.

It is clearly seen that such differences mostly nowhere reached ± 2% of porosity, which makes the default residual map (**Figure 10**) completely acceptable for evaluation of the most sensitive areas for interpolation. The south-western margin of the field is such an area, (**Figure 10**, residual value >13%), previously described as an area where kriging defined the most underestimated and overestimated values. Also, the high negative residual (< –8%) is mapped at the same corner of the field.

7. CONCLUSIONS

The estimations for reservoir »T«, (1st sandstone series of Lower Pontian age) in the Kloštar field, are shown on the maps and by the cross-validation results. Four interpolation methods were used – inverse distance weighting, nearest neighbourhood, moving average and kriging. The number of well (data) was 20. It is considered as the minimum data in sandstones for the modelling of an input dataset by an omnidirectional variogram. This variogram model is planned to improve when the number of inputs reach 30 values (in 2008).

The quality of porosity interpolation can be evaluated based on two criteria. The first, graphical one, includes the geological description of isoporosity line shapes, and also takes into consideration all available maps interpolated unofficially earlier by hand. The second, numerical criterion represents the estimation of interpretation quality with regards to the amount of mean square error (MSE). The comparison of MSE can exactly determine how a particular method is more successful in repeated estimation at existing locations. In this analysis the lowest MSE was accompanied by kriging (366.93), and the highest by the nearest neighbourhood method (389.00). The final decision was made using both criteria.

Moreover, the two methods described as exact interpolators (kriging and inverse distance weighting) are selected as the most appropriate for porosity mapping in the analysed reservoirs. In addition, their comparison is followed by point-error data analyses, improving the »classical« MSE calculation. The point-error (or residual) maps reveal the areas where estimation can be described as more at risk of being moderately subdued by method error. These areas are the south-western margin of the field and one of the wells located in the north–west.

There is a general expectation that geostatistical methods (like kriging) always lead to better maps than mathematically simpler methods. The obtained results confirm such an assumption and, based on estimation quality, the most appropriate method was kriging, followed by inverse distance weighting. The other two methods (nearest neighbourhood and moving average) did not produce acceptable results, mostly because they are not exact interpolators. The moving average parameter, radii of searching circle, was adapted, but results were not improved. It remains just a matrix smoothing tool. The nearest neighbourhood results were reflected through zones that cannot be considered as a geologically acceptable map, but only a schematic view of porosity distribution acceptable for quick insight.

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