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Stochastically improved methodology for probability of success (*POS*) calculation in hydrocarbon systems

Stohastično dopolnjena metodologija računanja verjetnosti uspeha (*POS*) v ogljikovodičnih sistemih

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Abstract

Geological risk of new hydrocarbon reserves discovering is usually calculated on deterministical or expert-opinion way, and expressed as ‘Probability Of Success’ (abbr. *POS*). In both approaches are included selections of single probability values for each geological event organised into geological categories that define hydrocarbon system. Here is described a hybrid, i.e. stochastical, model based on the deterministical approach. Here was given example from the Croatian part of the Pannonian Basin System (abbr. CPBS), improved with stochastically estimated subcategory for porosity mapped in the Stari Gradac-Barcs Nygat Field (Drava Depression). Furthermore, there is theoretically explained how such approach could be applied for two other subcategories – quality of cap rocks and hydrocarbon shows. Presented methodology could be advantageous in clastic hydrocarbon system evaluation.

Key words: geological risk, determinism, stochastics, Neogene, Northern Croatia

Izvleček

Geološko tveganje odkritja novih zalog ogljikovodikov navadno računajo deterministično ali po metodi ekspertnih mnenj in ga izražajo z »verjetnostjo uspeha« (*POS*, Probability of Success). Obe metodi temeljita na vrednostih verjetnosti posamičnih geoloških dogodkov, urejenih po geoloških kategorijah, ki opredeljujejo ogljikovodični sistem. Tu je opisan hibridni, tj. stohastični model, ki temelji na determinističnem načinu. Obravnavani primer je iz hrvaškega dela sistema Panonske kadunje (CPBS, Croatian part of the Pannonian Basin System), ki je dopolnjen s stohastično ocenjeno podkategorijo poroznosti, kartirano v polju Stari Gradac-Barcs Nygat (v Dravski kadunji). Sledi teoretska razlaga možnosti uporabe takega načina z nadaljnjima dvema podkategorijama – kakovostjo krovnih kamnin in ogljikovodičnih pojavov. Prikazana metodologija utegne biti učinkovita pri ocenjevanju klastičnih ogljikovodičnih sistemov.

Ključne besede: geološko tveganje, determinizem, stochastičnost, neogen, severna Hrvaška

Historical Review

More than 90 years have passed since the University Ljubljana in Slovenia was founded in 1919. Technical fields were united in the School of Engineering that included the Geologic and Mining Division, while the Metallurgy Division was established only in 1939. Today, the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy are all part of the Faculty of Natural Sciences and Engineering, University of Ljubljana.

Before World War II, the members of the Mining Section together with the Association of Yugoslav Mining and Metallurgy Engineers began to publish the summaries of their research and studies in their technical periodical Rudarski zbornik (Mining Proceedings). Three volumes of Rudarski zbornik (1937, 1938 and 1939) were published. The War interrupted the publication and it was not until 1952 that the first issue of the new journal Rudarsko-metalurški zbornik – RMZ (Mining and Metallurgy Quarterly) was published by the Division of Mining and Metallurgy, University of Ljubljana. Today, the journal is regularly published quarterly. RMZ – M&G is co-issued and co-financed by the Faculty of Natural Sciences and Engineering Ljubljana, the Institute for Mining, Geotechnology and Environment Ljubljana, and the Velenje Coal Mine. In addition, it is partly funded by the Ministry of Education, Science and Sport of Slovenia.

During the meeting of the Advisory and the Editorial Board on May 22, 1998, Rudarsko-metalurški zbornik was renamed into "RMZ – Materials and Geoenvironment (RMZ – Materiali in Geookolje)" or shortly RMZ – M&G. RMZ – M&G is managed by an advisory and international editorial board and is exchanged with other world-known periodicals. All the papers submitted to the RMZ – M&G undergoes the course of the peer-review process.

RMZ – M&G is the only scientific and professional periodical in Slovenia which has been published in the same form for 60 years. It incorporates the scientific and professional topics on geology, mining, geotechnology, materials and metallurgy. In the year 2013, the Editorial Board decided to modernize the journal's format.

A wide range of topics on geosciences are welcome to be published in the RMZ – Materials and Geoenvironment. Research results in geology, hydrogeology, mining, geotechnology, materials, metallurgy, natural and anthropogenic pollution of environment, biogeochemistry are the proposed fields of work which the journal will handle.

Editor-in-Chief

Zgodovinski pregled

Že več kot 90 let je minilo od ustanovitve Univerze v Ljubljani leta 1919. Tehnične stroke so se združile v Tehniški visoki šoli, ki sta jo sestavljala oddelka za geologijo in rudarstvo, medtem ko je bil oddelek za metalurgijo ustanovljen leta 1939. Danes oddelki za geologijo, rudarstvo in geotehnologijo ter materiale in metalurgijo delujejo v sklopu Naravoslovnotehniške fakultete Univerze v Ljubljani.

Pred 2. svetovno vojno so člani rudarske sekcije skupaj z Združenjem jugoslovanskih inženirjev rudarstva in metalurgije začeli izdajanje povzetkov njihovega raziskovalnega dela v Rudarskem zborniku. Izšli so trije letniki zbornika (1937, 1938 in 1939). Vojna je prekinila izdajanje zbornika vse do leta 1952, ko je izšel prvi letnik nove revije Rudarsko-metalurški zbornik – RMZ v izdaji odsekov za rudarstvo in metalurgijo Univerze v Ljubljani. Danes revija izhaja štirikrat letno. RMZ – M&G izdajajo in financirajo Naravoslovnotehniška fakulteta v Ljubljani, Inštitut za rudarstvo, geotehnologijo in okolje ter Premogovnik Velenje. Prav tako izdajo revije financira Ministrstvo za izobraževanje, znanost in šport.

Na seji izdajateljskega sveta in uredniškega odbora je bilo 22. maja 1998 sklenjeno, da se Rudarsko-metalurški zbornik preimenuje v RMZ – Materiali in geookolje (RMZ – Materials and Geoenvironment) ali skrajšano RMZ – M&G. Revijo RMZ – M&G upravljata izdajateljski svet in mednarodni uredniški odbor. Revija je vključena v mednarodno izmenjavo svetovno znanih publikacij. Vsi članki so podvrženi recenzijskemu postopku.

RMZ – M&G je edina strokovno-znanstvena revija v Sloveniji, ki izhaja v nespremenjeni obliki že 60 let. Združuje področja geologije, rudarstva, geotehnologije, materialov in metalurgije. Uredniški odbor je leta 2013 sklenil, da posodobi obliko revije.

Za objavo v reviji RMZ – Materiali in geookolje so dobrodošli tudi prispevki s širokega področja geoznanosti, kot so: geologija, hidrologija, rudarstvo, geotehnologija, materiali, metalurgija, onesnaževanje okolja in biokemija.

Glavni urednik

Introduction

Calculation of geological risk is a well-established tool for estimation of possible hydrocarbon reservoir in plays or prospects. Such calculations, in Croatia, are well described in the Sava and Drava Depressions [1–4]. The term ‘play’ in those papers is generally defined as a stratigraphical unit in the range of chronostratigraphic stage or sub-stage where hydrocarbon production already exists. The ‘prospect’ is a vertical surface projection of potential reservoir lateral borders. Such definition has been derived from Rose [5] or White [6] where ‘play’ is generally defined as an operational unit characterised by several prospects and/or fields and ‘prospect’ is an exploration (economic) unit. In general, any potential hydrocarbon system can be evaluated with Probability of success (abbr. *POS*) calculation.

Mathematically, calculation of *POS* is a simple multiplication of several, in most cases five, independent geological category probabilities. Of course, there are geological relations among some of them, but it is using this tool impossible mathematically expressed on any useful way. Each category is defined with several geological events, and each also has its own probability. Category probability is simple multiplication of selected event probability values, defined as discrete values in range 0–1. They are often listed in *POS* probability tables, based upon previous experience and expert knowledge from analysed subsurface. Such a table (Figure 1), defined through decades of research for the Croatian part of the Pannonian Basin System (abbr. CPBS), had been a source of detail probability values defined and applied in in the Bjelovar Subdepression as part of the Drava Depression. Sometimes such values remain as an

TRAP		**RESERVOIR**		**SOURCE ROCKS**		**MIGRATION**		**HC PRESERVATION**	
Structural		**Reservoir type**		**Source facies**		**HC shows**		**Reservoir pressure**	
Anticline and **buried hill** linked to basement	1.00	**Sandstone** clean and laterally extended; **Basement** granite, geiss, gabbro; **Dolomites and Algae reefs** (secondary porosity)	1.00	**Kerogen** type **I and/or II**	1.00	**Production** of hydrocarbons	1.00	**Higher** than hydrostatic	1.00
Faulted anticline	0.75	**Sabdstones,** rich in silt and clay; **Basement** with secondary porosity, limited extending; **Algae reefs**, filled with skeletal debris, mud and marine cements	0.75	**Kerogen** type **III**	0.75	Hydrocarbons **in traces**; **New gas** detected >10 %	0.75	**Approximately** hydrostatic	0.75
Structural nose closed by fault	0.50	**Sandstone** including significant portion of silt/clay particles, limited extending;	0.50	**Favourable palaeo-facies** organic matter sedimentation	0.50	**Oil** determined **in cores** (luminescent analysis, core tests)	0.50	**Lower** than hydrostatic	0.50
Any "positive" faulted structure, margins are not firmly defined	0.25	**Basement rocks**, including low secondary porosity and limited extending	0.25	**Regionally known** source rock facies, but not proven at observed locality	0.25	**Oil** determined **in traces** (lumin. anal., core tests)	0.25		0.25
Undefined structural framework	0.05	Undefined reservoir type	0.05	Undefined source rock type	0.05	Hydrocarbon are not observed	0.05		0.05
Stratigraphic or combined		**Porosity features**		**Maturity**		**Position of trap**		**Formation water**	
Algae reef form	1.00	**Primary** porosity **>15** %; **Secondary** porosity **>5 %**	1.00	Sediments are in **catagenesis phase** ("oil" or "wet" gas-	1.00	**Trap** is located in proven **migration distance**	1.00	**Still aquifer** of field-waters	1.00
Sandstones, pinched out	0.75	**Primary** porosity **5-15** %; **Secondary** porosity **1-5 %**	0.75	Sediments are in **metagenesis phase**	0.75	**Trap** is located **between two source rocks** depocentres	0.75	**Active aquifer** of field-waters	0.75
Sediments changed by **diagenesis**	0.50	**Primary** porosity **<10** %; **Permeability <1x10**(-3)** micrometer**2	0.50	Sediments are in **early catagenesis phase**	0.50	**Short migation pathway** (<=10 km)	0.50	**Infiltrated aquifer** from adjacent formations	0.50
Abrupt changes of petrophysical properties (caly, different facies)	0.25	**Secondary** porosity **<1 %**	0.25	Sediments are in **late diagenesis phase**	0.25	**Long migration pathway** (>10 km)	0.25	**Infiltrated aquifer** from surface	0.25
Undefined stratigraphic framework	0.05	Undefined porosity values	0.05	Undefined maturity level	0.05	Undefined source rocks	0.05		0.05
Quality of cap rock				**Data sources**		**Timing**			
Regional proven cap rock (seals, isolator)	1.00		1.00	Geochemical analysis on **cores and fluids**	1.00	**Trap** is **older than** matured **source** rocks	1.00		1.00
Rocks without reservoir properties	0.75		0.75	Analogy with **close located geochemical analyses**	0.75	**Trap** is **younger than** matured **source** rocks	0.75		0.75
Rocks permeable for gas (gas leakage)	0.50		0.50	**Thermal modeling** and calculation (e.g. Lopatin, Waples etc.)	0.50	**Relation** between trap and source rocks is **unknown**	0.50		0.50
Permeable rocks with locally **higher silt/clay content**	0.25		0.25	**Thermal modeling** at just a **few locations**	0.25		0.25		0.25
Undefined cap rock	0.05		0.05	Undefined data sources	0.05		0.05		0.05

Figure 1: *Example of relevant database prepared for the Bjelovar Subdepression* [after 2, 3].

internal document, but only if published [e.g., 2, 3] they make possible further independent evaluation of local or regional petroleum systems. Oppositely, such general tables, which can be applied as a rule of thumb, are missed in case of expert opinion applied for each particular well, exploration or development plan (Figure 2). In such case, single expert or team are completely responsible for given category values. Consequently, such process is subdued to “heavy” benchmarking, i.e. corrections are done with each new dataset (especially from wells). This methodology is not discussed here.

However, it is obvious that, using deterministic approach, at least several geological events (Figure 2) can be estimated from the range, i.e. from interval defined with values, number of data and, sometimes, measurement error. Moreover, in the case of low number of inputs, the Monte Carlo sampling can be applied for generation of artificial data, but it needs to be clearly stated in statistical results. However, the key question is “can any probability value for each geological event be considered certain or not”. If there is a measurable uncertainty (Figure 2), resulting in non-representative mean or variance, but the minimum and maximum could be approximated, the stochastics can be successfully applied, e.g., using 2nd introduction of uncertainty in cell-value estimations with sequential Gaussian simulations. Such application of stochastics and results are shown, for the CPBS, in estimation of the porosity, thickness and depth of hydrocarbon reservoirs [e.g., 7–9]. Similar approach obviously can be regularly applied for estimation of several events in *POS* calculation and eventually set up as standard part of that method.

Selection of stochastically mapped porosity in *POS* calculation

The hydrocarbon plays or prospects could be deterministically analysed by several, mathematically independent, geological categories. The most common are: (1) structures, (2) reservoirs, (3) migration, (4) source rocks and (5) preservation of hydrocarbons [e.g., 2, 3, 6, 10]. The values of events in the most category values can be evaluated from data collected from well files, logs, seismic, cores, descriptive geological interpretations or the comprehensive regional papers [e.g., 11–13]. Based upon those data,

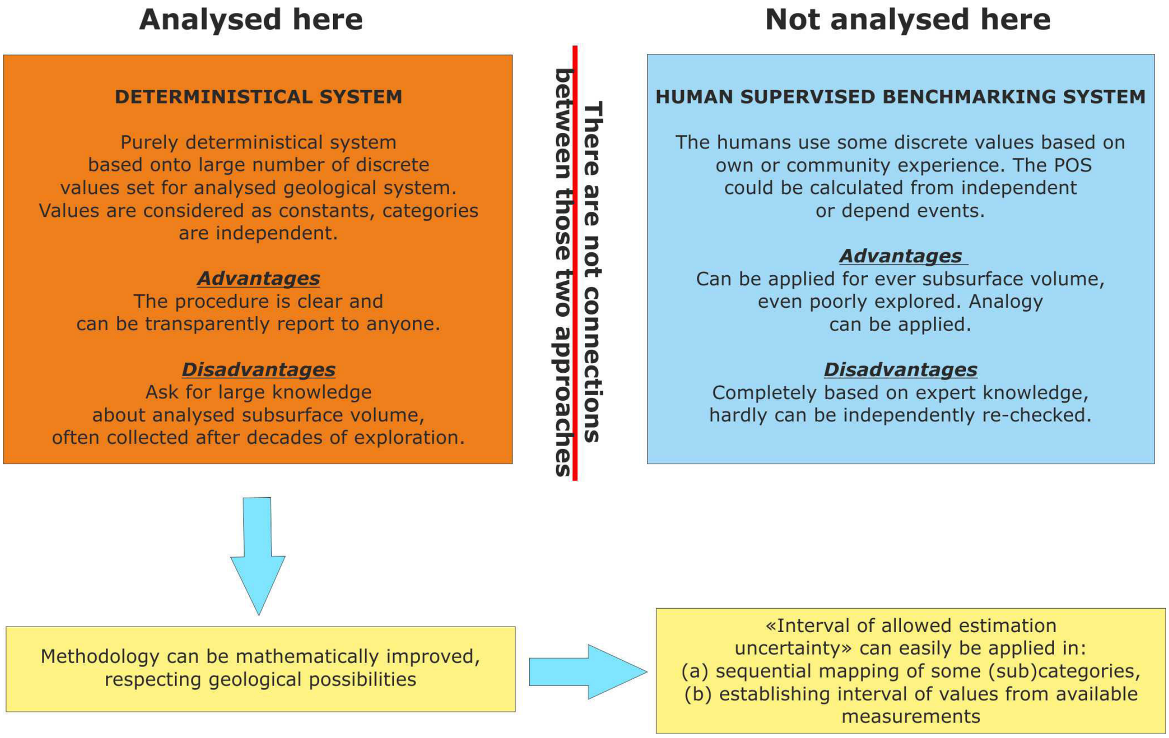

Figure 2: *Deterministical vs. human dominant benchmarking in evaluation of hydrocarbon systems.*

a value from the probability table can be easily selected, if such exists for the explored area (like Figure 1) or even from analogy based on regional geological models, especially depositional and tectonic data [e.g., 11]. In any case, *POS* table makes possible to calculate such value for any play or prospect in the area where it is defined by Equation 1:

$$POS = p\ (\text{structures}) \times p\ (\text{reservoir}) \times p\ (\text{migration}) \times p\ (\text{source rocks}) \times p\ (\text{preservation}) \qquad (1)$$

Where are:
POS - probability value of Probability of Success for analysed hydrocarbon system,
p - probability value of each considered geological category.

All geological events, subcategories, categories and *POS* are defined with numerical values. For the part of them inputs (laboratory measurements, loggings tools ...) strictly define the results (like kerogen type, quantity of hydrocarbons during drilling) and probability can be selected without uncertainties. However, some subcategories like 'Porosity features' (in the category 'Reservoir'), 'Quality of cap rocks' ('Trap'), and 'HC shows' ('Migration') can be calculated from cores, logs and diagrams, but very often as approximations. It means they includes uncertainties, but if lithology is well-known the minimum and maximum values (e.g., for porosity) could be clearly established. The methodology had been tested with porosity maps taken from the Badenian gas-condensate reservoir in the Stari Gradac-Barcs Nyugat Field [14]. The reservoir is of massive type, trapped with combined structural-stratigraphic closure, with very complex lithology divided in four lithofacies (but single hydrodynamic unit). Porosity is geostatistically mapped in the youngest lithofacies of the Badenian clastites. The porosity distribution corresponds with structural strike NW-SE [15], and maps had been calculated using 100 realizations of sequential Gaussian simulations. It means that each cell on the map is defined with minimum and maximum values (realization), as well as 98 others between them. All of them, as equally probable, had been summed and averaged. So the minimum (3.1 %), median (3.2 %) and maximum (3.53 %) average reservoir porosities are calculated, what was base for consequently calculation of three solutions for 'Original Gas In Place' (abbr. OGIP) volume [16].

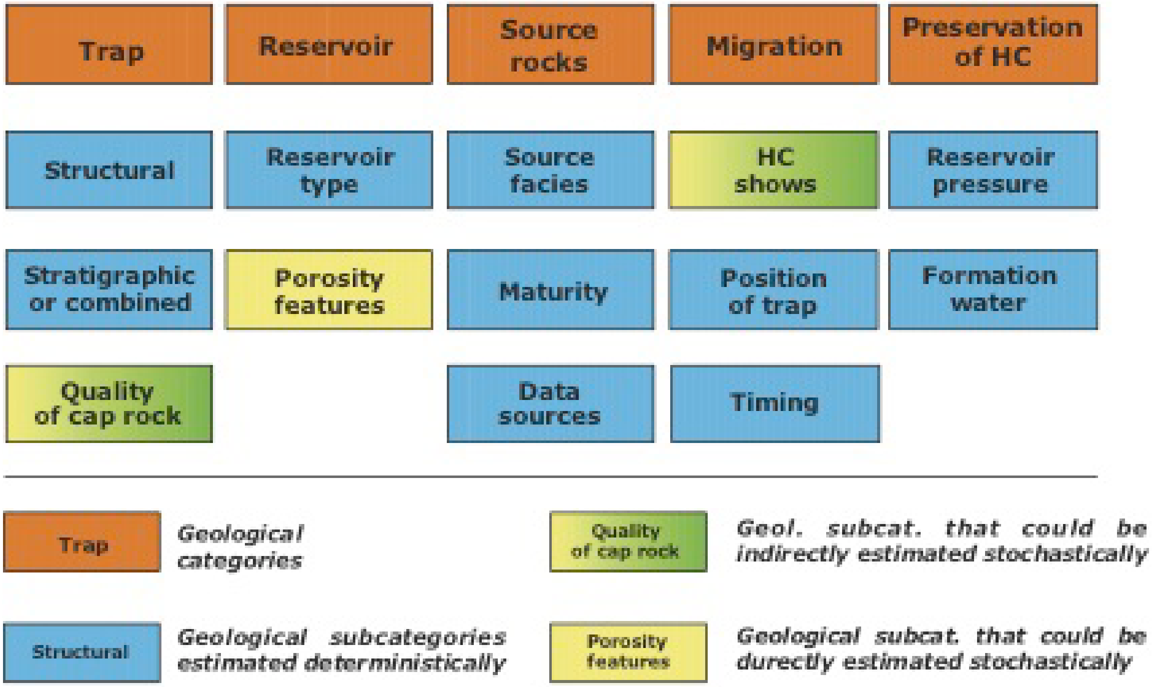

Figure 3: *Subcategories with can be determined exclusively deterministically and (in)directly stochastically.*

It is clear that all three average porosity values of the Badenian breccia reservoir in analysed gas field could be equally used as three values in ‘Porosity feature’ (Figure 3). If it is done so, the calculation based upon categories can be done with the following values. Structures: Trap is a faulted anticline (p = 0.75); Quality of cap rock is regionally proven (p = 1.00); Reservoir: Coarse-grained sandstones (p = 1.00); Primary porosity three values (3.1; 3.2; 3.53) < 5 % (p = 0.50); Source rocks: Kerogen type II (p = 1.00); Migration: Proven production (p = 1.00); Position of trap (p = 1.00); Trap is older than mature source rocks (p = 1.00); HC preservation: Higher than hydrostatic (p = 1.00); Still aquifer (p = 1.00). The total *POS* = 0.5 × 0.75 = 0.375. It is interesting that three ‘Porosity feature’ values had been used, and all three values are mathematically equally probable. However, they were all less than 5 %, which means that any chosen porosity was characterised with the same event probability (0.05), and *POS* was not changed.

However, the principle of using stochastics in deterministical calculation is clearly and correctly presented. Analyses showed that generally:

- Porosity subcategory can be easily characterised with three values, minimum, median, maximum,
- Those realizations are results of geostatistical simulations,
- Values could or could not correspond to more subcategory probabilities,
- Multiple subcategory probabilities would lead to multiple *POS* values.

Discussion about statistical basics and modifications introduced in *POS* calculation

Figure 1 summarised deterministical methodology published previously. It is opposite to the expert opinion and benchmarking based on new data. Although both approaches have pros and contras, here we consider deterministical as advantageous. The pure expertise can be too fluid and very hardly applied correctly in low to medium areas, when depending only or mostly on analogy (Figure 2). On contrary, in moderate to well explored petroleum provinces collected knowledge about hydrocarbon systems could be summarised in *POS* tables (Figure 1), where data from decades of exploration and production are summarised. In poorly explored or geological unknown hydrocarbon systems carefully analogy could be applied using *POS* tables from geologically similar areas. In any case, it is unfavourable to give expertise about any hydrocarbon system without any engineering ‘support tool’ and presented methodology (*POS*) is just such a tool.

Originally, the *POS* value is discrete, single value. However, if any category had more than one solution, *POS* would also be transferred into interval value. Multiple solutions could be reached using tools like geostatistical simulations or (sometimes) Monte Carlo sampling, where interpolated or estimated data can clearly reveal variable distribution (uniform, Gaussian etc.). Interestingly, if distribution is binomial it clearly indicated that mapping or estimation is wrongly applied simultaneously in: (1) two lithofacies, or (2) two plays or prospects (both are ‘bimod’ cases). In any case, distribution could be surely determined only from large dataset, which would be collected only in well-explored hydrocarbon systems. Intervallic expressed *POS* can be useful in reserves estimation. When proven volumes are given as probabilities, like P90 (at least 90 % of listed reserves will be recovered), P50 or P10, equiprobable *POS* values could be correlated with them.

The main advantage of stochastically calculated *POS* is set of equally probable outcomes that are all defined with continuous variable aerially distributed, like reservoir porosity. In such case, numerous statistical values can be easily calculated, like mod, median etc.

Conclusion

Hydrocarbon reservoir volume is always characterised with uncertainties, due to the limited number of available data. Evaluation of possible new hydrocarbon discoveries is often based onto *POS* methodology. The result is probability value in the range 0–1. Such methodology is well established and published for the Neogene sediments of the CPBS. In such approach (Figure 1) subcategories can be expressed exclusively deterministically with a single value. But some of them, described indirectly (descriptive, like 'HC shows' and 'Quality of cap rock') or directly (from measurements, like 'Porosity'), as interval value (Figure 3) could be evaluated with interval of values. All such interval data, for dominantly homogeneous reservoir, top or bottom layer, could be considered as equally probable values.

For example, in the case of 'Quality of cap rocks' their sealing properties cannot be directly measured without very special apparatus. However, they can be indirectly well deduced from: (a) possible 'HC shows' in the top, (b) porosity of cap rocks, or (c) regional geological model. Descriptively, they can vary between 'excellent seal' (cease migration of any gaseous molecules in subsurface) to 'temporary seal' (cease migration only of the largest molecules of heavy oil). On contrary, 'HC shows' can be directly measured along depths.

All descriptive evaluations and numerical data, if are numerous, can be transformed into event's probabilities (Figure 1). For example, new gas detected in quantity of (statistically representative) 10 % or more above seal rock will allow to select for it only two lowest probabilities (0.25 or 0.05; Figure 1), because sealing practically does not exist on geological significant period. It is often case in the Pliocene and Quaternary sands of the CPBS, where migrated thermogene or biogene ('in situ') methane cannot be efficiently trapped.

Presented stochastical approach is tested in the field located in the Drava Depression, where porosity was shown with maps (grids) constructed of numerous cells with numerical values. Other data were not analysed. The result showed relatively simple procedure how error in deterministical calculation of *POS* can be effectively decreased. The methodology can be easily and fast applied in any geological region where number of subsurface data easily allows applying deterministical approach in general (Figure 2).

All three "stochastically estimated" subcategories could be eventually described with minimum, median and maximum values. If each of such numerical values points to the different geological event (different probability; Figure 1) it would result in maximal 27 values of *POS*. In this way the pure deterministical calculation can be efficiently upgraded into a tool that gives range of maximum, median and minimum probabilities. Equiprobability is valid both for realizations as well as *POS* values and characterised with uniform distribution. In this way, potential hydrocarbon discovers would be described minimal and maximal *POS*, i.e. risk could be numerically expressed. It is why presented approach is considered as easily applying improvements of deterministical *POS* calculation.

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