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"Mathematical methods and terminology in geology 2018"

2nd Croatian scientific congress from geomathematics and terminology in geology

Matematičke metode i nazivlje u geologiji 2018

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održan na Rudarsko-geološko-naftnom fakultetu Sveučilišta u Zagrebu

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Za nakladnika

dr. sc. Zoran Nakić, red. prof. (o.d. dekana RGNF-a)

Urednici

dr. sc. Tomislav Malvić, red. prof.

dr. sc. Josipa Velić, prof. emer.

dr. sc. Rajna Rajić, red. prof.

Naklada

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Dr. Zoran Nakić, Full Prof. (o. h. of Dean)

Editors

Dr. Tomislav Malvić, Full Prof.

Dr. Josipa Velić, Prof. Emer.

Dr. Rajna Rajić, Full Prof.

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SADRŽAJ / CONTENT

PREDGOVOR

Nakon uspjeha koji je postigao 1. hrvatski skup iz geomatematike i geološkog nazivlja, na istome mjestu i u približno isto vrijeme godine organiziran je 2. takav skup po redu. Ovoga puta uz Rudarsko-geološko-naftni fakultet Sveučilišta u Zagrebu, kao suorganizator pridružila se i Geomatematička sekcija Hrvatskoga geološkoga društva. Razlog tomu je što veliki broj članova upravo te sekcije se je samostalno okupio 2016. godine i priredio prvi skup u ustanovi gdje ih je većina i razvijala geomatematiku i nazivlje, uz druga središta poput Geološkoga odsjeka PMF-a.

Time je nastavljena tradicija skupova započetih 2008. godine pod nazivom hrvatsko-mađarski geomatematički kongresi. Kako je u međuvremena hrvatska sekcija stvorila zavidan znanstveni opus, a rezultati geomatematičkih istraživanja na Sveučilištu u Zagrebu su iznimno brojni, te je članstvo sekcije naraslo na nekoliko desetaka članova, odlučili smo se biti prepoznatljivi pod svojim vlastitim, hrvatskim skupom.

Protekle dvije godine aktivnost i radovi koji su nastali iz njih bili su brojni. Oni su ujedno bili osnova za izdavanje najvažnijih rezultata koji su priređeni kao zasebni konferencijski radovi prikazani u zborniku recenziranih članaka. I ovaj put podijeljeni su u tri podcjeline: (a) matematičku geologiju u području prirodoslovlja, (b) matematičku geologiju u inženjerstvu, te (c) nazivlje općenito u geologiji. Vjerujemo kako će njihov sadržaj, kao i kvaliteta samoga skupa i zbornika, biti razlogom za preuzimanje ove publikacije i njezino čitanje, ali i citiranje u budućim radovima u istim ili sličnim poljima.

U Zagrebu, listopad 2018.

Znanstveno-programski odbor

FOREWORD

After success of the 1st Croatian conference from geomathematics and geological terminology, at the same place and in almost same time the 2nd such conference has been organised. This time, the Faculty of Mining, Geology and Petroleum Engineering (University of Zagreb) had the co-organiser in the Geomathematical section of the Croatian Geological Society. The reason is in large number of section contributed in organisation of the 1st conference in 2016, at the faculty where is many of them developed geomathematics and terminology, supported from other institution, e.g., Geological Department of the Faculty of Science (University of Zagreb).

In such way tradition started in 2008 with Croatian-Hungarian geomathematical congresses was continued. In the meantime, Croatian section created significant scientific record, together with impressive number of geomathematical and terminology results obtained at the University of Zagreb, and reflected in large membership increasing. It is why Croatian scientists decided to be recognisable with their own, Croatian conference.

In the last two years, activities and publications in Croatian were numerous. Also, they were basis for selection of the most important results, reviewed and published in the proceedings. They are selected in three groups: (a) mathematical geology in Natural sciences, (b) mathematical geology in Technical sciences, and (c) general terminology in geology. We believe that presented content, as well as quality of conference and proceedings, will be invitation for download and reading of published papers, and their citations in future papers of similar topics.

Zagreb, October 2018.

Scientific Programme Committee

2nd Croatian congress on geomathematics and geological terminology, 2018

Review scientific paper

Constant head permeameter tests for hydraulic conductivity of unconsolidated sediments and associated terminology

Kristijan Posavec[1]; Adriana Kukolja[1]; Valentina Kocijan[1]
[1] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Croatia

Abstract

Laboratory tests for hydraulic conductivity of unconsolidated sediments are presented and associated terminology used in groundwater literature and practice is discussed. Samples of unconsolidated sediments, i.e. gravels and sands deposited at two sites, Zagreb alluvial aquifer (Sava basin, Croatia) and Virovitica alluvial aquifer (Drava basin, Croatia) were tested in the laboratory using a constant head permeameter. Main features of the tests are presented and the results at two sites are compared. Discussion on terminology used to denote the capacity of a medium to transmit water in groundwater literature and practice is presented, referring to the ambiguity of terms most often used to its denotation. Today's most often denotations in groundwater literature and practice are hydraulic conductivity, K [L/T] (m/s in SI system) or coefficient of permeability, k [L/T] (m/s in SI system), the terms being used specifically for the flow of a single water phase through a porous media. In addition, discussion is broadened with the relation to the notation permeability, k [L^2] (m^2 in SI system) i.e. intrinsic or absolute or specific permeability, also denoted as k [L^2] (m^2 in SI system) when porous medium is 100% saturated with a single-phase fluid, i.e. water in considered case, and which are the property of the porous media only, not the fluid.

Keywords: hydraulic conductivity, permeability, intrinsic permeability, permeameter, terminology

1. Introduction

Test for hydraulic conductivity of unconsolidated sediments dates back to 1856, when Henry Darcy conducted the first documented test to determine the laws of the water flow through sands (**Darcy, 1856**). The parameter to which we today most commonly refer to as hydraulic conductivity, usually denoted as capital K [L/T] (m/s in SI system), Darcy denoted with the small letter k and termed as a coefficient dependent on the permeability of the layer in his work on the public fountains of the city of Dijon (**Darcy, 1856**). Today's terminology and notation has slightly changed with respect to Darcy's in majority of groundwater literature, naming parameter as hydraulic conductivity specifically for the flow of water through a porous media when dealing with the single water phase and symbolizing it as capital letter K. Hydraulic conductivity controls flow and transport processes in aquifers and is one of the most important sediment properties. It is a tensor, which means that its properties change with direction, i.e. they vary in space, usually having smaller values in vertical than in horizontal direction. The hydraulic conductivity characterizes the capacity of a medium to transmit water.

Laboratory tests of hydraulic conductivity most commonly encompass grain size analysis (**Hazen, 1892; Terzaghi, 1925; Carman, 1937; Kozeny, 1953; Vuković and Soro, 1992; Roscoe Moss Company, 2008**) and permeameter tests (**Freeze and Cherry, 1979; Todd and Mays, 2005; Malama and Revil, 2014**). Although grain size analysis is more often applied, permeameter tests are also in use. With respect to gravel and sand samples, constant head permeameter test is widely applied. Numerous tests of hydraulic conductivity have been obtained in both laboratory and the field in the past. One of the most comprehensive summary is given by **Davis, 1969**. Namely, gravels and clean sands with hydraulic conductivity larger than 10^{-5} m/s are tested in constant head cells while finer deposits like very fine or silty sands, silts and clays are tested in falling head cells and oedometers. Tests of hydraulic conductivity of unconsolidated deposits of Zagreb aquifer using constant head permeameter were applied in previous studies by **Ban, A. (2011)**, **Ivačić, V. (2014)**, **Gelo, N. (2014)**, **Peršić, S. (2014)** and **Čambala, M. (2017)**. Ban tested samples of unconsolidated material taken in the near vicinity of the river Sava and obtained hydraulic conductivities in the range of 10^{-4} m/s. Ivačić determined the hydraulic conductivity of the samples taken from the 50 m borehole in the area of the future well field Črnkovec and obtained the values in the range of 10^{-3} to 10^{-5} m/s. Gelo and Peršić studied the samples taken from 100 m borehole in the

Corresponding author: Kristijan Posavec
kristijan.posavec@rgn.hr

eastern part of the Zagreb aquifer and also obtained hydraulic conductivities in the range of 10^{-3} to 10^{-5} m/s while Čambala determined hydraulic conductivities in the range of 10^{-3} to 10^{-4} m/s in the central part of the Zagreb aquifer.

In presented research, samples of unconsolidated sediments, i.e. gravels and sands were collected at two sites, Zagreb alluvial aquifer (Sava basin, Croatia) and Virovitica alluvial aquifer (Drava basin, Croatia). Hydraulic conductivity of samples was tested in laboratory using constant head permeameter tests. Constant head test of the sediment taken from the shallow zone of the central part of the Zagreb aquifer near wellfield Velika Gorica contained about 60% of gravel and some 40% of sand size grains and showed hydraulic conductivities in the range of 10^{-5} m/s which was in line with the tests from previous authors. On the other hand, constant head test of the sediment taken from the Virovitica aquifer which contained more than 90% of gravel and less than 10% of sand size grains, showed higher values of hydraulic conductivity in the range of 10^{-2} m/s.

In addition, discussion on terminology used in groundwater literature and practice is presented in a separate section, referring to unambiguity of terms most often used to its denotation. Terms hydraulic conductivity, K [L/T] (m/s in SI system), coefficient of permeability, k [L/T] (m/s in SI system), permeability, k (L^2) (m^2 in SI system) and intrinsic or absolute or specific permeability, k [L^2] (m^2 in SI system) are discussed, pointing to denotations that often cause misunderstandings both in groundwater literature and practice.

2. Materials and methods

2.1. Theoretical background

John Cherry and Allan Freeze (**Freeze and Cherry, 1979**) wrote in their textbook and later Freeze repeated it in an article about the Henry Darcy and the Fountains of Dijon (**Freeze, 1994**): "The birth of groundwater hydrology as a quantitative science can be traced to the year 1856. It was in that year that a French hydraulic engineer named Henry Darcy published his report on the water supply of the city of Dijon, France. In the report, Darcy described a laboratory experiment that he had carried out to analyze the flow of water through sands. The result of his experiment can be generalized into the empirical law that now bears his name." Darcy's law for anisotropic porous media is later derived from the Navier-Stokes equation by using a formal averaging procedure (Neuman, 1975).

Darcy's law (**Darcy, 1856**) is empirical since it is based on results observed from a set of laboratory experiments conducted in an apparatus shown in **Figure 2.1**. Darcy conducted the experiment in October 1855 and February 1856 in a local hospital of the city of Dijon, France together with the engineer Charles Ritter with the aim to determine the law for the flow of water through sand. Apparatus consisted of vertical column with the height of 2.5 m built of a pipe of a 0.35 m in diameter, sealed with the plate on both ends. The column was connected to the hospital water supply system. The valve at the end of the inflow pipe enabled control of the water inflow while the valve on the outflow pipe enabled the control of the water outflow into the reservoir of known volume. The pressure in both ends of the column was measured in mercury manometers. The column had the vent installed, enabling removal of the air entrapped in the apparatus. The experiment was conducted in a number of series using the quartz sand from the river Saône which flows through the east of France.

Darcy's law can be written as:

$$Q = -KA\frac{h_2 - h_1}{l} \tag{1}$$

where
Q – flowrate [m^3/s],
K – hydraulic conductivity, proportionality factor which Darcy describes as a coefficient dependent on the permeability of the layer [m/s],
A – cross-section area of the sand column perpendicular to the flow direction [m^2],
l – the length of the sand column in Darcy apparatus [m],
h_1 *and* h_2 – heights in manometer tubes above the reference level measured below and above the sand column [m],

Hydraulic conductivity, K, proportionality factor which Darcy describes as a coefficient dependent on the permeability of the layer can be expressed as:

$$K = Cd^2\frac{\delta g}{\mu} = k\frac{\delta g}{\mu} \tag{2}$$

where
C – dimensionless coefficient [-],
d – representative grain diameter [m],
k – intrinsic permeability [m^2]
δ – water density [kg/m^3],
g – acceleration due to gravity [m^2/s],
μ – dynamic viscosity of water [Pa s],

Hydraulic conductivity, K denotes the capacity of a medium to transmit water and intrinsic permeability, k denotes the property of the porous media only, not the fluid, when dealing with the porous medium 100% saturated with a single water phase.

If equation 1 is written in differential form it becomes:

$$q = K\frac{dh}{dl} = Ki \tag{3}$$

where
q – specific discharge [m/s],
i – hydraulic gradient [-],

Darcy's law is linear since the plot of experimental observations of the specific discharge q versus the hydraulic gradient i indicate a straight line (**Figure 2.2**). If we consider the linear equation in one variable in a slope intercept form $y = ax$, where a is the slope of the line and intercept is equal to zero, i.e. the line crosses the y axis in the y coordinate equal to zero, i.e. in the origin, we can see that in Darcy's law K is the slope of the line which passes through the origin of a coordinate system (see **Figure 2.2**). As long as the plotted data of q versus i stay on the straight line, the flow is considered to be laminar, and Darcy's law valid. When deviation of the plotted data of q versus i from the straight line occurs, the flow is considered to be nonlinear and Darcy's law no longer valid. The lower limit of the validity of Darcy's law is connected with the existence of the threshold hydraulic gradient. The law does not hold at a very low head gradients in some fine-textured materials such as compacted clays due to electrostatic forces which exist in clayey soils (Yeh et al., 2015). The validity of Darcy's law is also described with the Reynolds number, Re [-]:

$$Re = \frac{(\delta q d)}{\mu} \tag{4}$$

where
d – characteristic length, generally considered as the effective grain size, or d_{10} (i.e. the grain size for which 10 percent of the sample by weight is finer) [m],

For the Reynolds number less than one, the flow is considered to be laminar and Darcy's law valid. For the Reynolds number in a range from 1 to 10, experimental tests have shown that Darcy's law may still be valid, as this is the case for groundwater flow. At large hydraulic gradient values (i.e. at $10 \leq Re < 100$) flow deviates from the linear relationship and the relation between q and i is no longer linear, although the flow can still be in the laminar flow regime or in transition regime. At $Re << 100$, turbulent flow takes place. The upper boundary of Re equal to 10 is though not strict. There are cases where the value of Reynolds number is somewhat above 10 and the specific discharge q versus hydraulic gradient i still plots on a straight line, indicating that the Darcy's law is linear and though valid. Therefore the validity of Darcy's law when conducting an experiment in a laboratory test is best checked by a specific discharge q versus hydraulic gradient i plots. But generally, suggested boundaries of Reynolds number apply in practice.

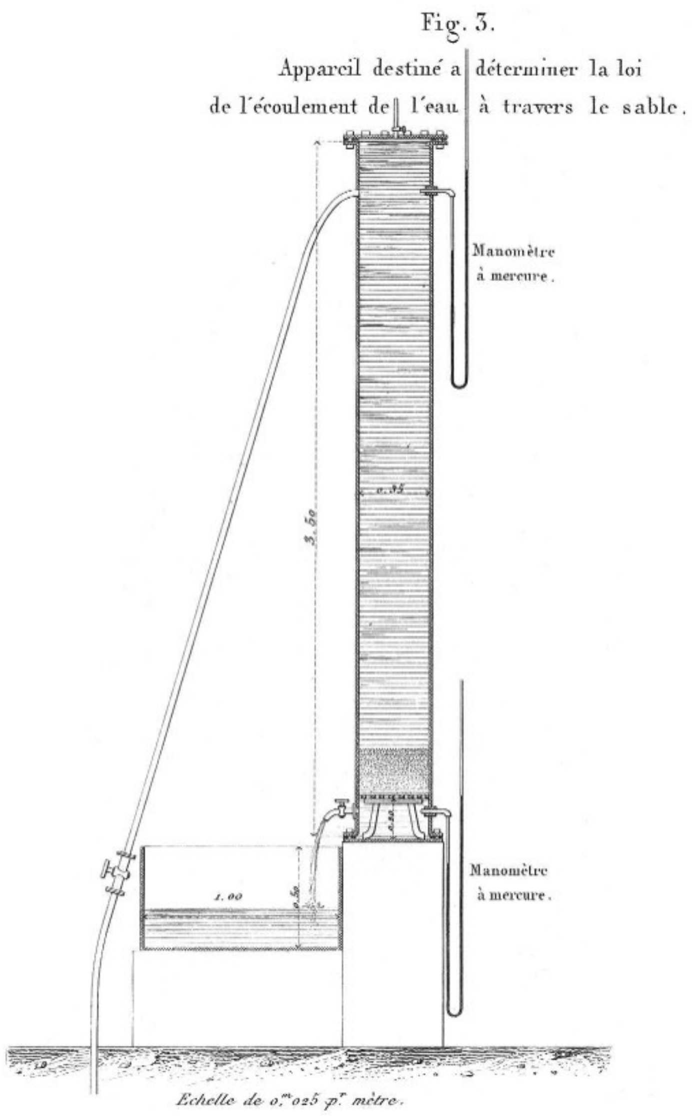

Figure 2.1: Darcy apparatus used in the development of Darcy's law (taken from **Darcy, 1856**, translation by **Glenn Brown and Bruno Cateni, 1999**, https://bae.okstate.edu/faculty-sites/Darcy/English/index.htm, accessed 8. 8. 2018)

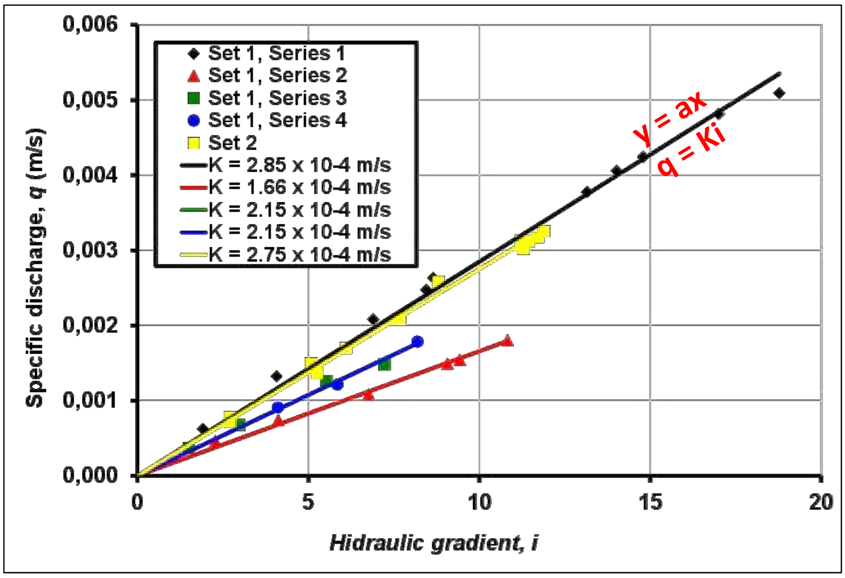

Figure 2.2: Darcy's data plotted as q versus i (taken and modified from **Darcy, 1856**, translation by **Glenn Brown, 2000**, https://bae.okstate.edu/faculty-sites/Darcy/Summary.htm, accessed 8. 8. 2018,)

2.2. Constant head permeameter test

Constant head permeameter tests are being conducted in an apparatus which is basically a modification of Darcy's apparatus (see **Figure 2.1**), retaining the same apparatus concept as Darcy's (**Figure 2.3**). The tests are regularly being conducted using standards (for example ASTM standard: D 2434 – 68 or ISO standard: CEN ISO/TS 17892-11:2004/AC). In order to obtain valid results, some prerequisites need to be satisfied for the laminar flow of water through granular soils under constant-head conditions (ASTM standard: D 2434 – 68): (1) continuity of flow with no soil volume change during a test; (2) flow with the soil voids saturated with water and no air bubbles in the soil voids; (3) flow in the steady state with no changes in hydraulic gradient, and (4) direct proportionality of velocity of flow with hydraulic gradients below certain values, at which turbulent flow starts. Samples should contain less than 10% of the material passing the 75-µm (No. 200) sieve and they should be selected by the method of quartering. Furthermore, any particles larger than 19 mm should be separated by sieving. Specimen should be compacted in a cell in successive layers to a height of about 2 cm above the upper manometer outlet. Entrapped air should be evacuated from the specimen using a vacuum pump under 50 cm Hg minimum for 15 min before the specimen is saturated. Air evacuation should be followed by a slow saturation of the specimen from the bottom upward under full vacuum in order to free any remaining air in the specimen. Adequate air removal from the specimen, flow system and manometer system is vital for the success of the permeameter test.

After preparation of specimen and apparatus, procedure is followed with a series of measurements of volume of water, V [L^3] (m^3 in SI system) discharged in time, t [T] (s in SI system) from which flow rate, Q [L^3/T] (m^3/s in SI system) is calculated. Specific discharge q is calculated as the ratio of the calculated flowrate, Q and the cell area, A [L^2] (m^2 in SI system) perpendicular to the flow direction. Hydraulic gradient, i is calculated as a ratio of the measured head difference, H [L] (m in SI system) in manometers and the distance between manometers, L [L] (m in SI system). After each measurement, specific discharge q versus hydraulic gradient i is plotted on the graph which enables insight into the current state of the flow, i.e. linear or nonlinear. Hydraulic conductivity, K is calculated based on Darcy's law and can be read out from the equation on the chart as the slope of the line which passes through the q versus i data set and origin of a coordinate system (see also section 2.1). Head differences between manometer outlets are increased by 0.5 cm for each measurement until departure of specific discharge q versus hydraulic gradient i becomes apparent, which means that flow had become nonlinear. As described in section 2.1, the validity of Darcy's law can also be tested by Reynolds number. In order to ensure laminar flow conditions, suggested values of initial hydraulic gradient, i for loose compactness ratings are from i = 0.2 to 0.3 which corresponds to the initial head differences between manometer outlets of 3 to 4 cm, and dense compactness ratings from i = 0.3 to 0.5, which corresponds to the initial head differences between manometer outlets of 5 to 7 cm. The lower values of i are applied to coarser soils and the higher values to finer soils.

Figure 2.3: Example of the constant head permeameter apparatus (manufacturer: ELE, United Kingdom; Laboratory of the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Croatia)

2.3. Samples of unconsolidated sediments for constant head tests

Samples of unconsolidated sediments, i.e. gravels and sands were taken at two sites.

The first site was Zagreb alluvial aquifer which is situated in the Sava river basin and characterized with its alluvial deposits. Aquifer is composed mainly of Quaternary sediments. This area was during the Pleistocene age covered with lakes and marshes while neighbouring mountains, Mt. Medvednica and Vukomeričke gorice hills, was land susceptible to intensive erosion. Weathered material was carried along the streams and deposited in lakes and marshes (Velić and Saftić, 1991). In beginning of the Holocene, climate and tectonic processes enabled river Sava to cut its course. With this event, transport of material from the Alps began (Velić and Durn, 1993). Transport of materials was of varying intensity due to frequent changes of climate conditions. During warm and wet periods, it was intensive while its intensity reduced during dry and cold periods. Beside climate changes, tectonic movements also influenced the deposition processes (Velić et al., 1999). Consequence of such deposition conditions was pronounced heterogeneity and anisotropy of the aquifer sediments as well as unequal distribution of the aquifer thicknesses. The composition of the lower Pleistocene deposits is predominantly yellowish-red, yellowish-orange and yellowish-brown, clayey silts/silty clays with sporadic lenses and interbeds of gravelly-sands. The lower and middle part of the Middle Pleistocene unit is predominantly composed of grey coloured sands while the upper part comprises grey coloured or red to yellowish-brown mottled silt and clay sized material (Velić and Durn, 1993). Frequent lateral changes of gravels, sands, silts and clays occur in the Upper Pleistocene unit. The Holocene is composed of pale, yellowish- grey coloured gravels and sands in which limestone cobbles prevail. Quaternary deposits are generally divided into three basic units: (1) aquifer system overburden built of clay and silt, (2) shallow Holocene aquifer built of alluvial deposits i.e. medium-grain gravel mixed with sands and (3) deeper aquifer from Middle and Upper Pleistocene built of lacustrine-marshy deposits, with frequent lateral and vertical alterations of gravel, sand and clay. Differentiation between shallow and deeper aquifers is stratigraphic since they are hydraulically connected and form a single aquifer from hydrogeological point of view. The sample of gravels and sands for the constant head test (**Figure 2.4**) was taken from shallow Holocene Zagreb aquifer, i.e. its central part near Velika Gorica wellfield. It contained about 60% of gravel and some 40% of sand size grains (**Figure 2.5**).

Figure 2.4: Gravel and sand sample for constant head test taken from shallow Holocene Zagreb aquifer

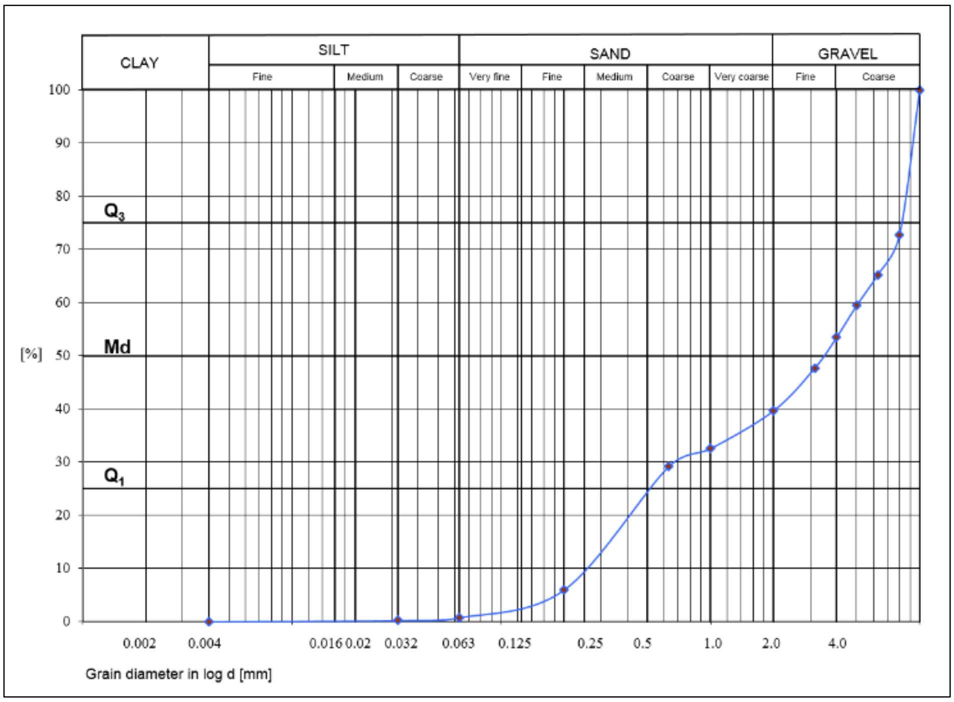

Figure 2.5: Grain size distribution of sample for constant head test taken from Zagreb aquifer

The second site was Virovitica alluvial aquifer, situated in the Drava river basin also characterized with alluvial deposits of Quaternary age. During the Pleistocene age deposition of aeolian sediments, i.e. loess sediments occurred in alteration with fluvial deposits. Denudation processes and tectonic processes enabled deposition of diluvia and pluvial sediments as well as alluvial sediments deposited by the river Drava. Quaternary deposits are characterized with the thick coarse-grained clastic deposits interlayered with thin fine-grained and clayey layers which enabled formation of thick aquifers, with thickness ranging up to 100 m and more (**„Službeni glasnik" of Virovitičko – podravska County No. 7A/00., 1/04., 5/07., 1/10., 2/12., 4/12., 2/13., 3/13**, http://zpuvpz.hr/prostorni-planovi-viroviticko-podravske-zupanije/, accessed 10.8.2018.). The sample of gravels and sands for the constant head test (**Figure 2.6**) taken from the shallow part of Virovitica aquifer contained more than 90% of gravel and less than 10% of sand size grains (**Figure 2.7**).

Figure 2.6: Gravel and sand sample for constant head test taken from shallow part of Virovitica aquifer

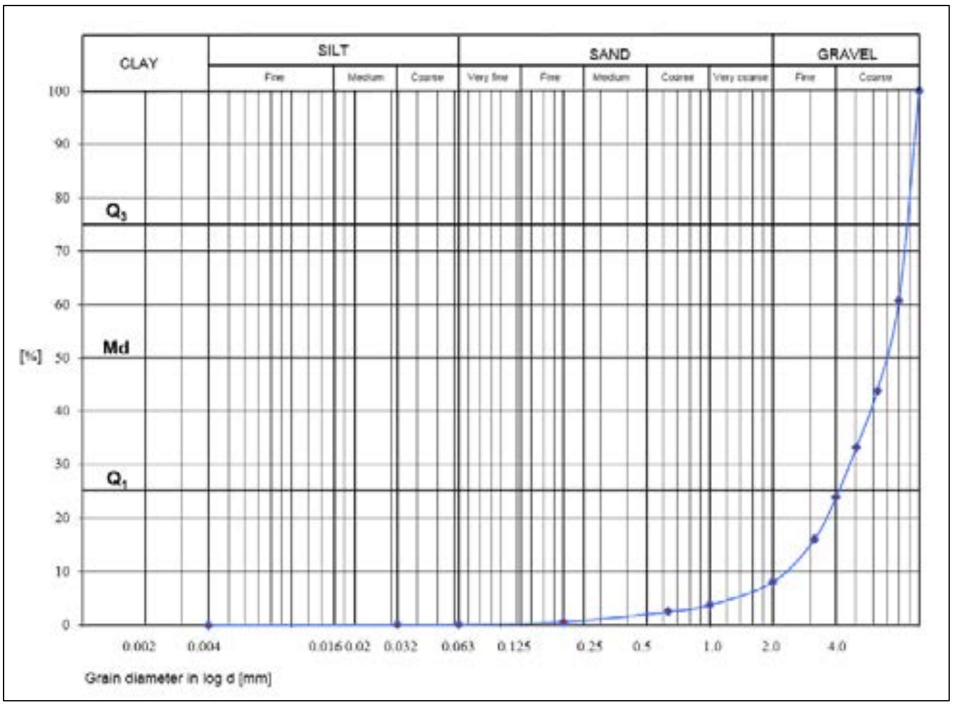

Figure 2.7: Grain size distribution of sample for constant head test taken from Virovitica aquifer

3. Results and discussion

3.1. Hydraulic conductivity of unconsolidated sediments

Results of the constant head permeameter tests for hydraulic conductivity of samples taken from Zagreb and Virovitica alluvial aquifer, i.e. from Sava and Drava river basins, are presented on **Figures 3.1** and **3.2**, plotted on charts as specific discharge, *q* versus hydraulic gradient, *i*. Hydraulic conductivity, *K* can readily be seen on the charts in presented trendline equations. Namely, as discussed in section 2.1, hydraulic conductivity, *K* is the slope of the trendline which passes through the *q* versus *i* data set and the origin of a coordinate system, i.e. in the y coordinate equal to zero.

Hydraulic conductivity of the sample taken from the Zagreb aquifer showed the value of K equal to 8.2×10^{-5} m/s. Series of 9 measurements were conducted. It can be seen that flow for applied hydraulic gradients in the final stage, i.e. for the final 2 measurements, became nonlinear. Therefore only the first 7 measurements were considered in the calculation of the K value during which the flow was still laminar. Obtained K value is within the range of the values expected for Zagreb aquifer. Namely, eastern parts of the Zagreb aquifer tend to have hydraulic conductivities in the range from 10^{-3} to 10^{-5} m/s while western parts have somewhat higher values of K, ranging up to 10^{-2} m/s.

The obtained hydraulic conductivity of the sample taken from Virovitica aquifer showed higher values of hydraulic conductivity, i.e. 1.8×10^{-2} m/s. The obtained value should though be taken with care since difficulties in measurements of the volume of water, V discharged in time, t were present due to high discharge rates, which affected the precision of measurements. Nevertheless, it is evident that a sample with a high share of the gravel size particles, i.e. around 90% (see **Figure 2.7**), is bound to yield high hydraulic conductivities as well. Furthermore, taking into account high discharge rates during testing, obtained high hydraulic value can though be considered relevant.

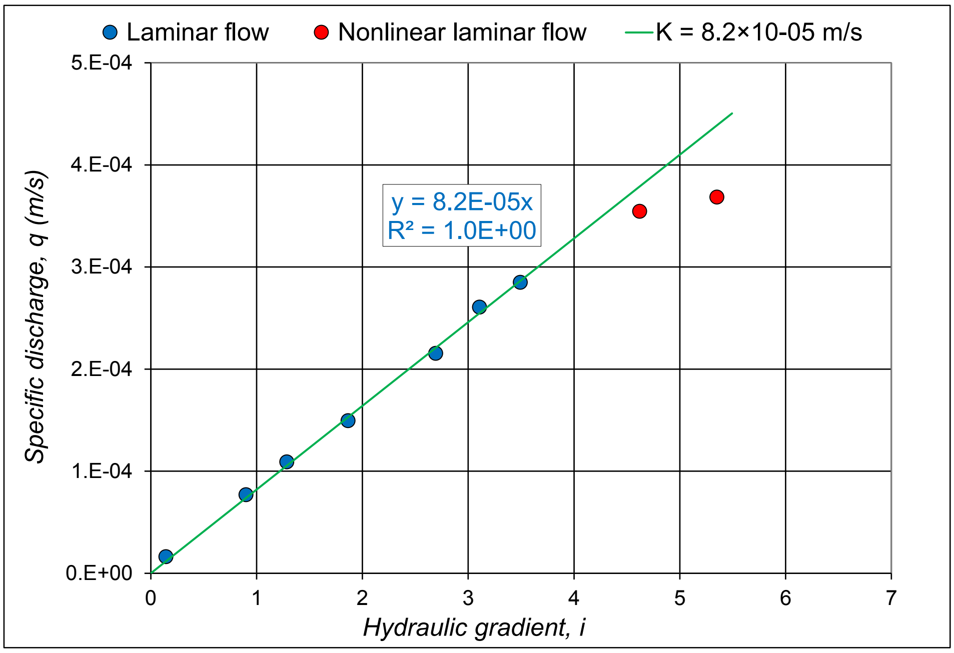

Figure 3.1: Permeameter constant head test data for sample taken from Zagreb aquifer plotted as q versus i

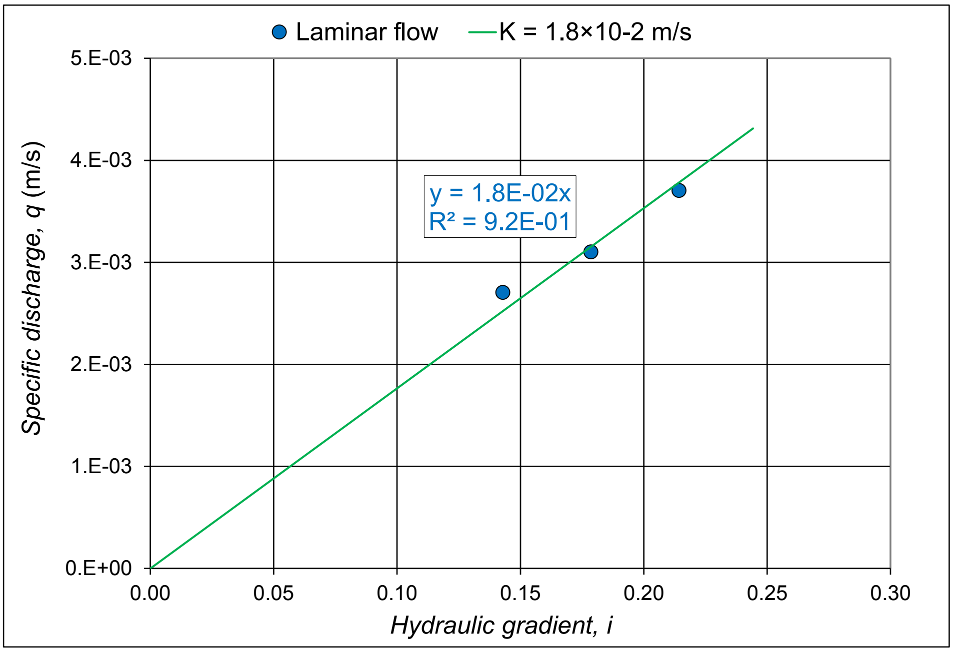

Figure 3.2: Permeameter constant head test data for sample taken from Virovitica aquifer plotted as *q* versus *i*

3.2. Discussion on terminology used in groundwater literature and practice

Terminology used in groundwater literature and practice for characterization of the capacity of a medium to transmit water often cause misunderstandings. One of the most often one is replacing the terms *hydraulic conductivity*, *K* [L/T] or *coefficient of permeability, k* [L/T] with the term *permeability, k* (L^2).

The term *hydraulic conductivity*, *K* [L/T] and to a lesser extent term *coefficient of permeability, k* [L/T] are most frequently used in groundwater literature for denotation of the capacity of a medium to transmit water while the term *permeability*, usually symbolized by the small letter *k* [L^2] is used in the petroleum industry where the fluids of interest are oil, gas and water (**Domenico and Schwartz, 1990**). While hydraulic conductivity characterizes the capacity of a medium to transmit water, permeability characterizes the capacity of a medium to transmit any fluid. Permeability is a property of the porous media only, not the fluid. Therefore using the terms *hydraulic conductivity*, *K* [L/T] or *coefficient of permeability,* [L/T] unambiguously with the term *permeability, k* (L^2) is erroneous and can cause confusion.

Terms *hydraulic conductivity* or *coefficient of permeability* are used specifically for the flow of water through a porous media when dealing with the single water phase. The former is commonly symbolized with the capital letter *K* while the latter is symbolized with the small letter *k*, both in units of L/T (m/s in SI system). Although the majority of the groundwater literature uses the term *hydraulic conductivity*, *K* [L/T] to denote the capacity of a medium to transmit water, the term *coefficient of permeability, k* [L/T] and erroneously *permeability, k* [L^2] are also used. Namely, standards for permeameter tests like the ASTM or ISO standard both have terms *permeability* in their titles. ISO standard CEN ISO/TS 17892-11:2004/AC is titled "Geotechnical investigation and testing - Laboratory testing of soil - Part 11: Determination of permeability by constant and falling head (ISO/TS 17892-11:2004) although within the text the term *coefficient of permeability, k* [L/T] is used. ASTM standard D 2434 – 68 also bears the term permeability in its title "Standard Test Method for Permeability of Granular Soils (Constant Head)" but also uses the term *coefficient of permeability, k* [L/T] within the text. Furthermore, term *permeability* can often be heard in groundwater, civil engineering, geotechnical and agricultural community while having in mind units [L/T], not [L^2].

Another often seen misunderstanding is related to the terms *intrinsic* or *absolute* or *specific permeability, k* [L^2] (m^2 in SI system), which are used in groundwater literature to characterize the property of the porous media only, not the fluid, when porous medium is 100% saturated with a single-phase fluid, which is the case when dealing with groundwater. Although the term *intrinsic permeability, k* [L^2] is often correctly used in groundwater literature, there are cases when notation *permeability, k* [L^2] is used instead or even cases when literature suggests that the term *intrinsic permeability, k* [L^2] could be shortened to the term *permeability, k* [L^2], as usually done in practice.

Groundwater literature and practice in Croatia offers different notations. **Miletić and Miletić (1981)** use the term *coefficient of hydraulic conductivity, K* [L/T] to denote the capacity of a medium to transmit water while they use the term *coefficient of filtration, k* [L^2] to characterize the property of the porous media only, not the fluid. **Mayer, D (1993)** uses term similar to **Miletić and Miletić (1981)** to denote the capacity of a medium to transmit water, i.e. *coefficient of hydraulic conductivity, K* [L/T] and the term *actual permeability, k* [L^2] to characterize the property of the porous media only. **Urumović, K. (2003)** denotes the capacity of a medium to transmit water as *hydraulic conductivity, K* [L/T] and the property of the porous media only, not the fluid, as *intrinsic or specific permeability, k* [L^2] although states that terms *intrinsic or specific permeability* are shorter called *permeability*. **Bačani, A. (2006)** uses similar terms, i.e. *hydraulic conductivity, K* [L/T] to denote the capacity of a medium to transmit water and *intrinsic permeability or permeability, k* [L^2] to denote the property of the porous media only, not the fluid.

In order to avoid confusion and misunderstandings with the petroleum industry it would be of interest for groundwater, civil engineering, geotechnical, and agricultural scientists, engineers and practitioners to use unique terms for the capacity of a medium to transmit water when the fluid of interest is single water phase, i.e. groundwater, and for the property of the porous media only, not the fluid, when porous medium is 100% saturated with a single-phase fluid, i.e. groundwater.

Therefore is suggested, when dealing with the porous medium 100% saturated with a single water phase, i.e. groundwater, to use the term *hydraulic conductivity*, *K* [L/T] to denote the capacity of a medium to transmit water and the term *intrinsic permeability, k* [L^2] to denote the property of the porous media only, not the fluid, since those are correct and most often used terms in groundwater literature.

4. Conclusions

Constant head permeameter tests for hydraulic conductivity of unconsolidated sediments conducted on gravel and sand samples taken from Zagreb alluvial aquifer (Sava basin, Croatia) and Virovitica alluvial aquifer (Drava basin, Croatia) showed substantial differences in values of obtained hydraulic conductivities. Sample taken from the shallow zone of the central part of the Zagreb aquifer near wellfield Velika Gorica contained more fine grained material, about 60% of gravel and some 40% of sand size grains versus more than 90% of gravel and less than 10% of sand size grains contained in the sample taken from the Virovitica alluvial aquifer. Therefore sample taken from the shallow part of the Virovitica alluvial aquifer showed higher value of hydraulic conductivity, in the range of 10^{-2} m/s, while sample taken from the Zagreb aquifer showed a value of hydraulic conductivity in the range of 10^{-5} m/s. Based on previous research it can though be concluded that obtained results are site specific, i.e. strongly dependent on the sampling location. Namely, eastern parts of the Zagreb aquifer tend to have hydraulic conductivities in the range from 10^{-3} to 10^{-5} m/s while western parts have somewhat higher values of *K*, ranging up to 10^{-2} m/s.

Tests were conducted in the laboratory using the ASTM standard D 2434 – 68 and an apparatus which is basically a modification of Darcy's apparatus used in his work on the public fountains of the city of Dijon conducted in 1856. Within this work Darcy conducted the first documented experiment to determine the laws of the water flow through sands. The year 1856 was the year of the birth of groundwater hydrology as a quantitative science and the law he obtained bears his name. Darcy's law is empirical, like Ohm's and Fourier's law. It is also linear, as one of the many that describe physical and chemical processes on earth. The key parameter in groundwater science and Darcy's law, the hydraulic conductivity, *K* is actually the slope of the line which passes through the *q* versus *i* dataset and the origin of a coordinate system. And as long as the plotted data of *q* versus *i* stay on the straight line, the flow is considered to be laminar, and Darcy's law valid. When deviation from the straight line occurs, the flow is considered to be nonlinear and Darcy's law no longer valid. Although the validity of Darcy's law can also be tested by Reynolds number, the *q* versus *i* plot is the only reliable measure to determine whether the flow is linear or nonlinear in a permeameter constant head test.

Although Darcy's law is more than 160 years old, terminology related to parameters describing the flow of water through porous medium still differs in groundwater literature. Terms hydraulic conductivity, *K* [L/T] (m/s in SI system), coefficient of permeability, *k* [L/T] (m/s in SI system), permeability, *k* (L^2) (m^2 in SI system) and intrinsic or absolute or specific permeability, *k* [L^2] (m^2 in SI system) are often unambiguously used, causing misunderstandings both in groundwater literature and practice. One of the most often used unambiguity's are the terms *hydraulic conductivity*, *K* [L/T] or *coefficient of permeability, k* [L/T] and the term *permeability, k* (L^2). The term *hydraulic conductivity*, *K* [L/T] and to a lesser extent term *coefficient of permeability, k* [L/T] are most frequently used in groundwater literature for denotation of the capacity of a medium to transmit a single water phase while the term *permeability*, usually symbolized with the small letter *k* [L^2] is used in the petroleum industry where the fluids of interest are oil, gas and water. Furthermore, permeability is a property of the porous media only, not the fluid. Therefore using these terms unambiguously is erroneous and can cause confusion. Another often misunderstanding comes from the terms *intrinsic* or *absolute* or *specific permeability, k* [L^2] (m^2 in SI system), which are also used to characterize the property of the porous media only, not the fluid, when porous medium is 100% saturated with a single-phase fluid, as for example groundwater. Those terms are, probably due to simplicity, often erroneously shortened to the term *permeability* in groundwater literature and practice.

Therefore is suggested to groundwater, civil engineering, geotechnical, and agricultural scientists, engineers and practitioners to use the term *hydraulic conductivity*, *K* [L/T] to denote the capacity of a medium to transmit water and the term *intrinsic permeability, k* [L^2] to denote the property of the porous media only, not the fluid, when dealing with the porous medium 100% saturated with a single water phase, i.e. groundwater in order to avoid confusion and misunderstandings with the petroleum industry.

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Extended abstract in Croatian

Testovi hidrauličke vodljivosti nekonsolidiranih sedimenata u permeametru sa stalnom razinom i pridružena terminologija

U radu su prikazani laboratorijski testovi hidrauličke vodljivosti nekonsolidiranih sedimenata te je dana rasprava o pridruženim terminima koji se koriste u literaturi i praksi. Uzorci nekonsolidiranih materijala, šljunaka i pijesaka koji su taloženi na dvije istraživane lokacije, zagrebačkom aluvijalnom vodonosniku (Savski bazen, Hrvatska) i virovitičkom aluvijalnom vodonosniku (Dravski bazen, Hrvatska), testirani su u laboratoriju primjenom permeametra sa stalnom razinom. Prikazane su glavne karakteristike eksperimenata i usporedba rezultata s dva istraživana područja. Dana je i rasprava vezana za terminologiju koja se koristi u hidrogeološkoj literaturi za označavanje kapaciteta porozne sredine da provodi vodu, s osvrtom na dvosmislenost najčešće korištenih termina. Termini koji se danas najčešće koriste u hidrogeološkoj literaturi i praksi su hidraulička vodljivost, *K* [L/T] (m/s u SI sustavu) ili koeficijent propusnosti, *k* [L/T] (m/s u SI sustavu), a koriste se specifično za označavanje jednofaznog tečenja vode kroz porozni medij. U dodatku, rasprava je proširena na termine propusnost, *k* [L^2] (m^2 u SI sustavu) odnosno unutarnju, apsolutnu ili specifičnu propusnost, također označavanu kao *k* [L^2] (m^2 u SI sustavu) za porozni medij koji je 100% saturiran s jednofaznim fluidom tj. vodom u razmatranom slučaju, a koji predstavljaju karakteristike isključivo porozne sredine, ne i fluida.

Terminologija koja se koristi u hidrogeološkoj literaturi i praksi za označavanje kapaciteta porozne sredine da provodi vodu često dovodi do nesporazuma. Jedan od najčešćih nesporazuma je zamjena termina *hidraulička vodljivost*, K [L/T] ili *koeficijent propusnosti*, k [L/T] s terminom *propusnost*, k (L^2).

Termin *hidraulička vodljivost*, K [L/T] i u manjoj mjeri termin *koeficijent propusnosti*, k [L/T] najčešće su korišteni termini u hidrogeološkoj literaturi za označavanje kapaciteta porozne sredine da provodi vodu dok se termin *propusnost*, uobičajeno označavan s malim slovom k (L^2) koristi u naftnoj industriji gdje su fluidi od interesa nafta, plin i voda (**Domenico i Schwartz, 1990**). Dok hidraulička vodljivost označava kapacitet porozne sredine da provodi vodu, propusnost označava kapacitet porozne sredine da provodi bilo koji fluid. Propusnost je karakteristika isključivo porozne sredine, ne i fluida. Stoga je korištenje termina *hidraulička vodljivost*, K [L/T] ili *koeficijent propusnosti*, k [L/T] jednoznačno s terminom *propusnost*, k (L^2) pogrešno i može dovesti do nesporazuma.

Termini *hidraulička vodljivost* ili *koeficijent propusnosti* koriste se specifično za označavanje tečenja vode kroz poroznu sredinu u slučaju kada se radi o jednofaznom tečenju. *Hidraulička vodljivost* se obično označava s velikim slovom *K* dok se *koeficijent propusnosti* obično označava s malim slovom *k*, a izražavaju se u jedinicama L/T (m/s u SI sustavu). Iako velika većina hidrogeološke literature koristi termin *hidraulička vodljivost*, K [L/T] za označavanje kapaciteta porozne sredine da provodi vodu, termin *koeficijent propusnosti*, k [L/T] i pogrešno termin *propusnost*, k (L^2) također su u upotrebi. Naime, norme za permeametarske testove kao što je to ASTM norma ili ISO norma koriste termin *propusnost* u svojim naslovima. ISO norma CEN ISO/TS 17892-11:2004/AC nosi naslov "Geotehnička ispitivanja i testiranja – laboratorijska testiranja tla – Dio 11: Određivanje propusnosti primjenom testa sa stalnom i promjenjivom razinom (ISO/TS 17892-11:2004)", iako se unutar samog teksta norme koristi termin *koeficijent propusnosti*, k [L/T]. ASTM norma D 2434 – 68 također nosi termin *propusnost* u svom naslovu „Standardna metoda za testiranje propusnosti zrnastih tala (stalna razina)", ali također koristi termin *koeficijent propusnosti*, k [L/T] unutar samog teksta norme. Nadalje, vrlo često se u hidrogeološkoj, građevinarskoj, geotehničkoj i agronomskoj zajednici može čuti termin *propusnost*, dok se zapravo imaju na umu jedinice [L/T], a ne [L^2].

Sljedeći najčešći nesporazum vezan je uz termine *unutarnja* ili *apsolutna* ili *specifična propusnost*, k [L^2] (m^2 u SI sustavu), koji se u hidrogeološkoj literaturi koriste za označavanje karakteristika isključivo porozne sredine, ne i fluida, kada je porozna sredina 100% saturirana jednofaznim fluidom, kao što je to slučaj kad se radi o podzemnoj vodi. Iako se termin *unutarnja propusnost*, k [L^2] često ispravno koristi u hidrogeološkoj literaturi, ima slučajeva kada se umjesto njega koristi termin *propusnost*, k [L^2], a i slučajeva kada literatura sugerira da se termin *unutarnja propusnost*, k [L^2] skraćeno može zvati *propusnost*, k [L^2], kao što se to često i koristi u praksi.

Hidrogeološka literatura i praksa u Hrvatskoj koriste različite termine. **Miletić i Miletić (1981)** koriste termin *koeficijent hidrauličke provodljivosti*, K [L/T] za označavanje kapaciteta porozne sredine da provodi vodu dok koriste termin *koeficijent filtracije*, k [L^2], za označavanje karakteristika isključivo porozne sredine, ne i fluida. **Mayer, D (1993)** koristi slične termine kao i **Miletić i Miletić (1981)** za označavanje kapaciteta porozne sredine da provodi vodu, tj. *koeficijent hidrauličke provodljivosti*, K [L/T] te termin *stvarna propusnost,* k [L^2] za označavanje karakteristika

isključivo porozne sredine, ne i fluida. **Urumović, K. (2003)** označava kapacitet porozne sredine da provodi vodu kao *hidraulička vodljivost*, K [L/T], a karakteristike isključivo porozne sredine, ne i fluida, kao *unutarnja* ili *specifična propusnost*, k [L^2] iako navodi da se termini *unutarnja* ili *specifična propusnost*, k [L^2] kraće zovu *propusnost*. **Bačani, A. (2006)** također koristi slične termine, tj. *hidraulička vodljivost*, K [L/T] za označavanje kapaciteta porozne sredine da provodi vodu i *unutarnja propusnost* ili *propusnost*, k [L^2] za označavanje karakteristike isključivo porozne sredine, ne i fluida.

Kako bi se izbjegli nesporazumi unutar hidrogeološke, građevinarske, geotehničke i agronomske znanstvene i inženjerske zajednice, ali i nesporazumi s naftnom industrijom, bilo bi od interesa da se koriste jedinstveni termini za označavanje kapaciteta porozne sredine da provodi vodu kada je fluid od interesa jednofazni, tj. podzemna voda, i za označavanje karakteristika isključivo porozne sredine, ne i fluida, kada je porozna sredina 100% saturirana jednofaznim fluidom tj. podzemnom vodom.

Stoga se predlaže korištenje termina *hidraulička vodljivost*, K [L/T] za označavanje kapaciteta porozne sredine da provodi vodu i termina *unutarnja propusnost*, k [L^2] za označavanje karakteristike isključivo porozne sredine, ne i fluida, kada se radi o podzemnoj vodi tj. poroznoj sredini 100% saturiranoj jednofaznim fluidom tj. vodom s obzirom da su to ispravni i najčešće korišteni termini u hidrogeološkoj literaturi.

Ključne riječi: hidraulička vodljivost, propusnost, unutarnja propusnost, permeametar, terminologija

Authors contribution

Kristijan Posavec (PhD, Professor, Hydrogeology) provided a theoretical background and discussion on terms used in groundwater literature and practice. **Adriana Kukolja** (Student, Geological Engineering) provided examples of measurements from conducted permeameter test. **Valentina Kocijan** (Student, Geological Engineering) provided examples of measurements from conducted permeameter test.

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Original scientific paper

Application of Simpson´s and trapezoidal formulas for volume calculation of subsurface structures - recommendations

Josipa Pavičić[1]; Željko Andreić[1]; Tomislav Malvić[1]; Rajna Rajić[1]; Josipa Velić[1]

[1] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Croatia

Abstract

In nature, most of the subsurface geological structures have an asymmetric shape. To estimate the volume of such structures numerical integration is used. Two methods have been analysed for volume estimation of geological structures: trapezoidal and Simpson´s method. Both methods estimate the volume of the structure, because they have a certain error in the calculation. Two examples of the hypothetical hydrocarbon reservoirs are presented: massive and layered ones. Differences between volume calculations obtained by trapezoidal and Simpson formulas mostly are not significant. Larger number of sections generally leads to smaller differences between volumes calculated by trapezoidal and Simpson rules. In even number of sections, the recommendation is to apply Simpson and top formulas. If number of sections is odd, the combination of Simpson's formula for $\boldsymbol{n-1}$ sections, trapezoidal for $\boldsymbol{n}$-*th* section and top formulas for the rest is appropriate.

Keywords: anticline, numerical integration, trapezoidal rule, Simpson´s rule

1. Introduction

Knowing the approximate volume of the structures is necessary for, e.g., economic analysis, prediction of migration, geological evolution etc. After geological, geophysical and geochemical research and drilling explorations such volume calculation can be performed. Such analysis is also often part of stratigraphy, reservoir, petrophysical or similar modelling. Volume calculation is in most cases part of hydrocarbon reserves estimation, and is largely dependent on size and reliability of input dataset(s). We present reservoir volume calculation by applying two rules: trapezoidal and Simpson´s ones. Their results are compared and recommendation of application, based on the number of isopaches, is given.

2. Basics about numerical integration

Geological structures such as anticlines are the most common hydrocarbon traps (e.g., **Malvić & Velić, 2008**). However, such structures mostly have partially irregular shape and geometrical approximation with truncated cone is not ideal (e.g., **Malvić et al., 2014**). For this reason analytical integration cannot be applied to estimate volume of such structures. However, if the area $A(x)$ of cross section parallel to the plane yz (**Fig. 1**) is known, integral formulation (**Eq. 1)** can be used to compute the volume of a body in certain boundaries - a, b.

$$V = \int_a^b A(x)dx \qquad \text{Eq. 1}$$

Corresponding author: Josipa Pavičić
josipapavicic2003@gmail.com

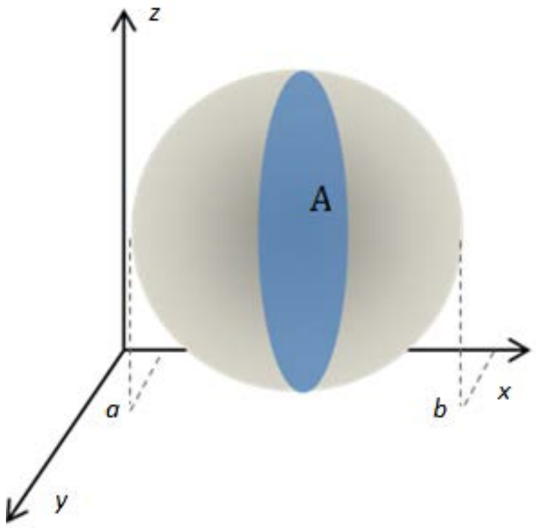

Figure 1: A solid object with boundaries extending from $x = a$ to $x = b$

In this way the volume of irregular body cannot be exactly calculated. Consequently, approximate methods for the volume calculation are used like trapezoidal and Simpson´s method (e.g., **Scitovski, 2014**).

2.1. Trapezoidal rule

Trapezoidal rule is based on the method in which curve f is approximated with straight line L, as shown on **Fig. 2**. The area bounded by the curve f, lines $x = a$ and $x = b$, and the axis x is approximated by the area of the trapezoid with the bases of lengths $f(a)$ and $f(b)$, and the height $(b - a)$ (e.g., **Čančarević, 2016**). Equation of the line L passes through the points $A(a, f(a))$ and $B(b, f(b))$ is (**Eq. 2**)

$$L(x) = \frac{f(b)-f(a)}{b-a}(x - a) + f(a). \qquad \text{Eq. 2}$$

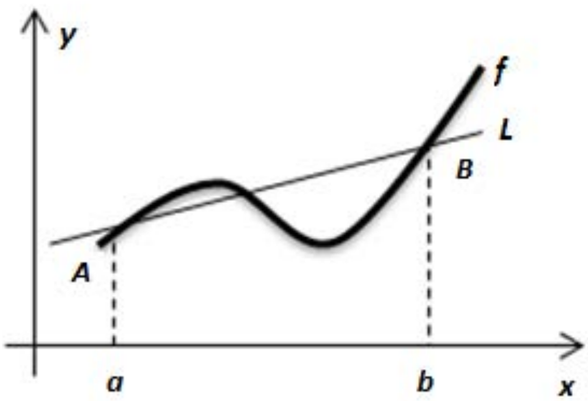

Figure 2: Approximation of the curve f with straight line L

The area of the trapezoid is obtained by integrating function L (**Eq. 3**) on the segment $[a, b]$, so we have (**Eq. 3**):

$$\int_a^b f(x)dx \approx \int_a^b L(x)dx = \frac{b-a}{2}\left(f(a) + f(b)\right). \qquad \text{Eq. 3}$$

With this method approximation is relatively good, but there are still possible errors. So, to minimize the error it is necessary to divide interval $[a, b]$ with points $a = x_0, x_1, x_2, \dots, x_{n-1}, x_n = b$ on n equally long segments, **Figure 3**.

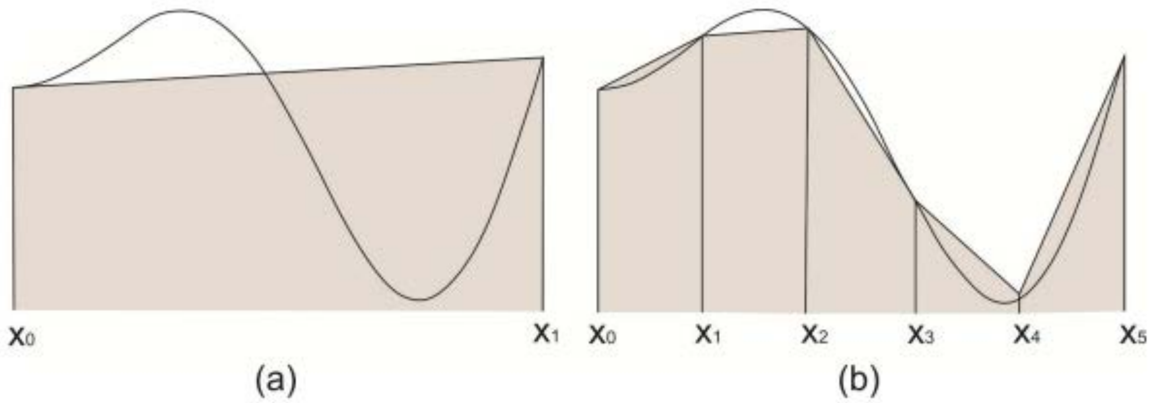

Figure 3: Trapezoidal rule with one interval (a) and five subintervals (b)

Final form of the trapezoidal rule is **(Eq. 4)**:

$$\int_a^b f(x)dx \approx \frac{h}{2}\left(y_0 + y_n + 2(y_1 + y_2 + \cdots + y_{n-1})\right) \quad \text{Eq. 4}$$

where are:

$y_0 = f(x_0), y_1 = f(x_1), \ldots, y_{n-1} = f(x_{n-1}), y_n = f(x_n)$;

$h = \frac{b-a}{n}$ *- length of each subinterval.*

With more subintervals the error is smaller, but still present. To calculate the error obtained with trapezoidal rule, the second derivation of function f is required, (**Eq. 5**):

$$\varepsilon \leq \frac{(b-a)h^2}{12} M \quad \text{Eq. 5}$$

where are:

ε *- error*;

$M = \max\limits_{x \in [a,b]} |f''(x)|$;

$h = \frac{b-a}{n}$ *- length of each subinterval.*

If *f* is a first degree polynomial, respectively function whose graph is a straight line, solution error is zero.

2.1. Simpson´s rule

Simpson´s rule is based on the idea to approximate the curve f with a second-degree polynomial (**Eq. 6**):

$$P(x) = a_0x^2 + a_1x + a_2. \quad \text{Eq. 6}$$

Graph of the function P is a parabola (see **Fig. 4**), where unknown coefficients a_0, a_1, a_2 are calculated from **Eq. 7**:

$$P(a) = f(a),\ P\left(\frac{a+b}{2}\right) = f\left(\frac{a+b}{2}\right), P(b) = f(b). \quad \text{Eq. 7}$$

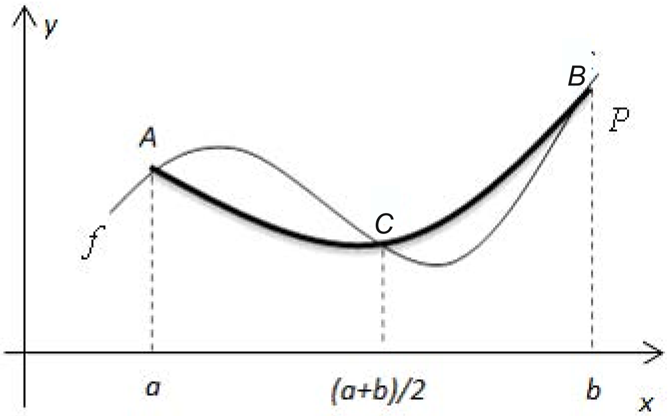

Figure 4: Interpolation of the curve f with P

Then, integration of function P on segment $[a, b]$ is performed, **Eqs. 8** and **9:**

$$\int_a^b P(x)dx = \int_a^b (a_0 x^2 + a_1 x + a_2)dx = \frac{1}{6}(b-a)\left(f(a) + 4f\left(\frac{a+b}{2}\right) + f(b)\right); \quad \text{Eq. 8}$$

$$\int_a^b f(x)dx \approx \int_a^b P(x)dx = \frac{1}{6}(b-a)\left(f(a) + 4f\left(\frac{a+b}{2}\right) + f(b)\right). \quad \text{Eq. 9}$$

Like in the trapezoidal rule, for more precise result it is required to divide interval $[a, b]$ into smaller equidistant intervals. Interval $[a, b]$ is divided with points $a = x_0, x_1, x_2, \dots, x_{n-1}, x_n = b$ on even number $n = 2m$ subintervals of the same length $h = \frac{b-a}{n}$, **Figure 5**.

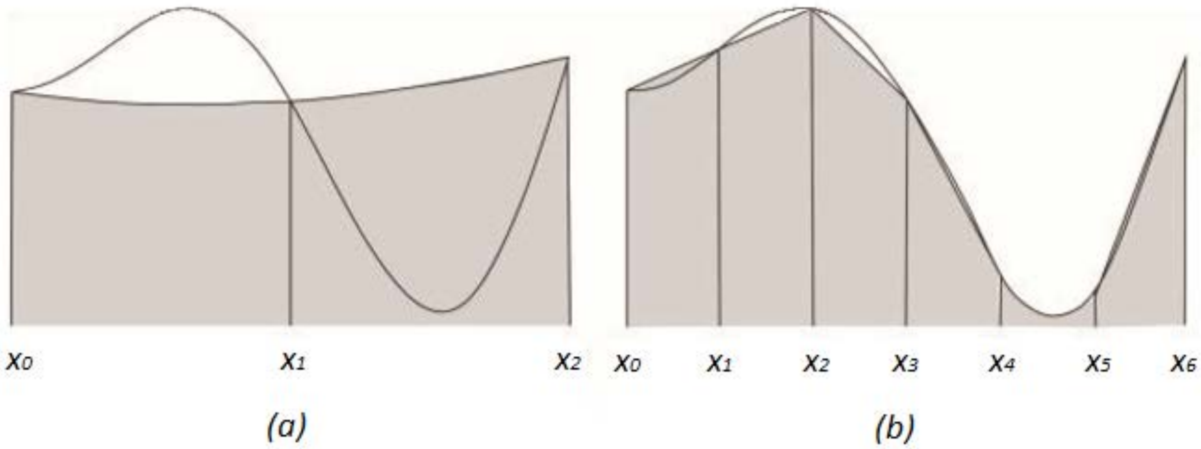

Figure 5: Simpson's rule with two subintervals (a) and with $2m = 6$ subintervals (b)

The equation **Eq. 9** is used on the segments $[x_0, x_2]$, $[x_2, x_4]$, ..., $[x_{n-4}, x_{n-2}]$, $[x_{n-2}, x_n]$ (each segment consists of two subintervals). After summing up the results, general form of Simpson´s rule is obtained (**Eq. 10**):

$$\int_a^b f(x)dx \approx \frac{h}{3}\left(y_0 + y_n + 4(y_1 + y_3 + \dots + y_{n-1}) + 2(y_2 + y_4 + \dots + y_{n-2})\right) \quad \text{Eq. 10}$$

where are:

$y_0 = f(x_0), y_1 = f(x_1), \dots, y_{n-1} = f(x_{n-1}), y_n = f(x_n);$

$h = \frac{b-a}{n}$ – *length of each subinterval*.

Although this method is more precise then trapezoidal method, error exists due to approximation. It can be calculated with **Eq. 11**:

$$\varepsilon \leq \frac{(b-a)h^4}{180} M; \qquad \text{Eq. 11}$$

where are:

ε – *error*;

$M = \max_{x \in [a,b]} |f^{iv}(x)|$;

$h = \frac{b-a}{n}$ - *length of each subinterval* (*further in the text is marked with „e"*).

Observe that in the case when f is a polynomial whose degree is at most three, the result is precise, i.e. error is zero.

3. The application of numerical integration in the description of the hydrocarbon reservoir

Numerical integration is used in calculating the approximate volume of hydrocarbons reservoirs. Geology problems of this type have been studied earlier (e.g., **Malvić et al., 2014**). With the aim of economic benefit, it is necessary to get enough data for mapping and volume calculations, with minor or no additional need to collect new data. Moreover, hydrocarbon reservoirs are most commonly closed with structural traps, i.e. anticlines. Such examples (e.g., **Malvić and Velić, 2008; Velić, 2007; Velić et al., 2015)**, based on this structure, are used in this analysis (**Figs. 6** and **7**).

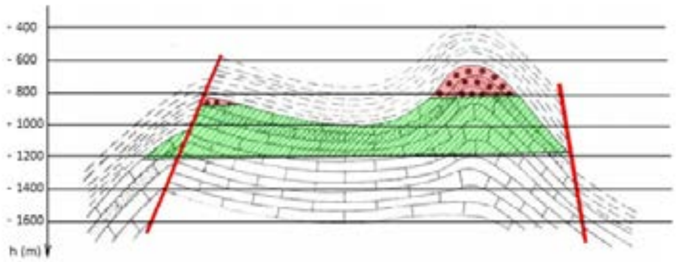

Figure 6: Massive type of the hydrocarbons reservoir

Massive type of reservoir (**Fig. 6**) is hydrocarbon accumulation in the "massive" rock section (usually several lithotypes) with known and well reservoir properties. Similarly, but not the same, "layered" reservoir (**Fig. 7**) is trapped into one strata or depositional unit, bordered with known bottom and roof (isolator) beds. Such reservoir usually has better (isotropic on smaller scale) petrophysical properties than the massive one.

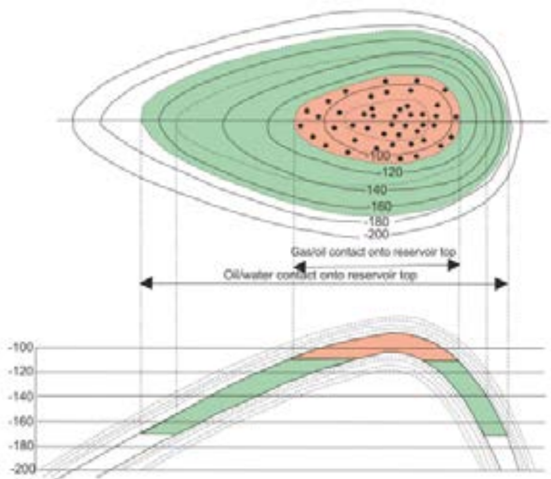

Figure 7: "Layered" reservoir as irregular brachianticline

3.1. Volume calculation in massive reservoir

Isopach (contour) map for the top of massive reservoir is shown at **Fig. 8**. The contact is above the basement, so the volume is calculated between such contact and the top map. Brachianticline is shown using equidistance of 5 m, and structure dips are less than 20°.

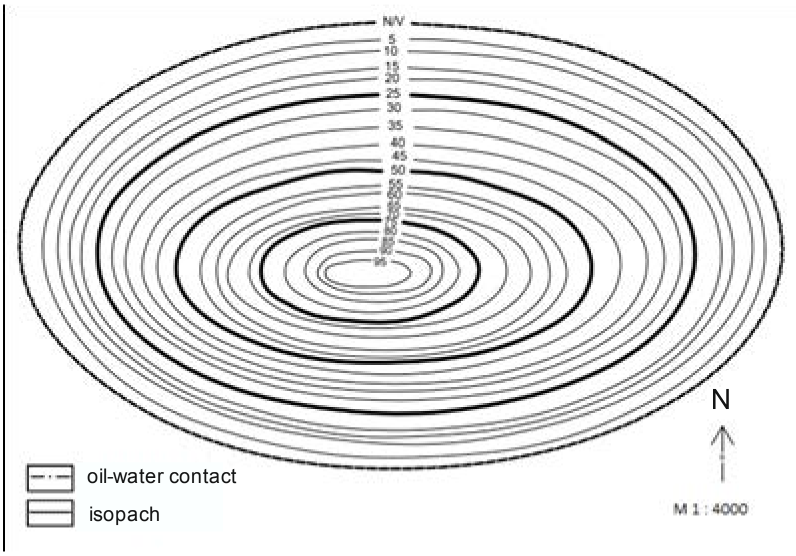

Figure 8: *Isopach map of massive type reservoir. Volume between contact water/hydrocarbons – reservoir top. Top height is 1 m.*

So, the structure has been cut with isopach planes, every 5 m (equidistance). Section areas are measured by planimeter, instrument used for measuring the area of irregular surfaces (e.g., **Malvić, 2015**). Absolute difference between starting and ending point observed on planimeter during measuring of isopach is multiplied by a multiplying constant (which depends on scale). The result is area bounded with observed isopach in squared meters. Here the scale 1:4000 has been multiplied with constant of 1600. The areas a_i are shown in **Table 1.**

Isopach no.	1st starting point of planimeter	2nd finishing point of planimeter	$\lvert 1^{st} - 2^{nd} \rvert$	Absolute area a_i [m^2]
0	4202	6372	2170	3 472 000
1	6434	8405	1971	3 153 600
2	1094	2891	1797	2 875 200
3	2939	4559	1620	2 592 000
4	1619	3086	1467	2 347 200
5	4675	5982	1307	2 091 200
6	4450	5620	1170	1 872 000
7	5710	6730	1020	1 632 000
8	6759	7646	887	1 419 200
9	7768	8522	754	1 206 400
10	8593	9233	640	1 024 000
11	9325	9842	517	827 200

12	37	467	430	688 000
13	566	890	324	518 400
14	1025	1273	248	396 800
15	1374	1544	170	272 000
16	1651	1755	104	166 400
17	1848	1906	58	92 800
18	1955	1987	32	51 200
19	2046	2058	12	19 200
20	2106	2109	3	4800

Table 1: Planimeter results for section crossing massive reservoir (contact-top)

3.1.1. Case 1: massive reservoir divided with even number of sections

First case included even number of section, i.e. odd number of isopach. Results obtained with Simpson´s formula are shown in **Table 2**. The preciseness has been simulated with different equidistance - 5, 10, 25 and 50 m. Moreover, the total volume of reservoir is always increased with small additional volume above the last isopach, named as "top". This volume is defined by height smaller than equidistance. The volume V_T of the top (**Eq. 14**) is calculated as an arithmetic average of the results of the following two formulas, i.e. pyramidal (**Eq. 12**) and spherical approximation (**Eq. 13**), given, e.g., in **Korać (2015)**:

$$V_p = \frac{h_n a_n}{3}, \qquad \text{Eq. 12}$$

where are:

V_p - *pyramidal approximation;*
h_n - *distance from the last isopach to the top of the structure;*
a_n - *area bounded with the last isopach;*

$$V_{sf} = \frac{h_n^3 \Pi}{6} + \frac{a_n h_n}{2}, \qquad \text{Eq. 13}$$

where are:

V_{sf} - *spherical approximation;*
h_n - *distance from the last isopach to the top of the structure;*
a_n - *area bounded with the last isopach;*

$$V_T = \frac{1}{2}\left(V_p + V_{sf}\right). \qquad \text{Eq. 14}$$

By summing a volume V_S calculated with Simpson´s formula (even sections) plus a volume V_T of the top structure, the total volumes are given in **Table 2**.

e (m)	Number of sections	Used areas	Volumes calculated with Simpson's and top formulas $V_S + V_T$ (m^3)
5	20	$a_0, a_1, \dots, a_{19}, a_{20}$	124 628 667
10	10	$a_0, a_2, \dots, a_{18}, a_{20}$	125 319 334
25	4	$a_0, a_5, a_{10}, a_{15}, a_{20}$	124 815 334
50	2	a_0, a_{10}, a_{20}	126 215 334

Table 2: Volume (**Figure 8**) calculated with Simpson's and top formulas for even number of sections

That was continued with calculation of the total volumes by replacing Simpson's with trapezoidal formula, that is, the total volumes are obtained by summing volumes V_t calculated with a trapezoidal formula and the volume V_T of the top. The results are given in **Table 3**.

e (m)	Number of sections	Used areas	Volumes calculated with trapezoidal and top formulas $V_t + V_T$ (m^3)
5	20	$a_0, a_1, \dots, a_{19}, a_{20}$	124 918 000
10	10	$a_0, a_2, \dots, a_{18}, a_{20}$	125 786 000
25	4	$a_0, a_5, a_{10}, a_{15}, a_{20}$	128 142 000
50	2	a_0, a_{10}, a_{20}	138 122 000

Table 3: Volume (**Figure 8**) calculated with trapezoidal and top formulas for even number of sections

To estimate the error, a deviation $\frac{|V_t - V_S|}{\min\{V_t, V_S\}}$ is calculated and the results are shown in percentage (**Table 4**). As can be seen, the deviation is nowhere larger than 20 %, what is considered as a limit to accept calculation with Simpson's formula as valid for structure volume (e.g., in **Malvić et al., 2104**; **Malvić, 2015**).

e (m)	Volumes calculated with Simpson's and top formulas $V_S + V_T$ (m^3)	Volumes calculated with trapezoidal and top formulas $V_t + V_T$ (m^3)	$\Delta V = \lvert V_t - V_S \rvert$ (m^3)	Deviations $\frac{\Delta V}{\min\{V_t, V_S\}}$ (%)
5	124 628 667	124 918 000	289 333	0.23
10	125 319 334	125 786 000	466 666	0.37
25	124 815 334	128 142 000	3 326 666	2.67
50	126 215 334	138 122 000	11 906 666	9.43

Table 4: Simpson's and trapezoidal (plus top) volumes of structure (**Figure 8**), and their deviations – even number of sections

3.1.2. Case 2: massive reservoir divided with odd number of sections

That case included odd number of sections, i.e. even number of isopach. However, Simpson's formula is designed only for even number of sections. So, the Simpson's rule was applied for the volume up to penultimate isopach, i.e. for $n - 1$ sections. Consequently, for the space between penultimate and last isopaches, trapezoidal rule has been used. At the end, the volume V_T of the "top" is added.

So, the total volume is a summation of $V_S^{(1,\dots,n-1)}$ (volume obtained by Simpson's formula for first $n - 1$ sections), $V_t^{(n)}$ (volume obtained by a trapezoidal formula for n-th section) and V_T (volume of the top). In **Table 5** is given a calculation for massive reservoir divided with odd number of sections. Differences between mixed and pure trapezoidal approach are shown in **Table 6**.

e (m)	Number of sections	Used areas	$V_S^{(1,\dots,n-1)}$ (m^3)	$V_t^{(n)}$ (m^3)	$V_S^{(1,\dots,n-1)} + V_t^{(n)}$ (m^3)	$V_S^{(1,\dots,n-1)} + V_t^{(n)} + V_T$ (m^3)
20	5	$a_0, a_4, a_8, a_{12}, a_{16}, a_{20}$	124 117 333	1 712 000	125 829 333	125 831 333

Table 5: Volume (**Figure 8**) calculated with Simpson's ($n - 1$ sections), trapezoidal (n-th section) and top (above n-th section) formulas – odd number of sections

e (m)	Number of sections	Volume calculated with Simpson's (first $n-1$ sections), trapezoidal (n-th section) and top (above n-th section) formulas $V_S^{(1,\ldots,n-1)} + V_t^{(n)} + V_T$ (m^3)	Volume calculated with trapezoidal (n sections) and top (above n-th section) formulas $V_t^{(1,\ldots,n)} + V_T$ (m^3)	$\Delta V = \lvert V_t^{(1,\ldots,n-1)} - V_S^{(1,\ldots,n-1)} \rvert$ (m^3)	Deviation $\frac{\Delta V}{\min\{V_t^{(1,\ldots,n-1)}, V_S^{(1,\ldots,n-1)}\} + V_t^{(n)}}$ (%)
20	5	125 831 333	127 186 000	1 354 667	1.08

Table 6: Simpson's and trapezoidal total volumes of reservoir, and their difference and deviation – odd number of sections

3.2. Volume calculation in layered reservoir

In this case, layered reservoir with anticline trap is presented. However, the water-hydrocarbons contact cut both, reservoir top and bottom. So, the reservoir volume is a simple difference between volumes of contact-reservoir top and contact-reservoir bottom. Valid isopach map for volume contact-reservoir top is given previously at **Fig. 8**. However, the isopach map for volume contact-reservoir bottom is given at **Fig. 9**. Planimeter results for the isopachs on **Figure 9** are given in **Table 7**. For the isopach maps contact-top the values in **Tables 1-3** are valid also here.

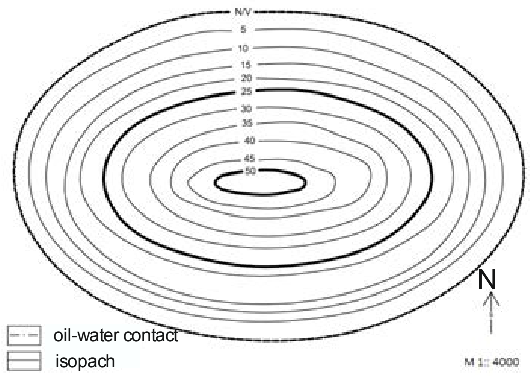

Figure 9: *Isopach map of layered type reservoir. Volume between contact water/hydrocarbons – reservoir bottom. Top height is 1 m.*

Isopach no.	1st starting point of planimeter	2nd finishing point of planimeter	|1st – 2nd|	Absolute area a_i [m^2]
0	1164	2010	846	1 353 600
1	2114	2754	640	1 024 000
2	2825	3332	507	811 200
3	3433	3820	387	619 200
4	3892	4185	293	468 800
5	4280	4482	202	323 200
6	4539	4670	131	209 600
7	4747	4835	88	140 800
8	4914	4962	48	76 800
9	5040	5061	21	33 600
10	5103	5105	2	3 200

Table 7: Planimeter results for section crossing layered reservoir (contact-bottom)

3.2.1. Case 1: layered reservoir divided with even number of sections

Here is used equidistance of 5 and 25 m. The results are compared for volume of n sections (even number) both for Simpson's and trapezoidal formulas, absolute differences and deviations (**Table 8**).

e (m)	Number of sections	Used areas	Volumes calculated with Simpson's and top formulas $V_S + V_T$ (m³)	Volumes calculated with trapezoidal and top formulas $V_t + V_T$ (m³)	$\Delta V = \lvert V_t - V_S \rvert$ (m³)	Deviations $\frac{\Delta V}{\min\{V_t, V_S\}}$ (%)
5	10	$a_0, a_1, \dots, a_9, a_{10}$	21 756 000	21 929 334	173 334	0.80
25	2	a_0, a_5, a_{10}	22 081 334	25 041 334	2 960 000	13.40

Table 8: Volume (**Figure 9**) calculated with Simpson's and trapezoidal formulas – n (even) sections (contact-bottom)

The error is, in all cases, less than 20% what means that Simpson's formula for n sections and selected equidistance can be used properly. Eventually, it was possible to calculate total volume of layered reservoir as the difference between contact/top and contact/bottom. The results are given in **Table 9**.

e (m)	Layered reservoir, total volume (top-bottom, m³)
5	102 872 666
25	102 734 000

Table 9: Total volume of layered bed in m³ – even number of sections

3.2.2. Case 2: layered reservoir divided with odd number of sections

Layered reservoir has also been divided with odd number of sections. It meant that mutually was applied Simpson's formula (for even number of sections, i.e. first $n-1$ sections), trapezoidal formula for the last (n^{th}) section and top formulas (above the n^{th} section), as shown in **Table 10**. For comparison, in **Table 11** are given results if only trapezoidal formula was applied for n sections.

e (m)	Number of sections	Used areas	$V_S^{(1,\dots,n-1)}$ (m³)	$V_t^{(n)}$ (m³)	$V_S^{(1,\dots,n-1)} + V_t^{(n)} + V_T$ (m³)
10	5	$a_0, a_2, a_4, a_6, a_8, a_{10}$	21 504 000	400 000	21 905 334

Table 10: Volume (**Figure 9**) calculated with Simpson's, trapezoidal and top formulas – odd number of sections (contact-bottom)

e (m)	Number of sections	Used areas	$V_t^{(1,\dots,n)} + V_T$ (m³)
10	5	$a_0, a_2, a_4, a_6, a_8, a_{10}$	22 449 334

Table 11: Volume (**Figure 9**) calculated with trapezoidal formula - odd number of sections (contact-bottom)

Those two approaches yielded slightly different results, which are compared in **Table 12** for equidistance of 10 m. Differences were much less than 20 %, so mutual Simpson's and trapezoidal approach was valid for using.

Volume calculated with Simpson's (first n−1 sections), trapezoidal (n-th section) and top (above n-th section) formulas $V_S^{(1,\dots,n-1)} + V_t^{(n)} + V_T$ (m^3)	Volume calculated with trapezoidal (n sections) and top (above n-th section) formulas $V_t^{(1,\dots,n)} + V_T$ (m^3)	$\Delta V = \lvert V_t^{(1,\dots,n-1)} - V_S^{(1,\dots,n-1)} \rvert$ (m^3)	Deviation $\frac{\Delta V}{\min\left\{V_t^{(1,\dots,n-1)}, V_S^{(1,\dots,n-1)}\right\} + V_t^{(n)}}$ (%)
21 905 334	22 449 334	544 000	2.48

Table 12: Simpson's and trapezoidal total volumes of reservoir, and their difference and deviation – odd number of sections (contact-bottom)

Now, it was possible to calculate the total volume of layered reservoir as a difference between volumes contact/top – contact/bottom (**Table 13**).

e (m)	Layered reservoir, total volume (top-bottom, m^3)
10	103 414 000

Table 13: Total volume of layered reservoir – odd number of sections

5. Conclusions

The understanding of calculation procedure is more important than data quantity. Presented results proved that statement. It is also necessary to understand mathematical backgrounds of given approaches as a base for regular and correct calculations of subsurface structure's volumes. Here are the main recommendations and conclusions derived from presented methods and results:

1. Simpsons's rule is more accurate because it depends on h^4 and error will reach zero faster unlike trapezoidal rule where error depends on h^2. For Simpson's rule, error is zero when f is a polynomial whose degree is at most three, while for a trapezoidal rule error is zero when f is a polynomial of the first degree.
2. Method of calculation depends on the number (more is better) of sections (e.g., **Table 9**), and more – whether such number is even or odd.
3. The new approach is proposed for odd number of sections. Simpson's formula is used till penultimate isopach (even number of parts), and volume of the last section is calculated using the trapezoidal rule. The result is a sum of those two volumes.
4. All volumes need to be increased with a volume of the top, i.e. volume above the last isopach.
5. Different calculations, for the same number of sections, can be relatively compared using the deviation formula.
6. Described approach is valid for using in the case of "symmetrical" structures like anticlines or gently elongated brachianticlines.

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Abstract in Croatian

Preporuke za uporabu Simpsonove i trapezne formule kod izračuna volumena dubinskih struktura

Procjenu volumena geoloških struktura možemo izračunati integriranjem. Kako dubinske strukture najčešće nisu pravilnih oblika ne može se primijeniti analitičko integriranje već se koristi numeričko integriranje, tj. trapezna i Simpsonova formula. Oba pristupa približno određuju volumen ležišta. Ovdje su opisana dva primjera dubinskih struktura, ujedno i ležišta ugljikovodika. To su masivno i slojno ležište. Razlike između volumena dobivenih trapeznom i Simpsonovom formulom uglavnom nisu velike. Veći broj odsječaka u pravilu vodi do manjeg odstupanja između rješenja dobivenih trapeznim i Simpsonovim pravilom. Kod parnoga broja odsječaka preporučena je uporaba Simpsonove formule te one za kapu. Kod njihova neparnoga broja predložen je izračun prema Simpsonovoj formuli za dio volumena koji uključuje *n-1* odsječaka, zatim prema trapeznoj za *n*-ti odsječak, te prema formulama za volumen kape za ostatak iznad toga odsječka.

Ključne riječi: antiklinala, numerička integracija, trapezno pravilo, Simpsonovo pravilo

Authors contribution

Josipa Pavičić (undergraduate student) finished this topic as her bachelor thesis, interpolated maps, using planimeter and make calculations. **Željko Andreić** (Full Professor) supervised mathematical equations and style. **Tomislav Malvić** (Full Professor) and **Josipa Velić** (Prof. Emerita) supervised the geological interpolation, planimeter results and reservoir geology theory. **Rajna Rajić** (Full Professor) supervised mathematical consistency of mathematical part, especially numerical integration formulas.

2nd Croatian congress on geomathematics and geological terminology, 2018

Review scientific paper

Fluid flow in porous carbonates, theoretical and practical considerations

Željko Andreić[1]; Uroš Barudžija[1]; Tomislav Malvić[1]; Josipa Velić[1]; Ivo Velić[2]
[1] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Croatia
[2] Croatian Geological Summer School, Pančićeva 5, Zagreb, Croatia

Abstract
The fluid flow in carbonates represent mainly the flow in non-homogeneous medium. Such rocks are characterised both with primary and secondary porosities, where the second one is often isotropic only in strictly limited volumes of the depositional unit. Here are discussed several examples taken from the carbonate rocks of the Adriatic Carbonate Platform deposits in Croatia, on millimetre scale, well cemented, and partially dissolved and fractured. The distribution and the flow of fluids in such a medium, especially in two-phase liquid system, highly depends on wettability and capillary motion. These values need to be considered for modification of Darcy's Law, i.e. the values of the filtration coefficient and thickness of the sample.

Keywords: carbonates, porosity, Adriatic Carbonate Platform, fluid flow equations, Croatia

1. Introduction

Each sedimentary rock is characterized by total porosity: primary, secondary, or both. The value of such petrophysical variable is defined by their depositional model, grain packing and grain size, and by the processes of deposition, compaction and fracturing as well. As such processes are more or less stochastic, it is hard to quantify them with linear or deterministic models. However, some probability values and general equations can be derived for fluid flows in such rocks. Here we concentrated onto carbonate samples, taken from the rocks belonging to the Mesozoic Adriatic Carbonate Platform deposits from Croatia, i.e. the rocks reflecting dozens of millions years of the geological evolution. The presented model is fundamental to understand how the depositional evolution of Mesozoic carbonates reflects in the total porosity rock model and possible fluid flow in such a medium.

1.1. General observation on theoretical porosity packing model in clastic rocks

The total porosity is the direct consequence of the mineral grains (detritus) in rock. There are two theoretical models that describe how ideally spherical grains can pack – cubic and rhombohedral packing. The cubic packing (**Figure 1.1**) includes the maximal theoretical total porosity, i.e. pore volume. In the nature, it cannot be easily reached, due to several factors, such as real grain shapes (due to weathering), compaction, cementation, fracturing and faulting. Such grain pack is not in the mechanically stable state. Theoretical total porosity for cubic packing is 47 %.

Corresponding author: Uroš Barudžija
uros.barudzija@rgn.hr

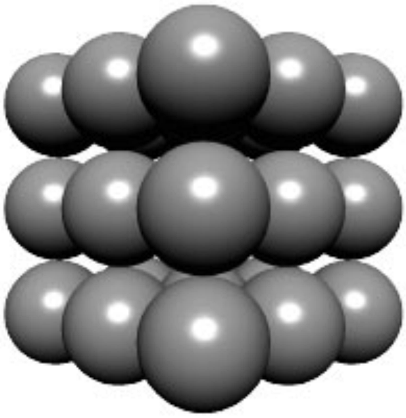

Figure 1.1: Ideal cubic packing of mineral grains (taken from Velić et al., 2015a; http://www.glossary.oilfield.slb.com/Terms/c/cubic_packing.aspx , accessed 3. 6. 2018)

Rhombohedral packing (**Figure 1.2**) is more compact. As a consequence, maximal total porosity for rhombohedral packing is lower than in the cubic model, and it is 26 %. Mechanically, rhombohedral packing is more stable and it is more often found in the natural depositional environments, but having lower total porosity, due to the presence of fine detritus (clay and silt particles) and due to the cementation of the pores.

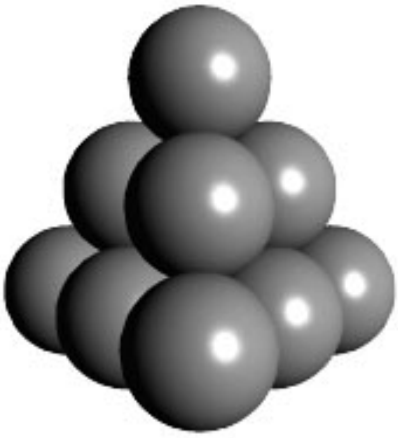

Figure 1.2: Ideal rhombohedral packing of mineral grains (taken from Velić et al., 2015a; http://www.glossary.oilfield.slb.com/Terms/r/rhombohedral_packing.aspx , accessed 3. 6. 2018)

The compaction is the second important variable responsible for the decrease of total porosity. Such process continuously is active during consolidation and burial of clastics, due to lithostatic pressure. Mathematical relation between the depth and the total porosity of sandstones in the Northern Croatia Neogene subsurface deposits is established by Malvić et al (2005). Statistical analysis of the data from the Velika Ciglena syncline showed that the present-day difference in the sandstone units of the same lithostratigraphic member more than 500 m can clearly explain the decrease of total porosity. The similar effects are observed in the Galovac-Pavljani anticline, also in the Bjelovar Subdepression.

1.2. General observations on the lithostratigraphy of the Southern Croatia (dominated by carbonates)

The lithostratigraphy of the Adriatic Carbonate Platform (the Southern Croatia) had been summarized, for the first time, in Velić et al. (2015b; **Figure 1.3**) and Malvić et al. (2015; **Figures 1.4** and **1.5**). It included entire pre-Mesozoic, Mesozoic and post-Mesozoic, mainly carbonate sequences, as well as Cenozoic clastic rocks and deposits. In pre-Mesozoic, Mesozoic and partly in post-Mesozoic sequences, the thick carbonate succession predominate. In the rocks from Carboniferous to Miocene, four megasequences have been identified: (i) a pre-platform succession, ranging in age from Late Carboniferous (Middle Pennsylvanian) to Early Jurassic (Early Toarcian; **Brušane** and **Baške Oštarije Formations**); (ii) an Early Jurassic to Late Cretaceous platform megasequence (**Mali Alan Formation**); (iii) a Paleogene to Neogene post-platform megasequence (**Raša Formation**); and (iv) a Neogene to Quaternary (Pliocene to Holocene) megasequence (**Istra** and **Ivana Formations**).

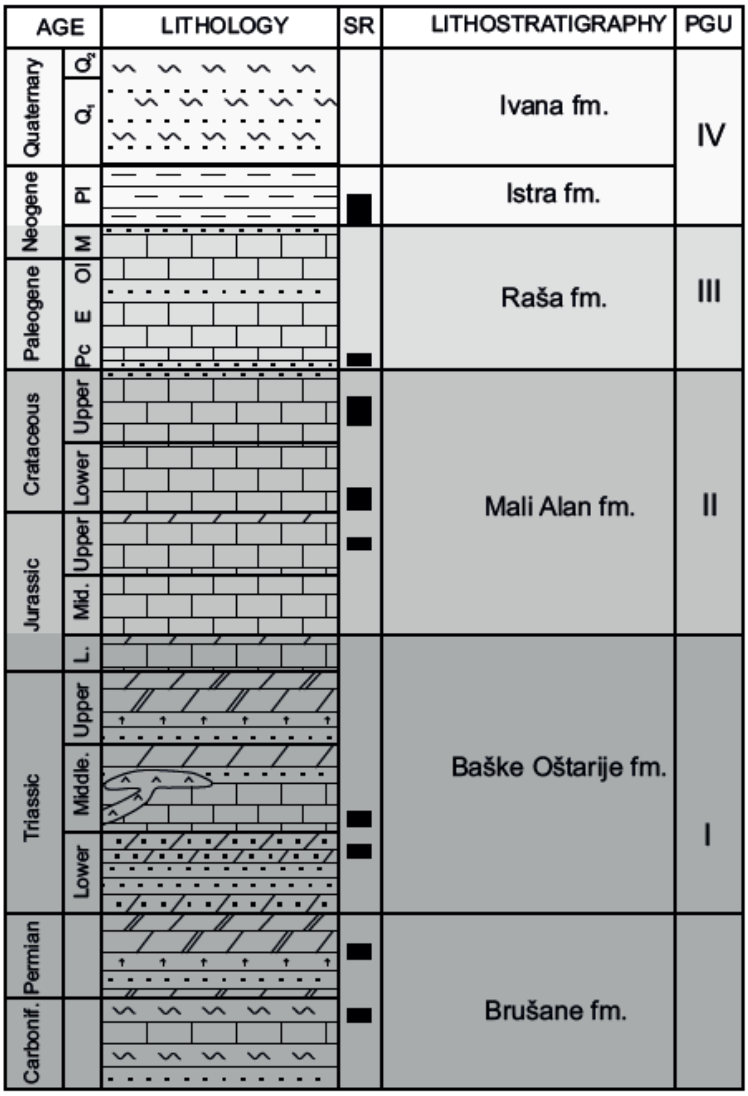

Figure 1.3: Generalised stratigraphic column for the Croatian part of the Adriatic Basin with formations, potential source rock intervals and petroleum geological units, as defined in Velić et al. (2015b)

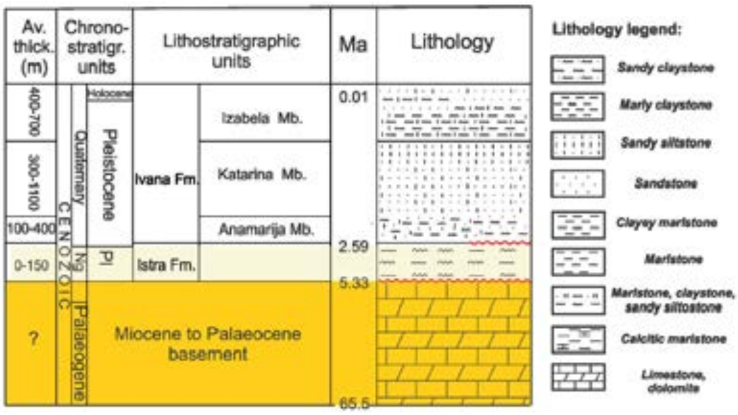

Figure 1.4: Lithostratigraphic division (formations and members) of the Pliocene, Pleistocene and Holocene sediments in the Croatian part of the Po Depression (Malvić et al., 2015b)

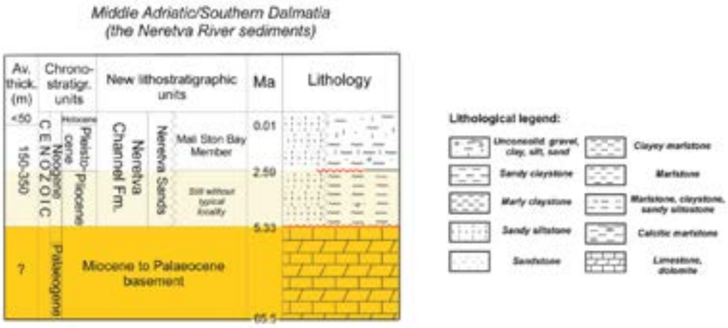

Figure 1.5: Lithostratigraphic division (formations and members) in the shallow offshore sea in Southern Dalmatia - Neretva and Korčula Channels (Malvić et al., 2015b)

2. Basics about analysed carbonate samples

Three representative limestone samples have been micropetrographically analysed. The sample BGuč-3B (**Figure 2.1)** represent ooid grainstone type of shallow-water marine limestone (classification after Dunham, 1962; suitable for the macroscopic determination of limestones), or as the oosparitic type of shallow-water marine limestone (classification after Folk, 1959, 1962; suitable for the microscopic determination of limestones). Mosaic calcite cement (**Figure 2.1 -** orange areas, between dark ooids) binds carbonate grains together, and pores can be only locally observed within the cement (**Figure 2.1** small white areas – not to be mistaken with the large white gap, originated while thin-section has been prepared!). Limestone belongs to the oldest Middle Jurassic deposits of the Biokovo Mt., and the sample is taken from the thick-bedded ooid grainstone, having occasional sections with index foraminifera species *Gutnicella cayeuxi* (LUCAS). These limestones are deposited in the subtidal environments, where the ooids had been flooded by storm tides and waves from the marginal ooid bank.

The sample JB-3B (**Figure 2.2)** represents pelletal (Favreina sp.) packstone type of shallow-water limestone (classification after Dunham, 1962) or pelmicritic type of limestone (classification after Folk, 1959, 1962), which is partly recrystallized during diagenesis. These fecal pellets, carbonate grains produced by crustacean decapods, indicates calm, subtidal environment, with the low water energy and rapid lithification of a carbonate mud.

Sample Jb-5 (**Figure 2.3)** represent fenestral micritic limestone. The pores (white areas in figure **Figure 2.3**) are partly filled with calcite cement (the contrast of microphotograph is not optimal to clearly observe crystal boundaries within cement!). The sample indicates shallowing of the sea, from the subtidal marine environment (lagoon) into intertidal (changing flood and ebb zone) and supratidal (emerging zone).

Lab tests were not performed in this sample analyses, i.e. they are solely micropetrographically analysed. For sure, such tests would largely improve researching results, so it is planned in future. But, common for all samples is that they are taken from surface or very shallow outcrops.

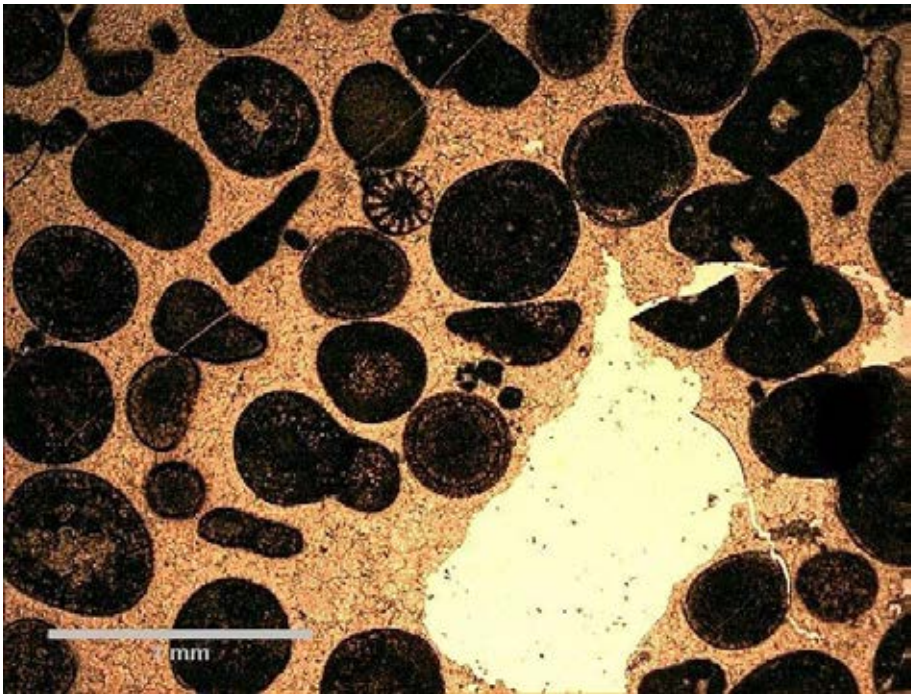

Figure 2.1: BGuč-35, ooid grainstone, Middle Jurassic, Biokovo Mt. (Southern Croatia)

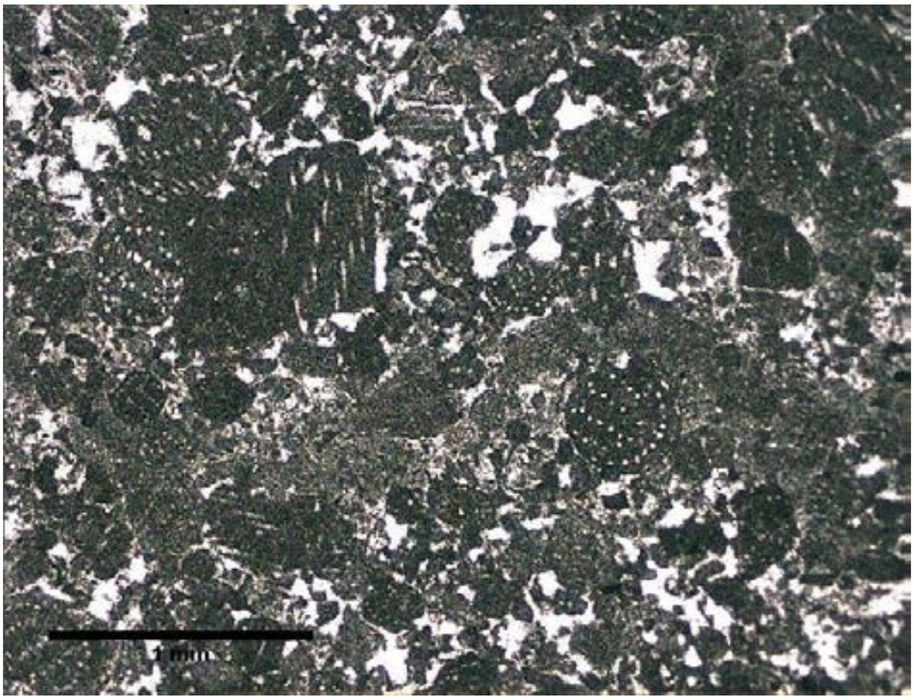

Figure 2.2: JB-3B, pelletal packstone, Lower Cretaceous (Valanginian), Baredine Cave (Istria)

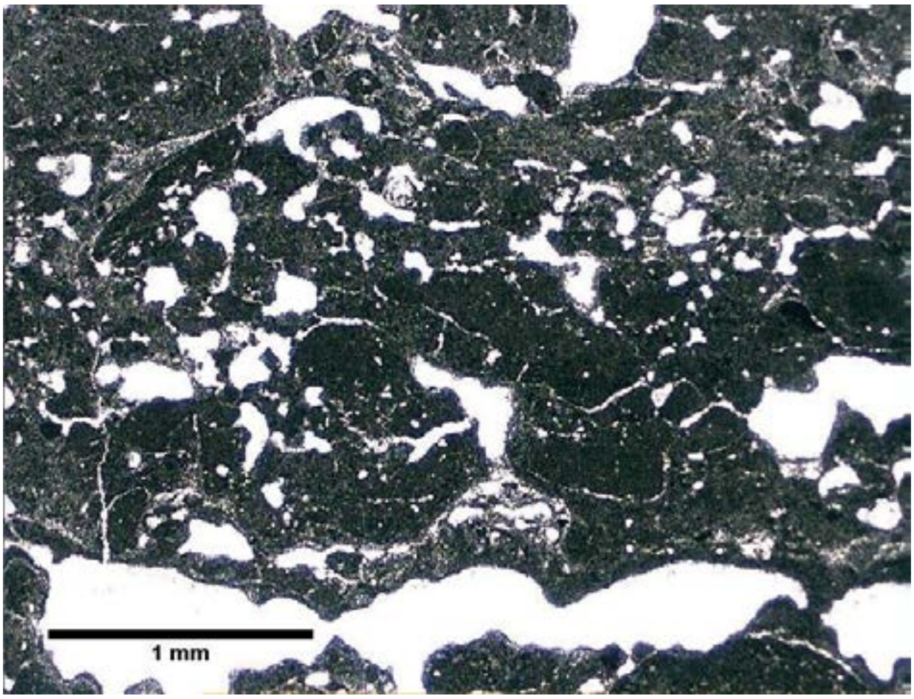

Figure 2.3: JB-5, fenestral mudstone, Lower Cretaceous (Valanginian), Baredine Cave (Istria)

3. Mathematical equations for fluid flow in carbonates with secondary porosity

Traditionally, total porosity is described with porosity coefficient (sometimes simply: porosity). which is defined (**Equation 3.1**) as the ratio of a total volume of pores and a total volume of the rock:

$$k = \frac{V_p}{V} \quad \text{Eq. 3.1}$$

Where:
k - is the porosity coefficient,
V_p - is a total pore volume in a given sample and
V - is the total volume of the sample.

Obviously, $0<k<1$, with $k=0$ implying solid (impermeable) rock and $k=1$ representing empty space. It is named as primary porosity, as it represents the main porosity present in a solid material. If, through time and under influence of some outside factors, the porosity is altered (for instance by compacting the material or by chemically bleaching some part of it via diagenetic processes), it is named as the secondary porosity (**Figure 3.1**). It can be shown that for a homogenous material, the volume ratios equal area ratios obtained from the cut-through of the sample, providing another way of measuring porosity of such materials.

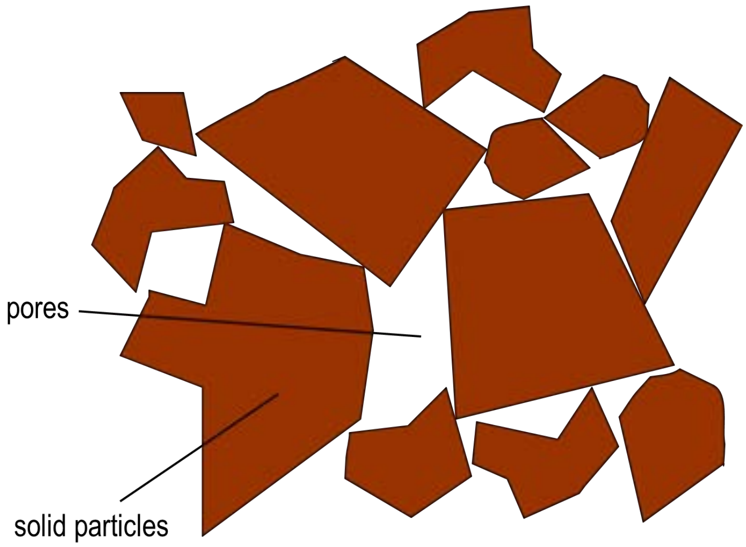

Figure 3.1: A cut-through of a porous material

If material is fully saturated with some liquid and individual pores are small, the flow of liquid experiences large resistance, dominated by forces at the liquid-solid boundaries, and is thus laminar in nature. If the fluid is Newtonian, the Bernoulli equation can be used and is reduced to a simpler form called Darcy law (**Equation 3.2**):

$$v_d = k\frac{\Delta h}{l} \qquad \text{Eq. 3.2}$$

Where:

v_d - is the apparent flow velocity (Darcy's velocity) which fluid would have if flowing through the whole volume of the sample (meaning that the actual velocities in pores are much larger),

k - is the coefficient of filtration (which is proportional, but not equal to the porosity coefficient),

Δh - is the change in the energy of the fluid (in units of height) and l is the thickness of the sample. The coefficient of filtration is usually determined experimentally as it is very difficult to obtain otherwise.

Modern research is concentrated on modelling porous materials and calculating the fluid flow through them, using either Darcy law or some different set of flow properties. So far, no general model that can be successfully applied to real situations is produced, illustrating the intricacies and complexity of fluid flow through a porous medium.

3.1. Wettability

There are several rock and fluid properties (and forces) that mutually interact inside rock pore volume. Here are selected two of them as probably the most important for defining fluid saturation and flow.

The wettability (or wetting) is property of a liquid to maintain contact with a solid surface, resulting from intermolecular interactions at their contact. The degree of wetting (wettability) is determined by a force balance between adhesive and cohesive forces, e.g., for system oil-water in rock pores (**Equation 3.3a, b, c**).

$$A_T = \sigma_{SO} - \sigma_{SW} \qquad \text{Eq. 3.3a}$$

$$\cos ⟦\theta_{WO}⟧ = (\sigma_{SO} - \sigma_{SW})/\sigma_{WO} \qquad \text{Eq. 3.3b}$$

$$A_T = \sigma_{WO} x \cos\theta_{WO} \qquad \text{Eq. 3.3c}$$

Where are:

A_T - adhesion/surface tension;
σ_{SO} - surface tension between solid/rock and oil;
σ_{SW} - surface tension between solid/rock and water;
σ_{WO} - surface tension between water and oil;
θ_{WO} - wetting angle between water and oil (calculate from denser toward lighter fluid).

3.2. Capillary action

Capillary action (sometimes capillarity, capillary motion, capillary effect, or wicking) is the ability of a liquid to flow in narrow spaces without the assistance of, or even in opposition to, external forces like gravity. The effect can be seen in porous materials, and occurs because of intermolecular forces between the liquid and surrounding solid surfaces. If the diameter of the pore is sufficiently small, then the combination of surface tension in liquid and adhesive forces between the liquid and solid wall migrate fluid upward (wetting) or downward (non-wetting). See **Figure 3.2**.

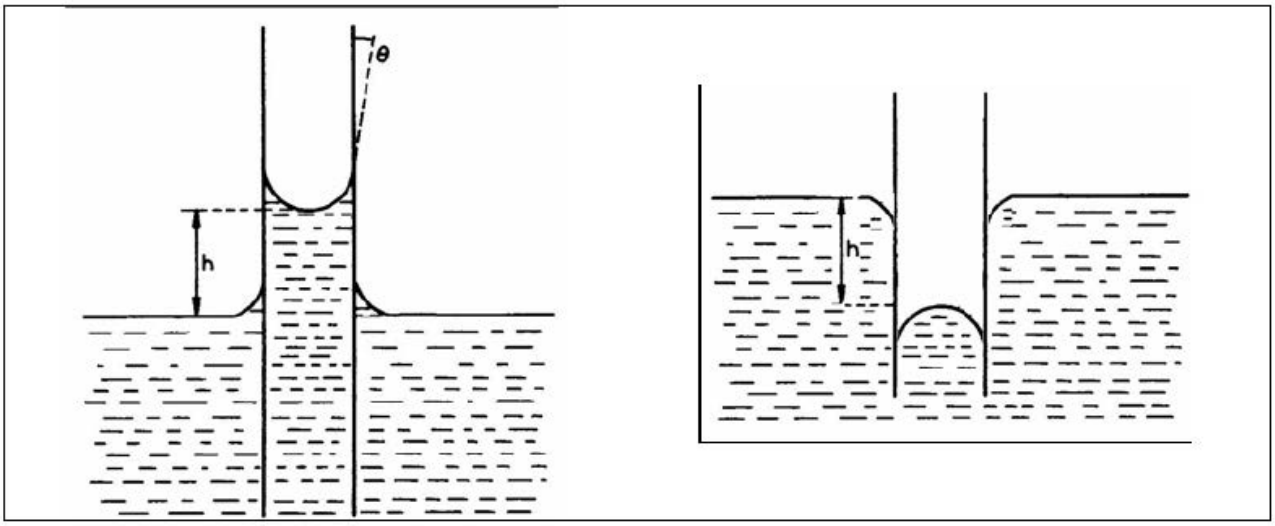

Figure 3.2: Capillary motion upward (left, wetting phase, e.g., water) and downward (right, non- wetting phase, e.g., oil). Taken from Malvić and Velić (2008).

Capillary action/pressure is inversely proportional to pore diameter, and proportional to surface tension (**Figure 3.3**). So, in fine grained rocks, like fine-grained sandstones, siltstone, especially claystone, capillary pressure is higher and, consequently, permeability lower or non-existent, especially for non-wetting fluid.

However capillary pressure plays important role also in porous, reservoir rocks, like sandstones or carbonates. Due to low capillary motion, permeability in reservoirs is high, and primarily such rocks are saturated with water. When secondary migration brought hydrocarbons (especially oil) in such rock volume, new reservoir would be formed with completely gravitational exchange of fluid. The upper part of the reservoir would be completely saturated with hydrocarbons (oil), lower part with water, and contact would be just line (sharp). However, capillary pressure, together with wettability, is reason that reservoir also included some percentage of water and contact between fluid is never sharp, but zone with gradually distributed saturation of hydrocarbons and water. As a consequence, saturations in reservoir is a result of the capillary-gravitational equilibrium (**Equation 3.4**):

$$p_C = h \cdot (\rho_W - \rho_{NW}) \cdot g \qquad \text{Eq. 3.4}$$

Where are:

p_C - capillary pressure;

h - height above level with water saturation of 100 %;
ρ_W - density of wetting phase;
ρ_W - density of non-wetting phase;
g - gravity.

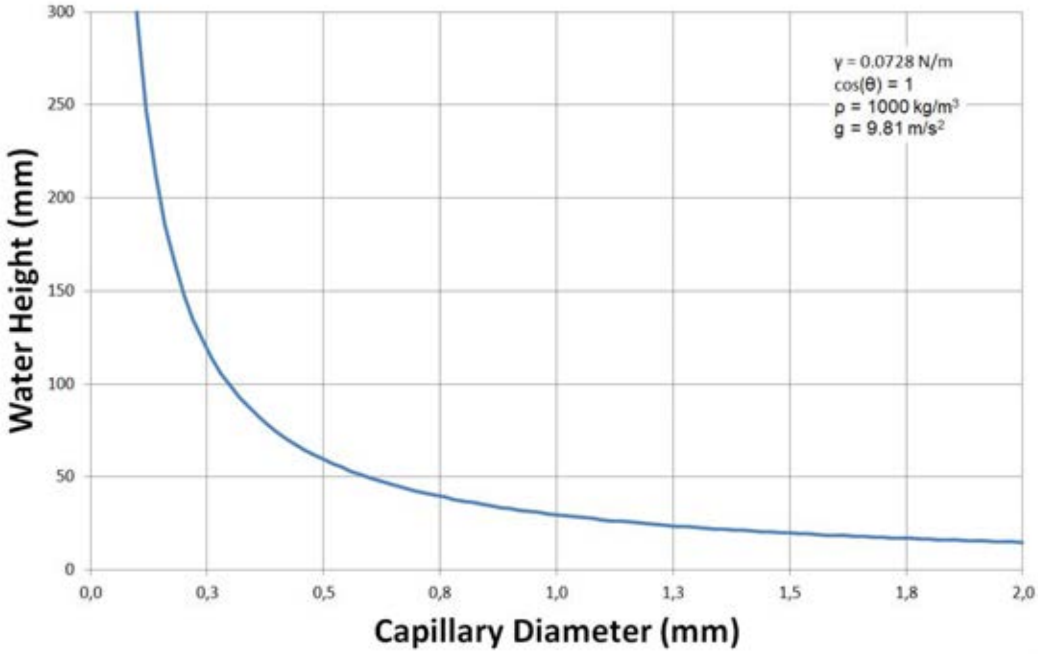

Figure 3.3: Capillary diameter vs. water column height. Taken from https://en.wikipedia.org/wiki/Capillary_action (9 June 2018).

3.4. Wettability and capillarity in the case of two fluids (oil and water)

If adhesion/surface tension A_T>0 (θ_{WO}<90°) denser fluid (water) will better wetting solid. If A_T<0 lighter fluid (oil) will do the same. And in the case A_T=0 both fluids would have the same wettability. Wettability of water is higher than from oil (**Figure 3.4**). However, in some carbonate reservoirs when oil has high portion of asphaltenes, it can be inverted, and instead of bounded water, part of oil will be permanently bounded over the detritus.

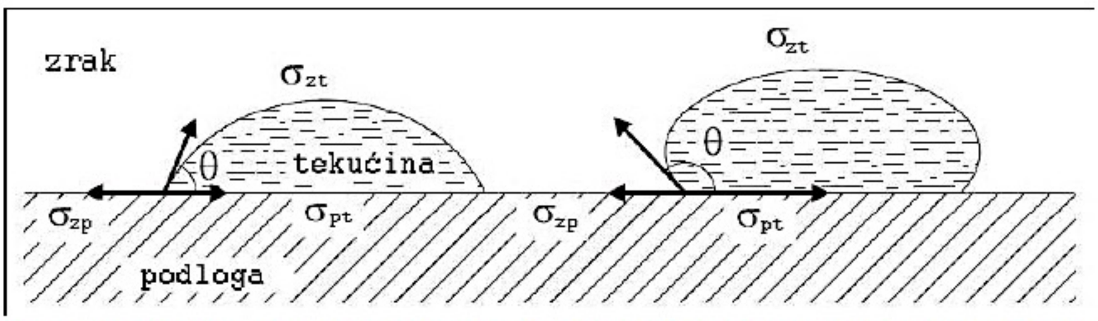

Figure 3.4: Wetting fluid (left) and non-wetting fluid (right) on the solid base (σ_{zt} - surface tension air-fluid, σ_{zp}- surface tension air-solid, σ_{pt} – surface tension solid – fluid). Taken from Malvić and Velić (2008).

4. Discussion and conclusion

Fluid flow in carbonates is never uniform, and depends on several factors. Geologically, carbonates are often characterised with secondary porosity originate from different factors, like dissolving, fracturing, faulting or cementation. No one will not result in homogeneous alteration. Consequently, carbonate porosity cannot be described with homogeneous model, i.e., in the best case, it can be extrapolated as isotropic, encompassing only part of volume of single depositional unit. There are two other unfavourable factors in carbonate reservoirs are object of consideration. The first one is wettability, which sometime can favour oil as wetting phase. The second is relatively small primary (depositional) porosity, reflected in smaller effective porosity, high portion of bounded water and large capillary motion.

In fact, some secondary permeability can have included significant parts of analysed carbonate, although the entire depositional unit is characterised with very low, mostly matrix porosity (e.g., Russel-Houston et al., 2013). But such cases are hard to described (here by fractal nature) and are mostly unique model. Also, migration of fluids can be observed in the early phase of the deposit diagenesis, e.g., during the process of dolomitization. For one such single-phase case for hydrologic simulation on carbonate platform had been done by Kaufman (1994). Such model consisted from platform-reef complex surrounded by basinal shale and showed that "most pore fluids in the shale migrated to the surface at velocities less than 0.1 mm/yr and basin-derived fluids are focused into the reef from only a limited distance of 10 km.".

Considering analysed samples and their total porosity (consequently effective as well as permeability) there are two unfavourable factors in carbonates. Those are simple cementation (including dissolving) and dolomitization. Both will decrease total porosity and connected variables, but both need to be analysed separately at each location/outcrop where sample(s) from particular lithostratigraphic and chronostratigraphic unit of the Adriatic Carbonate Platform (the AdCP) has been taken. Generally, total porosity in typical carbonates of the AdCP varies from few to more than ten percentages. Based on lab, e-log and other analyses such values can be reliable estimated from enough number of samples. Results can be compared with different graphs, e.g., published in Lucia (1995), and together with detritus size and type, selected into kinds of different packstones.

All of these facts define the carbonates as rocks with relative small permeability (absolute and relative), and strictly limited volumes available for fluid flow. So, the problems can be solved if Darcy equation is applied (variable "l") only on geological defined flow units and coefficient of filtration (variable "k") in the law be defined taking into account primary and secondary porosity, cementation rate, wettability of fluids and capillarity.

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Abstract in Croatian

Protok fluida u šupljikavim karbonatnim stijenama, teorijska i praktična razmatranja

Protok fluida u karbonatnim stijenama nije moguće opisati homogenim protokom. Razlog tomu je što takve stijene najčešće uključuje obje vrste šupljikavosti – prvotnu i drugotnu, a ova druga se može opisati izotropnom razdiobom samo u ograničenom (i malome) volumenu promatrane stijene. U radu je opisano nekoliko uzoraka karbonatnih stijena prikupljenih u prostoru Jadranske karbonatne platforme (Hrvatska). Njihove dimenzije su opisane milimetarskim mjerilom, a obilježava ih jaka cementacija te djelomično otapanje i raspucanost. Protok i raspodjela fluida u takvom stijenskom prostoru, posebice u dvofaznim slučajevima, snažno ovisi o močivosti i kapilarnim silama. Stoga se te sile moraju uzeti u obzir kada se protok opisuje Darcyjevim zakonom, tj. kod izračuna vrijednosti koeficijenta filtracije i debljine uzorka.

Ključne riječi: karbonati, šupljikavost, Jadranska karbonatna platforma, jednadžbe protoka fluida, Hrvatska

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Authors contribution

Željko Andreić (Full Prof.) provided the basics of Darcy law. **Uroš Barudžija** (Assist. Prof.) made sections photos and described origin and types of the samples. **Tomislav Malvić** (Full Prof.) made reviews of wettability and capillary motion equations and selected lithostratigraphic sections. **Josipa Velić** (Prof. Emerita) and **Ivo Velić** (Senior Scientist) performed the field work, collected and prepared rock samples, described depositional environments and geological evolution, and selected lithostratigraphic sections.

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Original scientific paper

Determination of soil and groundwater contamination resulting from the hydrocarbon exploitation activity

Karolina Novak Mavar[1]; Ivana Kapustić Pavić[2]
[1] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Croatia
[2] INA-Oil Industry Plc., Croatia

Abstract

In order to create the basis for systematic environmental monitoring and eventual remediation procedures, at sites potentially contaminated by different activities, qualitative and quantitative determination of soil and groundwater contamination status must be carried out. Although European Union has not regulated the area of soil protection by a separate directive so far, the requirements for protection of this environmental component are set in other regulations, in particular the *Directive 2004/35/EC on environmental liability with regard to the prevention and remedying of environmental damage* and the *Directive 2010/75/EU on industrial emissions*. Mentioned acts clearly define the activities which can cause environmental damage and therefore are responsible for prevention measures application and remediation. Given that Croatian regulation prescribes only the methodology for monitoring soil quality of agricultural land, underground contamination analysis described in this paper represents an example of pollution risk assessment at sites that do not meet the agricultural land standards. The selected site is connected with oil and gas production activities for many years. On the basis of conclusions of field research carried out by authorized company, involving soil and water sampling and laboratory analyses, and in order to help to obtain a clearer picture of pedosphere status and to make the conclusions regarding further monitoring, the maps of spatial distribution of pollutants are done in this paper.

Keywords: soil and underground water contamination, hydrocarbon exploitation, Nearest Neighbour method.

1. Introduction

Soil is the surface part of the Earth's crust, located between the lithosphere and the atmosphere. From the constructional point of view, it is about a natural mixture of mineral grains, i.e. unconsolidated set of solid particles of mineral and organic origin (**Maksimović, 2005**). Furthermore, the agronomic aspect defines the soil as a thin layer of lithosphere that supplies the plants with water and other essential substances, while pedochemistry considers the soil as a constituent of solid particles of organic and inorganic origin, water, air, and microorganisms, derived from the source rocks under the influence of pedogenic factors, through a series of processes.

Existence of numerous definitions indicates multifunctional character of soil. In addition to its primary role, i.e the production of organic matter in the photosynthesis process, there are some other important roles, such as the ecological-regulatory role, since the soil is a natural purifier and buffer due to filtering precipitation water, and binding pollutants by colloidal complex. Soil significantly affects the content and total amount of CO_2 in the atmosphere, and has the spatial role, representing the basis for urban expansion and integral element in the landscape design (**Bašić, 1994**).

The soil solid phase may refer to organic and mineral fraction. The organic fraction consists of roots and humic compounds (dead plant material in decomposition stages) which is important in the electrostatic adsorption of cations, water bonding, and the coherence of soil particles, i.e. it represents the main reactive phase for organic compounds (e.g. pesticides, oil). The soil mineral fraction contains quartz, other oxides, and clay minerals. The soil microbial biomass consist of many microorganisms which participate in oxidising plant and animal residues what results with generation of plants nutrients (**Bobić, 2005**).

Corresponding author: Karolina Novak Mavar
karolina.novak-mavar@oblak.rgn.hr

1.1. Environmental protection as a legal requirement

Soil is considered almost non-renewable natural resource, due to limited natural distribution, but also due to the fact that for generation of 1 cm of this resource more than a thousand years are needed. However, despite the fact that environmental protection has become an integral part of sustainable development of European society, and therefore it is present in the businesses that have some impact on the environment, systematic soil protection in the European Union is still missing.

Although some EU member states (e.g. Germany, Denmark, the Netherlands) have clearly set the standards for soil protection, most of the countries still have not. Namely, the *Thematic Strategy on Soil Protection in the EU* was adopted in 2006, but the adoption of soil protection related directive, which proposal is repeatedly considered, has not been achieved yet. Thus, certain provisions regarding soil management and protection can be found within the legal acts regulating other areas, in particular the *Directive 2004/35 /EC on environmental liability with regard to the prevention and remedying of environmental damage* and the *Directive 2010/75/EU on industrial emissions*, but also the *Directive 2008/98/EC on waste*, the *Directive 2000/60/EC on water* and the whole set of directives regulating dangerous substances in groundwater and the environment.

Mentioned EU regulation has been transposed into the legal order of the Republic of Croatia in a way that the *Environmental Protection Act (OG 80/13, 153/13, 78/15)* obliges legal entities (environmental polluters) to apply prevention measures, remediation activities, and environmental monitoring. Then, the *Regulation on Environmental Permit (OG 8/14, 5/18)* establishes industrial activities in Croatia that could cause soil, air and water pollution. Integrated pollution protection conditions are set, and for the purpose of carrying out remediation, a baseline study before the start of operation and after facility closure has to be done.

However, in Croatia, as it is the case in most of the EU countries, there is no statutory obligation to identify contaminated and potentially contaminated sites out of the system of environmental permits. As far as pollutants and threshold limits are concerned, Croatian regulation considers only the category of agricultural land through the *Agricultural Land Act (OG 20/18*) and the *Ordinance on the Protection of Agricultural Land from Pollution of Harmful Substances (OG 9 /14).* Therefore it is quite impossible to do systematically monitoring of the polluted land used for other purposes.

According to the *Agricultural Land Act (OG 20/18)* soil degradation means following: degradation in intensive production (physical, chemical and biological characteristics) (a), contamination of harmful substances and organisms (heavy metals, potentially toxic elements, pesticides, organic pollutants and pathogenic organisms) (b), displacement (water and wind erosion, crop rotation, storage space, waste or other soil cover) (c), and transformation (urban areas, industrial and energy facilities, roads, hydro accumulation and exploitation) (d). The *Ordinance on the Protection of Agricultural Land from Pollution Damag*e *(OG 9/14)* defines sources of pollution as follows: industrial production and services, industrial waste, urban waste, oil industry, mining, power plants, warehouses, military activity, transportation, incidents.

In Croatia, in the period from 2006 to 2008, a project entitled *Development of the Croatian Soil Monitoring Program with pilot project (LIFE05 TCY / CRO / 000105)* was carried out by the *Croatian Environment Agency* and *Faculty of Agriculture, University of Zagreb*. The project resulted in the *Program of Permanent Monitoring of Polluted Soils in Croatia* (**AZO, 2008**) which predicted polluted areas permanent soil monitoring for the sites selected according to the site activity. The program stated the need for the adoption of the *Regulation on the permanent monitoring of the Croatian soi*l, but so far only the *Ordinance on the methodology for monitoring the state of agricultural land (OG 43/14)* has been in force.

Croatian water quality standards are defined by the *Regulation on Water Quality Standards (OG 73/13, 151/14, 78/15, 61/16)*, while the quality of waste water is given through the *Ordinance on Limits of Waste Water Emissions (OG 80/13, 43/14, 27/15, 3/16).*

1.2. Hydrocarbon contamination

According to the *European Environment Agency (EEA)*, the EU has identified about 2.5 million sites potentially contaminated by various activities, such as mineral resources exploitation, electricity generation, waste management, transportation, military activity etc. Remediation necessity has been assigned for 14% of identified locations (https://www.eea.europa.eu/highlights/soil-contamination-widespread-in-europe).

Hydrocarbon contamination can be observed as Petroleum Hydrocarbons (PHC) and Total Petroleum Hydrocarbons (TPH). While the PHCs originate from crude oil, the TPHs refer to all hydrocarbons in the soil that can originate from crude oil and all derivatives.

Soil contamination with crude oil depends on crude oil composition. Crude oil consists of various hydrocarbons: saturated hydrocarbons, including alkanes (paraffins) and cycloalkanes (cycloparaffins or naphthenes) and aromatic hydrocarbons. One-ring aromatic compounds are referred to as BTEX (benzene, toluene, ethylbenzene and xylene). Alkanes are present at high concentrations, while naphthenes and aromatics are less represented. In the composition of the oil there are also non-hydrogen components: sulphur compounds (hydrogen sulphide, mercaptan (thiols), sulphides, disulphides, and thiophene), nitrogen and oxygen compounds, as well as heavy metals (V, Ni, Fe, Mo, Cu, Si, Al, Zn) (**Wang et al., 2017**).

Hydrocarbons penetrate rapidly into the ground, forming an impermeable film on the surface that prevents the flow of water and the normal exchange of gases with the atmosphere or with the gaseous phase of the soil, leading to the drying of the plant roots. By increasing the hydrocarbon content in the soil, the microbiological property is changed. Increased number of anaerobic bacteria leads to soil redox potential decreasing and gradual reduction of certain compounds (iron, manganese, sulphur, etc.), and imbalance in C:N ratio causing plant nutrition disturbance (**Kisić et al 2009**).

However, substances accumulated in the soil are exposed to biodegradation, transformation and synthesis into new compounds (finally to CO_2 and water). In this way all organic pollutants, such as *Polycyclic aromatic hydrocarbon s* (PAHs), pesticides and petrochemicals can be eliminated (**Bašić, 2015**). Biodegradation in soil depends on different factors, such as: lack of nutrients (lack of C, N, P, K, S and trace elements can decrease pollutant degradation), aerobic/anaerobic conditions (for most of pollutants aerobic conditions are required), water content (certain moisture level is needed for biodegradation), soil texture and structure, pH (acidic conditions are not suitable for most bacteria), temperature, other toxic compounds (their presence can inhibit the activity of the microorganisms), and solubility (soluble pollutant is available to the microflora) (**Bobić, 2005**).

It is indisputable that the soil plays important role of pollutants collector, but if their presence reach certain level, soil becomes pollution emission source, threatening water and all types of ecosystems.

2. Investigation on site pollution

Underground pollution investigation was done by authorized company during the years 2014, 2015 and 2016. Such investigation is usually conducted through information gathering, data analysis, and reporting. Preliminary research is the first phase aiming at determination of pollution risk by identifying potential sources of contamination and environmental receptors (soil, groundwater). The second phase refers to detailed investigation performed in case that preliminary investigation indicated some contamination. It includes sampling and analysis of soil and groundwater. To get a clear picture of pollution level it is important to know the history of site using, as well as topographic, geological and hydrogeological conditions.

The selected site, which can serve as an example of potential pollution investigation, is used for the temporary disposal and regeneration of technological fluids generated in technological processes such as drilling, overhaul activities, oil and gas production and transportation. The fluid is supplied by tankers and temporarily disposed into facility provided for this purpose. After gravity separation the lighter hydrocarbons are returned to the process (into dehydration), while the residual (dense) phase is submitted to an authorized legal entity or washed with warm water and dehydrating agents, and after passing the solidification process (mixing with sand, lime and various absorbers), as a stable phase, handed over to authorized company.

The facility in a form of pit (5000 m^3) is located on a gentle sloping ground. Its northern part is slightly buried, while the southern part is located at the ground level. Around the facility, an impermeable, clayey-dusty embankment is constructed. The bottom of the pit is constructed as a combination of sealing foil and gravel layer, thus achieving isolation from the environment. The soil is composed of low permeable (10^{-7} - 10^{-8} m/s) dusty-clayey-sandy material, with vertical and lateral variation of individual shares in composition.

Site investigation, carried out in 2014, included ground penetration at 6 locations surrounding the facility (P1, P-2, P-3, P-4, P-5 and P-6 wells, well depth was 10 m, drill hole diameter was 125 mm), and installation of permanent piezometers for monitoring purposes (at P-1, P -3, P-5 and P-6). Soil sampling was done by taking 1 sample per meter of drilling. In case of observed contamination it was necessary to take another sample on the same meter. Groundwater samples were taken out when entering the groundwater layer. Laboratory analyses, which included the parameters, as shown in **Table 1,** were done by accredited laboratory.

Table 1: Soil and groundwater analysis parameters

Soil analysis	Groundwater analysis
• TPH • PHC • Total BTEX • Individual BTEX • Heavy metals (Pb, Hg, Cd, Cr, Ni, Zn, Cu)	• pH • Colour, smell • Biochemical Oxygen Demand (BOD) • Chemical Oxygen Demand (COD) • Heavy metals (Cr, Cd, Hg, Pb) • PHC • Total BTEX • Individual BTEX

The results of laboratory analyses were compared with maximum permissible concentrations for individual pollutants (thresholds limits). Since, as stated before, the Croatian national regulation set groundwater contamination criteria only for agricultural land, the guidelines of the Dutch *Ministry of Housing, Spatial Planning and the Environment* (*Soil Remediation Circular 2009*) were applied. Depending on the spatial use of the soil, the guidelines prescribe the optimum concentrations level (concentration of certain pollutants which has minor environmental impacts) and intervention concentration level (a value indicating the need for rehabilitation).

The *Regulation on Water Quality Standards (OG 73/13, 151/14, 78/15, 61/16)* provides permitted concentrations of certain pollutants (Pb: 10 µg /l, Cd: 5 µg /l, Hg: 1 µg /l). However, the regulation does not provide values for Cr, so the generally accepted "Dutch standards" are also used to determine the level of groundwater contamination with Cr and petroleum hydrocarbon compounds. The analysis of the results included the criteria set out in the *Ordinance on Limits of Wastewater Emissions (OG 80/13, 43/14, 27/15, 3/16)*.

3. Testing results

Laboratory analyses carried out in 2014 showed concentrations of all examined parameters under permissible level, while increased groundwater content of heavy metals (Pb, Cd and Cr) was detected at four piezometers (P-1, P-3, P-5 and P-6). The analyses showed no increases in TPH and PHC concentrations.

The piezometers with increased concentrations of pollutants (P-1, P-3, P-5 and P-6) were included in the monitoring during 2015 and 2016 by testing the concentration of pollutants in groundwater samples during one hydrological year, i.e. considering the high and low water table (**Table 2**, **Figures 1-4**).

Table 2: Determined concentrations of certain pollutants in groundwater

Piezometers	Year of sampling	Cr	Cd	Hg	Pb	PHC	Benzene	Toluene	Ethylbenzene	Xylene	BTEX
		(µg/l)									
P-1	2015	**9.6**	<2.0	<0.2	<4.0	5.45	<2.0	<2.0	<2.0	<2.0	<2.0
	2016	**7.8**	<2.0	<0.2	<4.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
P-3	2015	**6.9**	<2.0	<0.2	<4.0	15.9	<2.0	<2.0	<2.0	<2.0	<2.0
	2016	<1.0	<2.0	<0.2	<4.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
P-5	2015	**5.1**	<2.0	<0.2	<4.0	25.2	<2.0	<2.0	<2.0	<2.0	<2.0
	2016	<1,0	<2.0	<0.2	<4.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
P-6	2015	**16.0**	<2.0	<0.2	4.3	15.6	<2.0	<2.0	<2.0	<2.0	<2.0
	2016	**10.2**	<2.0	<0.2	<4.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
Optimum concentrations		**1.0**	**5.0***	**1.0***	**10.0***	**50.0**	**0.2**	**7.0**	**4.0**	**0.2**	**<2.0**
Intervention concentration		30				**600.0**	**30.0**	**1000.0**	**150.0**	**70.0**	
* *According to Regulation on Water Quality Standards*											

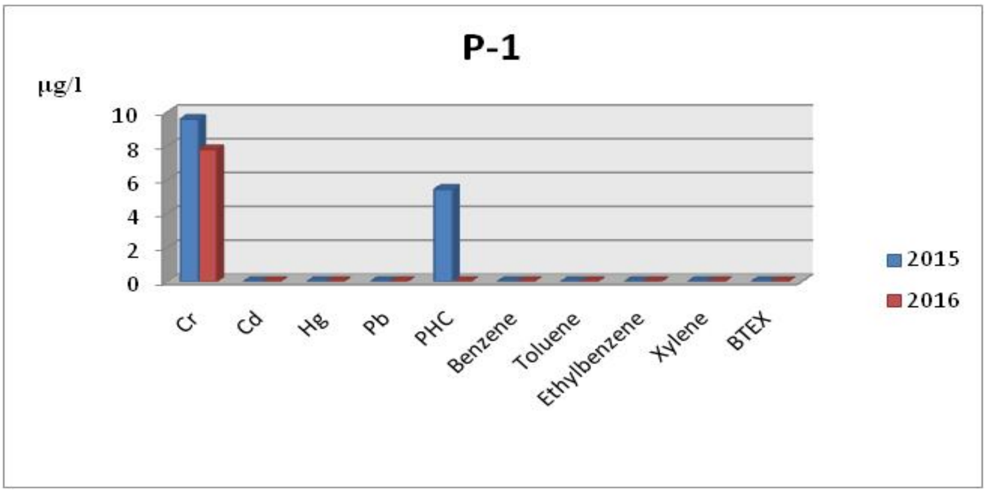


Figure 1: Concentration of groundwater pollutants measured at P-1

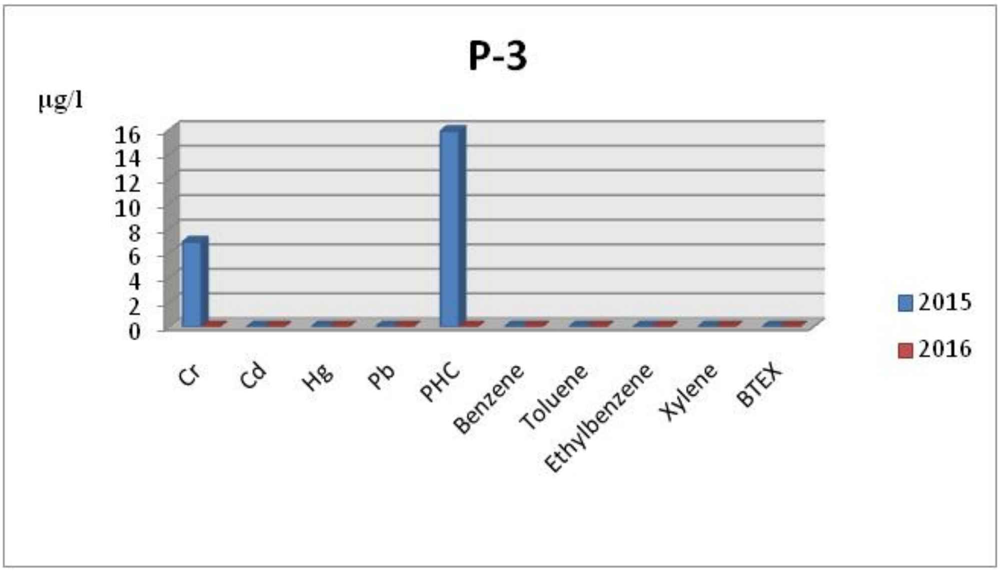


Figure 2: Concentration of groundwater pollutants measured at P-3

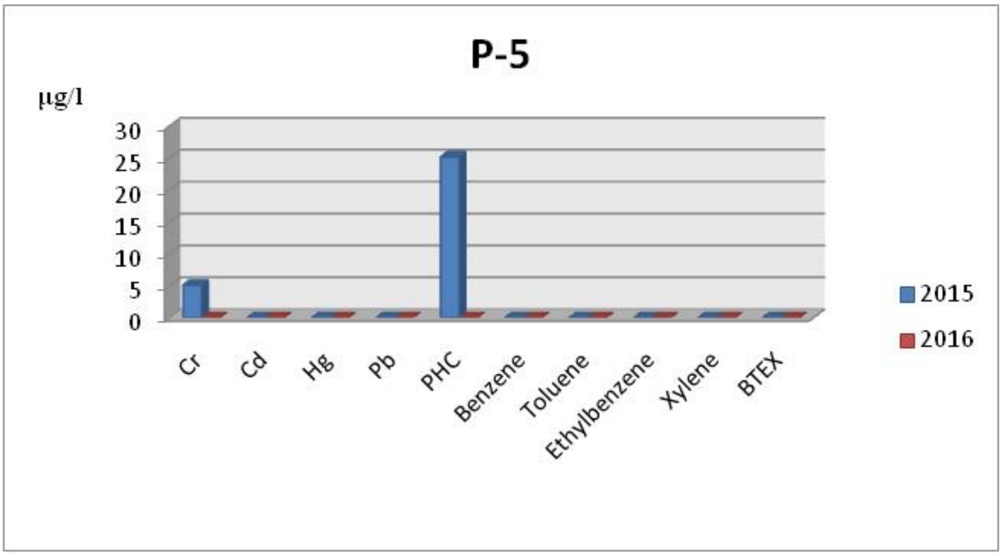


Figure 3: Concentration of groundwater pollutants measured at P-5

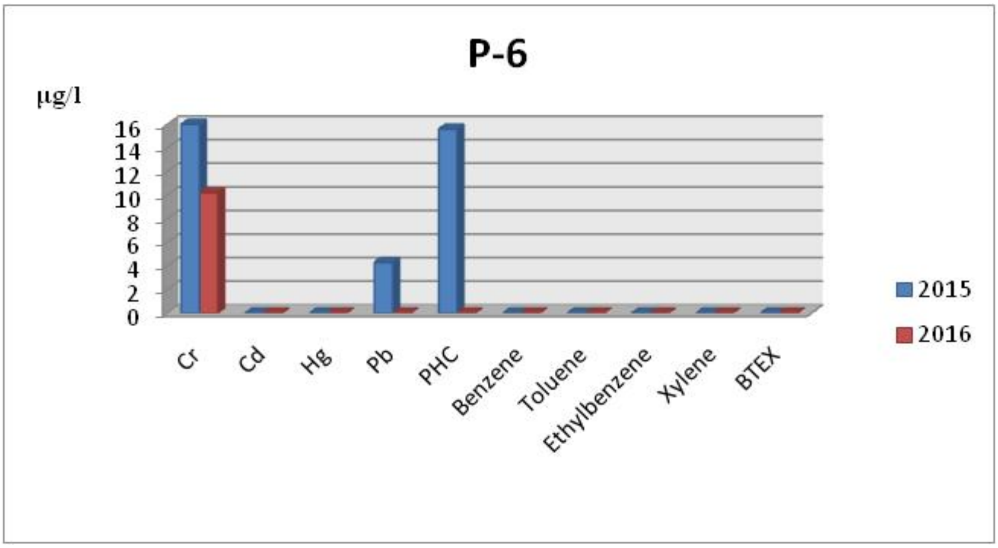
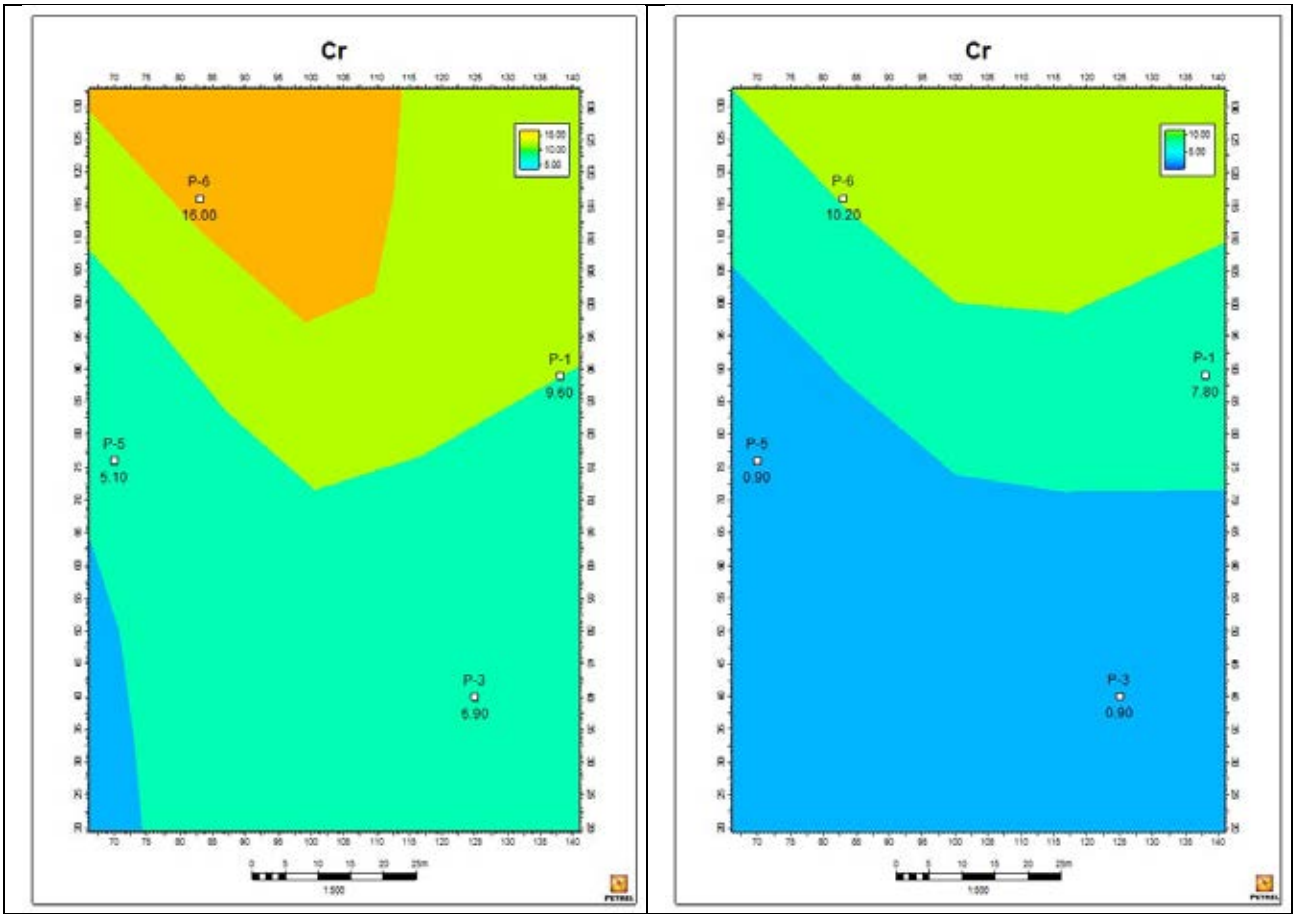


Figure 4: Concentration of groundwater pollutants measured at P-6

The laboratory analyses show an increase in Cr concentrations in 2015 at all piezometers, while in 2016 the increase in chromium concentrations was detected only at P-1 and P-6. However, determined concentrations are in the range between the optimal and the intervention values. The presence of increased hydrocarbon concentration is not recorded during the monitoring in 2015 and 2016.

5. Site maps of pollutants distribution using nearest neighbour technique

In order to show the distribution of pollutants in the underground, the maps were created using the Nearest Neighbours method. It is about a very simple mathematical method of estimation constant value within a polygon, which is recommended in case of a small number of data. If some data is missing, the gaps can be supplemented by this method in a relatively effective manner. The whole field is covered with a series of polygons. For the entire surface a value is assigned which is equal to the point value at the polygon centre. Although the map obtained by this method is not highly reliable, it provides an approximate distribution of the parameters, and based on it, one can conclude where to expand measurements network. The distribution maps of Cr concentrations measured at site in the groundwater in 2015 and 2016 were made using the Nearest Neighbour technique (**Figure 5**).



(a) (b)

Figure 5: Site map of distribution of Cr in groundwater obtained by Nearest Neighbours technique. According to concentrations measured in 2015 (a) and According to concentrations measured in 2016 (b)

The maps indicate a situation where the highest measured values appear in the northern part of the facility. Taking into account the concentrations measured in 2015, it is evident that the concentration of pollutant in the entire area is decreased in 2016.

5. Conclusion

Based on the conducted research done by authorized company the site is characterized as a location of low pollution risk since:

- the research did not show any increased concentrations of pollutants in soil layers;
- determined presence of increased concentration of Cr in groundwater is below the intervention values;
- the characteristics of the ground soil, which consists of low permeable dusty clayey to dusty sandy material, as well as hydrogeological characteristics of the site and the low mobility of heavy metals, reduce the possibility of significant pollutant spreading.

The investigated site was chosen as a potentially contaminated due to ongoing activities of oil and gas exploitation. Taking into consideration that the research did not show any presence of higher concentrations of petroleum hydrocarbons in the soil and groundwater, it is possible to assume that the registered increased concentrations of Cr are not the consequence of technological fluid regeneration. Since the site is still active, it is recommended to monitor the groundwater quality, including petroleum hydrocarbons content, in the future.

Since the site does not have contamination baseline state measured before start of operation, by additional investigation soil and groundwater contamination status in the immediate vicinity of the facility could be determined.

Collecting data on incidents that might be associated with the high content of pollutants in the groundwater would help also in obtaining a clear picture of the state.

The scope of the investigation work was not sufficient to determine groundwater contamination borders and contamination sources, therefore, performed investigation can be marked as a preliminary investigation phase. The same could be obtained by additional research which would include extended sampling network (detailed investigation). Due to the lack of data pollution mapping was limited to simple mapping technique (nearest neighbour technique). In case of more data, some advanced and more reliable geostatistical method (e.g. Kriging) could be used.

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Extended abstract in Croatian

Utvrđivanje stanja onečišćenosti tla i podzemne vode nastalog kao posljedica aktivnosti eksploatacije ugljikovodika

U svrhu stvaranja osnove za sustavno praćenje stanja okoliša i eventualnih postupaka sanacije, na lokacijama potencijalno onečišćenim različitim gospodarskim aktivnostima, potrebno je provesti kvalitativno i kvantitativno određivanje stanja onečišćenosti tla i podzemne vode.

Prema Europskoj agenciji za zaštitu okoliša (*European Environment Agency*, EEA) u Europi je identificirano čak 2,5 milijuna lokacija potencijalno onečišćenih uslijed obavljanja različitih djelatnosti, kao što su eksploatacija mineralnih sirovina, proizvodnja električne energije, gospodarenje otpadom, transport, vojna djelatnost i dr. Za 14 % identificiranih lokacija pretpostavilo se o potrebi provedbe remedijacijie (https://www.eea.europa.eu/highlights/soil-contamination-widespread-in-europe).

Premda Europska unija još uvijek nije regulirala područje zaštite tla zasebnom direktivom, zahtjevi za zaštitom ove okolišne sastavnice proizlaze iz drugih regulativa, prije svega *Direktive 2004/35/EZ o odgovornosti za okoliš u pogledu sprječavanja i otklanjanja štete na okolišu* i *Direktive 2010/75/EU o industrijskim emisijama*. Direktivama su jasno definirane djelatnosti koje mogu uzrokovati štetu u okoliš i koje stoga imaju odgovornost u smislu sprječavanja nastanka štete i sanacije okoliša kojemu je nanesena šteta.

Ispitivanje onečišćenosti podzemlja provodi se kroz skupljanje informacija, analizu podataka i sastavljanje izvješća. Preliminarna istraživanja predstavljaju prvu fazu istraživanja, a odnose se na određivanje rizika onečišćenja identifikacijom potencijalnih izvora onečišćenja i okolišnih receptora (tlo, podzemna voda). Drugu fazu ispitivanja čini detaljno ispitivanje onečišćenja lokacije, koje se provodi u slučaju da se preliminarnim istraživanjima utvrdi prisutnost onečišćenja, a obuhvaća uzorkovanje i analizu tla i podzemne vode. Za dobivanje jasne slike stanja lokacije potrebno je poznavanje povijesti korištenja lokacije te topografskih, geoloških i hidrogeoloških uvjeta.

Lokacija koja je uzeta za primjer istraživanja potencijalne onečišćenosti koristi se za potrebe privremenog odlaganja i regeneracije tekućih tehnoloških fluida nastalih u tehnološkom procesu bušenja, remonta, pridobivanja i transporta nafte i plina te drugog materijala nastalog u izvanrednim procesima pridobivanja nafte i plina na eksploatacijskim poljima.

S obzirom da nacionalna regulativa propisuje jedino metodologiju za praćenje stanja poljoprivrednog zemljišta, analiza onečišćenosti podzemlja, opisana u ovom radu, predstavlja primjer procjene rizika onečišćenosti na lokacijama koje ne zadovoljavaju standarde kakvoće poljoprivrednog zemljišta. Što se tiče definiranja onečišćenosti podzemne vode, pravni okvir predstavljaju *Uredba o standardu kakvoće voda (NN 73/13, 151/14, 78/15, 61/16)* i *Pravilnik o graničnim vrijednostima emisija otpadnih voda (NN 80/13, 43/14, 27/15, 3/16).* Sijedom navedenog, kod definiranja statusa onečišćenosti podzemlja korištena je postojeća nacionalna regulativa, ali i općeprihvaćeni nizozemski standardi u slučaju kada granične vrijednosti nisu definirane nacionalnom regulativom.

Na temelju zaključaka terenskih istraživanja obavljenih od strane ovlaštene kompanije, koja su uključila uzorkovanje i analizu tla i vode, a u svrhu dobivanja jasnije slike stanja pedosfere na lokaciji, u okviru ovog rada izrađene su karte prostorne razdiobe onečišćujućih tvari korištenjem metode najbližeg susjedstva.

Ključne riječi: onečišćenje tla i podzemne vode, eksploatacija ugljikovodika, metoda najbližeg susjedstva.

Authors contribution

Karolina Novak Mavar (PhD, Assistant Professor, Oil Engineering) provided major part of theoretical background, provided distribution maps and conclusions. **Ivana Kapustić Pavić** (Postdoctoral researcher, HSE specialist) provided the charts and some parts of theoretical background.

2nd Croatian congress on geomathematics and geological terminology, 2018

Review scientific paper

The Croatian dictionary of basic terms concerning unconventional hydrocarbon reservoirs

Monika Vidić[1], Josipa Velić[2], Tomislav Malvić[3]

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, [1]undergraduate student, [2]professor emerita, [3]professor

Abstract

The lifetime of existing conventional fields in Croatia, from which hydrocarbons are being obtained, is approaching the end. Therefore, due to the requisite for the new reserves, the interest for the unconventional reservoirs where significant potential reserves are anticipated appears. Future research and retrieval from such reservoirs requires highly developed Croatian geological terminology to evade any misunderstandings and errors in describing such spaces. Here is lexicographically presented a short Croatian-Croatian dictionary of the most important terms used in the processing and determination of unconventional reservoirs in the Croatian part of the Pannonian Basin System. Over the time, such a dictionary will need to be extended to the new concepts, particularly those related to mapping and assessing the economics of the rocks of unconventional reservoirs.

Keywords: unconventional reservoirs, Croatian terminology, definitions

1. Introduction

The southwest part of the Pannonian Basin System (PBS) belongs to Croatia and has been explored to a high degree over the past 60 years (i.e. **Velić, 2007**). Existing fields that are being exploited are already in the late phase and their lifetime is approaching the end. At the time when energy independence has an increasingly important role, there is a strong need for the renewal of the reserves. Therefore, more and more attention is being paid to the study of potential unconventional reservoirs of this territory. Such reservoirs can be assumed in the Croatian part of the Pannonian Basin System with high probability, due to there are numerous conventional hydrocarbon systems with proven source rocks and migration pathways. There are two possible types of unconventional reservoirs in the Croatian part of the PBS. Those are marls of the source rocks and low permeability sandstones at the edges of proven conventional reservoirs. In both of the groups the aim is to prove economically significant and recoverable quantities of hydrocarbons. However, in order to be able to describe and categorize the possible reserves in accordance with the regulations, it is necessary to have developed necessary terminology within the professional vocabulary of the standard Croatian. For that reason, here is a lexical, Croatian-Croatian dictionary of basic terms related to unconventional reservoirs. By further exploring and exploiting, as well as by writing appropriate regulations on categorizing such reservoirs, this basic set of concepts will need to be prudently and distinctly expanded.

This paper is also a continuation of work on the development of geological terminology within the Croatian Geological Society and from professors at the University of Zagreb. It follows the presentation of the Croatian professional terminology given by **Mesić Kiš (2016)** for Geostatistics and **Malvić & Velić (2016)** for geomathematical concepts in economic geology and geological probability at the 1st Croatian Congress for mathematical geology and geological terminology.

2. Dictionary of selected terms

secondary migration – a process in which hydrocarbons migrate from source rocks to the trap, where they accumulate, and its range extends from several hundred meters to several kilometres.
Note: Secondary migration is not a fully effective process, namely, never are all the hydrocarbons expulsed, and as a result, part of the hydrocarbons generated remains trapped in low-permeability lithofacies, which, if economically viable, may represent unconventional reservoirs.
See: hydrocarbon expulsion

hydrocarbon expulsion – a hydrocarbon migration process which involves their initial (primary) migration within the source rock, entering the reservoir rock and the beginning of the secondary migration.
See: primary migration; secondary migration

kerogen – the main organic matter in the source rocks, the insoluble polymer of a high molecular weight which is the starting material for the hydrocarbon generation.
Note: The source rocks in the Croatian part of the Pannonian Basin System are predominantly kerogen II and III carriers, with type II considered to be related with generating liquid hydrocarbons, while type III has a lower generative hydrocarbon capacity and is generally considered to be releasing gases (i.e. **Velić, 2007**).

marl, marlstone – source rocks in the Croatian part of the Pannonian Basin System, possible unconventional reservoirs in some parts of this area.
Note: large volumes of detritus that gave such rocks were deposited during the Upper Badenian and Sarmatian in the marine, and in the time of the Pannonian and the Lower Pontian in the lacustrine environment (i.e. **Velić, 2007; Malvić 2012; Velić et al., 2015**). Their deposition was mostly interrupted by the activity of alluvial fans (Badenian, Sarmatian) and turbidites (Pannonian, Pontian). Significant marl volumes have been proved to be source rocks in varying degrees of thermal maturity which have generated hydrocarbons in the past and present potential unconventional reservoirs nowadays.
Example:

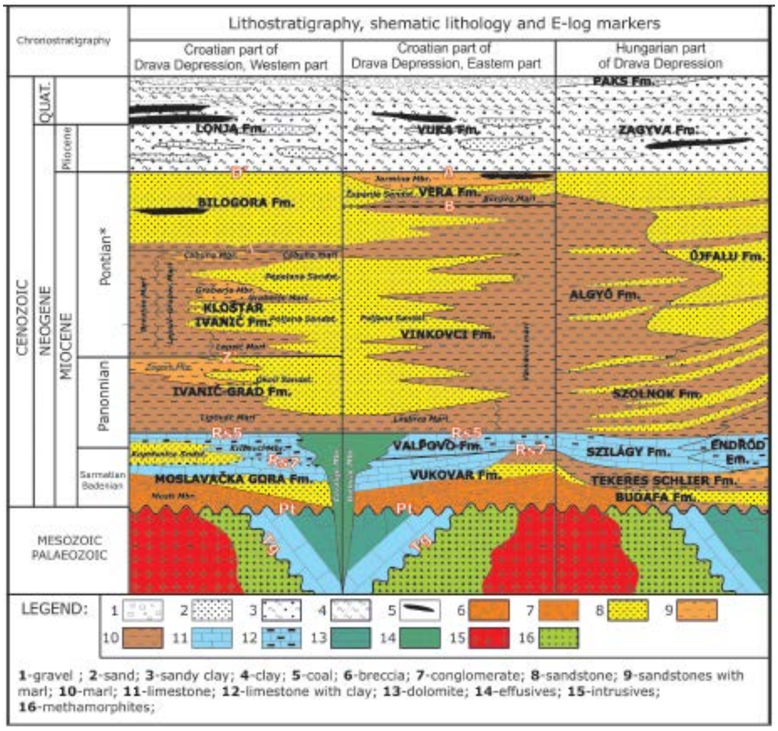

Figure 1: Great thickness of marls inside lithostratigraphic members of Drava depression, pay attention to the lithology no. 10 in legend (from: **Malvić et al., 2014**)

See: source rock

source rock – rock from which at a certain level of thermal maturity is generated, released and expulsed an economically viable volume of hydrocarbons (**Velić, 2007**).
Note: Source rocks with something greater permeability can represent unconventional reservoirs due to the easier stimulation of additional migration of the residual amounts of hydrocarbons after primary migration. Likewise, source rocks richer in organic matter and/or kerogen types I and II will generate and retain higher amounts of hydrocarbons than those of opposite traits.
See: marl, unconventional reservoir

unconventional reservoir – a reservoir which, compared to conventional one, is characterized by an effective porosity and permeability whose values are usually less than 10 % and 10^{-3} μm^2 (1 mD).
Note: Those values make unconventional reservoirs 10 to 100 times less permeable than conventional (i.e. **Malvić & Majstorović Bušić, 2012**). Exploitation of such reservoirs requires more complex and several times more expensive recovery methods such as hydraulic fracturing, horizontal and multilateral drilling. The recovered quantities and the time of recovery are several times shorter than in conventional reservoirs, which greatly reduces their profitability.
See: source rock

primary migration – migration of hydrocarbons within the fracture system of the source rock, whereby the length of that path is most often expressed in hundreds of meters. Fractures are usually very small and are classified as micro-fractures.
See: hydrocarbon expulsion

low permeable sandstone – marly and silty sandstones, which represent possible unconventional reservoirs in the Croatian part of the Pannonian Basin System (**Figure 1**, lithology no. 9 in legend).
Note: Such lithofacies were deposited in the edging parts of the brackish environment during the Pannonian and the Lower Pontian. The detritus was transported by the turbidity currents that brought materials from the Eastern Alps (i.e. **Velić, 2007; Malvić 2012**).
See: unconventional reservoir

remained hydrocarbons in source rocks – hydrocarbons that remained captivated in the source rock after their primary migration.
Note: Primary migration is not a fully effective process, particularly concerning the oil. The portion of remaining hydrocarbons ranges from 20 % to 70 % of the generated hydrocarbons depending on their molecular mass. The higher the molecular mass of the hydrocarbons, the lesser their mobility.
See: source rocks

unconventional reservoir trap – a structure where hydrocarbons accumulate in unconventional reservoirs.
Note: It may be a common structural trap, sometimes limited by a fault, especially in cases of the low-permeability reservoirs such as those of fine-grained sandstones and siltstones (i.e. **Velić et al., 2015**). In unconventional reservoirs of very low permeability (marls, shales) source rocks themselves represent a trap, but not in the classical petroleum geology sense, that is always determined by stratigraphy, tectonics and relation of the pressure and capillary forces.
See: unconventional reservoir

3. Conclusion

Even though only ten geological terms were given, their meaning is crucial for understanding and describing unconventional reservoirs expected to be brought to exploitation in the Croatian part of the Pannonian Basin System. There are clearly distinguished two basic lithofacies in which can be assumed hydrocarbon reserves in unconventional reservoirs. Those are marls as source rocks proven from Upper Badenian to Lower Pontian. The ones richer in organic matter, kerogen type II and thermally mature have been proven to have generated hydrocarbons that were expulsed - they were released on the migration path and accumulated in numerous conventional reservoirs. Low-permeability sandstones dating from Pannonian and Lower Pontian are located on migration paths of hydrocarbons, which are today also proven in conventional reservoirs of well-permeable, middle-grained sandstones, mostly in (faulted) anticlines. Over the time, by accessing the recovering from unconventional reservoirs, the knowledge and clear distinction of terms such as primary and secondary migration, source rocks, expulsions, releasing and unconventional traps will be necessary. In addition to these terms, it will be necessary to develop and lexically elaborate a number of other terms related to geology concerning the unconventional reservoirs, but also the economics of gaining from them.

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2nd Croatian congress on geomathematics and geological terminology, 2018

Pregledni znanstveni rad

Hrvatski rječnik osnovnih pojmova nekonvencionalnih ležišta ugljikovodika

Monika Vidić[1], Josipa Velić[2], Tomislav Malvić[3]
Sveučiliste u Zagrebu, Rudarsko-geološko-naftni fakultet, Pierottijeva 6, 10000 Zagreb, [1]studentica preddiplomskog studija, [2]profesorica emerita, [3]redoviti profesor

Sažetak
Radni vijek postojećih konvencionalnih polja iz kojih se pridobivaju ugljikovodici u Hrvatskoj se približava kraju. Uslijed potrebe za novim rezervama, budi se zanimanje za nekonvencionalna ležišta u kojima su predviđene značajne potencijalne rezerve. Buduće istraživanje i pridobivanje iz takvih ležišta zahtijeva razvijenu vrlo jasnu hrvatsku geološku terminologiju, kako bi se izbjegli svi nesporazumi i pogrješke kod opisivanja takvih prostora. Ovdje je leksikografski prikazan kratak hrvatsko-hrvatski rječnik najvažnijih pojmova koji se koriste prigodom obradbe i određivanja nekonvencionalnih ležišta u hrvatskom dijelu Panonskoga bazenskog sustava. Vremenom će takav rječnik biti potrebno proširivati novim pojmovima, posebice onima vezanim uz kartiranje i ocjenu ekonomičnosti stijena nekonvencionalnih ležišta.

Ključne riječi: nekonvencionalno ležište, hrvatsko nazivlje, definicije

1. Uvod

Hrvatskoj pripada jugozapadni dio Panonskoga bazenskog sustava (skr. PBS) koji je u posljednjih 60 godina u visokoj mjeri istražen (npr. **Velić, 2007**). Postojeća polja privedena eksploataciji već su u poodmakloj fazi i njihov radni vijek se bliži kraju. U doba kada energetska neovisnost ima sve značajniju ulogu, javlja se potreba za obnovom rezervi. Stoga se sve veća pozornost pridaje istraživanju potencijalnih nekonvencionalnih ležišta toga prostora. Ona se u hrvatskom dijelu Panonskoga bazenskog sustava (skr. HPBS) mogu pretpostaviti s velikom vjerojatnošću, posebice u svjetlu činjenice kako su u tom prostoru otkrivena brojna konvencionalna ležišta s dokazanim matičnim stijenama i migracijskim putovima. Dvije su moguće vrste nekonvencionalnih ležišta HPBS-a. To su lapori matičnih stijena te slabopropusni pješčenjaci na rubovima dokazanih konvencionalnih ležišta. U obje skupine cilj je dokazati ekonomski značajne i pridobive količine ugljikovodika. Ipak, da bi se moguće rezerve uopće mogle opisati te kategorizirati u skladu s propisima, potrebno je unutar strukovnoga nazivlja standardnoga hrvatskog jezika imati razvijenu potrebnu terminologiju. Stoga je ovdje načinjen, leksikografski, hrvatsko-hrvatski rječnik osnovnih pojmova koji se odnose na nekonvencionalna ležišta. Daljnjim istraživanjem te privođenjem proizvodnji, te pisanjem odgovarajućih propisa o kategorizaciji takvih ležišta, ovaj osnovni skup pojmova trebat će smišljeno i jasno proširiti.

Ujedno ovaj rad predstavlja nastavak rada na razvoju geološke terminologije unutar aktivnosti Hrvatskoga geološkog društva i nastavnika geologije na zagrebačkom sveučilištu. On prati način prikaza hrvatske strukovne terminologije koju su na 1. hrvatskom kongresu o geomatematici i geološkom nazivlju dali **Mesić Kiš (2016)** za područje geostatistike te **Malvić i Velić (2016)** za geomatematičke pojmove u ekonomskoj geologiji i geološkoj vjerojatnosti.

2. Rječnik pojmova

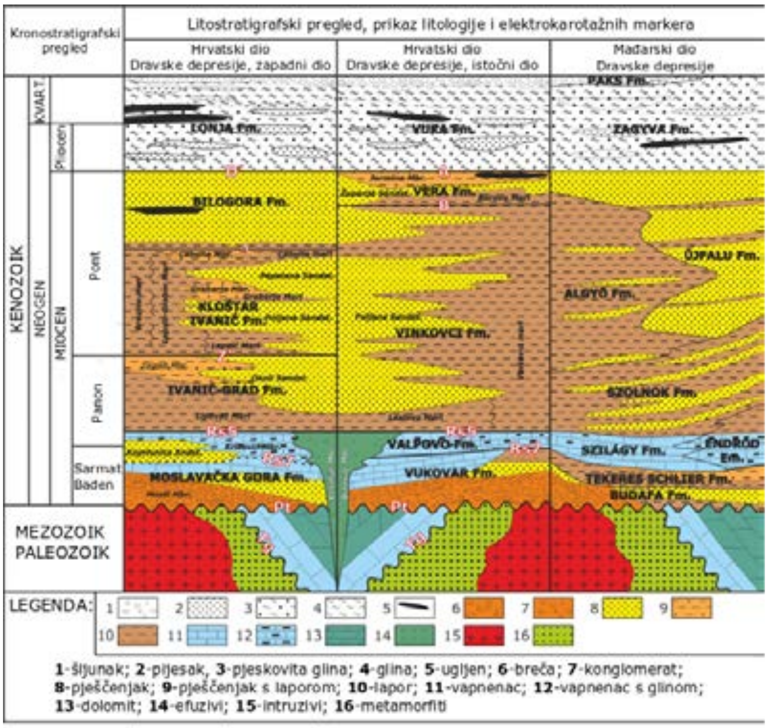
drugotna (sekundarna) migracija – proces kretanja ugljikovodika od matične stijene do zamke gdje započinje nakupljanje ugljikovodika, a njezin raspon može biti od nekoliko stotina metara do nekoliko kilometara.
Napomena: Drugotna migracija nije u potpunosti djelotvoran proces, naime, nikada se ne otpuste sve količine ugljikovodika, stoga kao posljedica dio generiranih ugljikovodika ostaje zarobljen u slabopropusnim litofacijesima koji posljedično, ako se radi o ekonomski isplativim količinama, mogu činiti nekonvencionalna ležišta.
Vidi: istiskivanje ili otpuštanje ugljikovodika
Engl. *secondary migration*

istiskivanje (ekspulzija) ili otpuštanje ugljikovodika – proces migracije ugljikovodika koji obuhvaća njihovu prvotnu migraciju unutar matične stijene te ulazak u ležišne stijene i početak drugotne migracije.
Vidi: prvotna migracija; drugotna migracija

Engl. *hydrocarbon expulsion*

kerogen – glavna organska tvar u matičnim stijenama, odnosno netopljivi polimer velike molekularne mase koji predstavlja ishodišnu tvar za postanak ugljikovodika.
Napomena: Matične stijene u hrvatskom dijelu Panonskoga bazenskog sustava pretežito su nosioci kerogena II i III, pri čemu se onome tipa II pripisuje postanak tekućih ugljikovodika, dok kerogen tipa III ima niži generativni kapacitet ugljikovodika i općenito se smatra da se iz njega izdvajaju plinovi (npr. **Velić, 2007**).
Engl. *kerogen*

lapor – matične stijene u hrvatskom dijelu Panonskoga bazenskog sustava, moguća nekonvencionalna ležišta u nekim dijelovima toga prostora.
Napomena: veliki volumeni detritusa koji je dao takve stijene odlagani su tijekom gornjega badena i sarmata u morskom, a u vrijeme panona i donjega ponta jezerskom okolišu (npr. **Velić, 2007; Malvić 2012; Velić et al., 2015**). Njihovo taloženje najčešće je prekidano aktivnošću aluvijalnih lepezi (baden, sarmat) i turbidita (panon, pont). Značajni volumeni lapora dokazano su matične stijene u različitim stupnjevima zrelosti, a one koje su generirale ugljikovodike i potencijalna nekonvencionalna ležišta.
Primjer:



Slika 1: Velike debljine lapora unutar litostratigrafskih članova Dravske depresije, obratiti pozornost na legendu pod brojem 10 (iz: **Malvić et al., 2014**)

Vidi: matična stijena
Engl. *marl, marlstone*

matična stijena – stijena iz koje se pri određenoj razini termalne zrelosti generira, otpušta i istiskuje ekonomski isplativa količina ugljikovodika (**Velić, 2007**).
Napomena: Matične stijene s nešto većom propusnošću mogu predstavljati nekonvencionalna ležišta uslijed lakšega poticanja dodatne migracije zaostalih količina ugljikovodika nakon prvotne (primarne) migracije. Također, matične stijene bogatije organskom tvari i/ili karogenima tipa I i II generirat će i zadržati veće količine ugljikovodika od onih suprotnih svojstava.
Vidi: lapor, nekonvencionalno ležište
Engl. *source rock*

nekonvencionalno ležište – ležište koje se u odnosu na konvencionalno odlikuje efektivnom šupljikavošću i propusnošću čije su vrijednosti najčešće manje od 10 % te 10^{-3} μm^2 (1 mD).
Napomena: Te vrijednosti ukazuju na 10 do 100 puta manju propusnost od konvencionalnih ležišta (npr. **Malvić & Majstorović Bušić, 2012**). Iskorištavanje takvih ležišta zahtijeva složenije i višestruko skuplje metode pridobivanja poput hidrauličkog lomljenja, vodoravnog i multilateralnog bušenja. Pridobivene količine i vrijeme pridobivanja su nekoliko puta kraća negoli kod konvencionalnih ležišta, što uvelike smanjuje njihovu isplativost.
Vidi: matična stijena
Engl. *unconventional reservoir*

prvotna (primarna) migracija – migracija ugljikovodika unutar pukotinskoga sustava matične stijene, pri čemu se dužina toga puta najčešće izražava u stotinama metara. Pukotine su obično vrlo male pa ih se svrstava u mikropukotine.
Vidi: istiskivanje ili otpuštanje ugljikovodika
Engl. *primary migration*

slabopropusni pješčenjaci – laporoviti i siltni pješčenjaci koji predstavljaju moguća nekonvencionalna ležišta u hrvatskom dijelu Panonskoga bazenskog sustava (**slika 1**, litološka oznaka broj 9).
Napomena: Takvi litofacijesi su odlagani u rubnim dijelovima bočatih okoliša tijekom panona i donjega ponta. Detritus je prenašan turbiditnim strujama koje su donosile materijal iz Istočnih Alpa (npr., **Velić, 2007; Malvić 2012**).
Vidi: nekonvencionalno ležište
Engl. *low permeable sandstone*

ugljikovodici preostali u matičnoj stijeni – ugljikovodici koji su nakon prvotne (primarne) migracije ostali zarobljeni u matičnoj stijeni.
Napomena: Prvotna migracija nije u potpunosti djelotvoran proces, što se osobito odnosi na naftu. Količine preostalih ugljikovodika se, ovisno o molekularnoj masi, kreću od 20 % do 70 % nastalih. Što je veća molekularna masa ugljikovodika, manja je njihova pokretljivost.
Vidi: matična stijena
Engl. *remained hydrocarbons in source rocks*

zamka nekonvencionalnoga ležišta – mjesto nakupljanja ugljikovodika u nekonvencionalnom ležištu.
Napomena: Može biti uobičajena strukturna zamka, ponekad ograničena rasjedom, posebice u slučajevima slabopropusnih ležišta poput sitnozrnatih pješčenjaka i siltita (npr. **Velić et al., 2015**). Kod nekonvencionalnih ležišta vrlo male propusnosti (lapori, šejlovi) matične stijene same po sebi predstavljaju zamku, ali ne u klasičnom naftnogeološkom smislu, koje su uvijek određene stratigrafijom, tektonikom te odnosom tlaka i kapilarnih sila.
Vidi: nekonvencionalno ležište
Engl. *unconventional reservoir trap*

3. Zaključak

Iako je riječ o samo deset geoloških pojmova, njihovo značenje ključno je za razumijevanje i opisivanje nekonvencionalnih ležišta kakva se očekuje privesti pridobivanju u prostoru hrvatskoga dijela Panonskoga bazenskog sustava. Jasno su razlučene dvije osnovne vrste litofacijesa za koje se predviđa dokazivanje rezervi ugljikovodika u nekonvencionalnim ležištima. To su lapori kao matične stijene dokazane od gornjega badena do donjega ponta. Oni bogatiji organskom tvari, kerogenom tipa II i termalno zreli dokazano su generirali ugljikovodike, koji su istisnuti - otpušteni na migracijski put te su nakupljeni u brojnim konvencionalnim ležištima. Slabopropusni pješčenjaci panona i donjega ponta smješteni su na migracijskim putovima ugljikovodika koji su također danas dokazani u konvencionalnim ležištima dobropropusnih, srednjozrnatih pješčenjaka, uglavnom u (rasjednutim) antiklinalama. Kako će se vremenom pristupiti pridobivanju iz nekonvencionalnih ležišta, poznavanje i jasna odredba pojmova poput prvotne i drugotne migracije, matične stijene, istiskivanja, otpuštanja i nekonvencionalne zamke bit će nužnost. Uz te pojmove bit će potrebno razviti i rječnički obraditi još niz drugih pojmova vezanih uz geologiju koja se odnosi na nekonvencionala ležišta, ali i ekonomiku pridobivanja iz njih.

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2nd Croatian congress on geomathematics and geological terminology, 2018

Preliminary communication

Deep mapping of hydrocarbon reservoirs in the case of a small number of data on the example of the Lower Pontian reservoirs of the western part of Sava Depression

Josip Ivšinović[1]
[1] INA d.d., Trg G. Szabe 1, 44310 Novska, HR;

Abstract

Production of hydrocarbons from Lower Pontian reservoirs of Sava Depression is in "mature" stage, which involves the application of secondary methods (formation water injection). Due to the small number of injection wells, mapping methods have been applied in this paper are: the nearest neighbourhood and the inverse distance. Both methods have been applied on Lower Pontian reservoirs of oil-gas field "A" (Western part of Sava depression), which is in the secondary phase of hydrocarbon production. The mapped parameter is the amount of injected brine water and its spatial distribution in reservoir "L".

Keywords: Inverse Distance Weighting, Nearest neighbourhood method, Sava Depression, Croatia

1. Introduction

The production of hydrocarbons from the Lower Pontian reservoir of Sava Depression is in "mature" stage. Oil and gas fields in Sava Depression are in the secondary or tertiary stage of production. The most effective secondary method of recovery is injection of formation water for reservoir pressure support. Injection systems consist of a small number of injection wells, and thus a smaller set of data for the mapping. Previously applied deterministic methods for mapping of Lower Pontian (Kloštar-Ivanić formation) reservoirs were (e.g., **Balić et al., 2008; Husanović & Malvić 2014**): inverse distance weighting, moving average, nearest neighbourhood, kriging and cokriging (with cross-validation of models). The methods used for a large number (more than 20) (e.g., **Balić et al., 2008; Husanović & Malvić 2014**) of input data were: kriging and cokriging (with cross-validation of models). For the application of the above mentioned methods, requires a reliable variogram model, which in the case of small input data set, is not applicable. The most suitable methods of mapping for small input data number (less than 15) are: nearest neighborhood and inverse distances (e.g., **Husanović & Malvić 2014**). The paper describes the geological characteristics of the study area, the mapping methods and the application on the injection wells of oil-gas field "A".

2. Geological characteristics of study area

The oil-gas field „A" is located in the western part of Sava Depression, in Croatian part of the Panonian Basin System. The typical geological column of field „A", including, Kloštar Ivanić formation, is shown in **Figure 2.1.**

Corresponding author: Josip Ivšinović
josip.ivsinovic@ina.hr

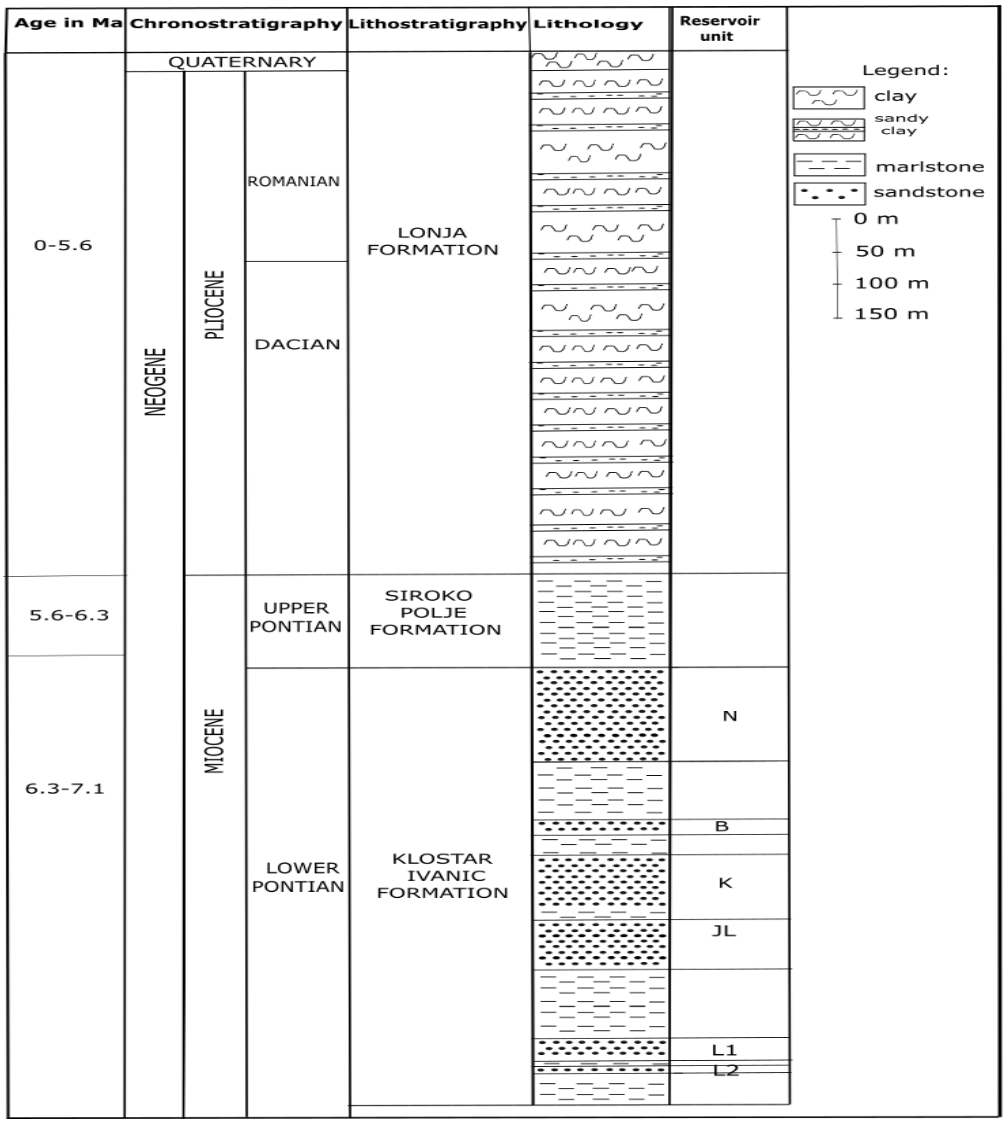

Figure 2.1: Geological column of field "A"

The lithological property of the Lower Pontian reservoirs of formation Kloštar Ivanić is a good sort of medium-clastic particles. In the lower part of the reservoir there are mostly hard sandstones, which, according to the roof part of the formation, and especially in the Široko Polje (Upper Pontian) formation, become weakly bonded and even milled, unbound sands. The target of this study is the "L" reservoir, which is shown on thickness map **(Figure 2.2**).

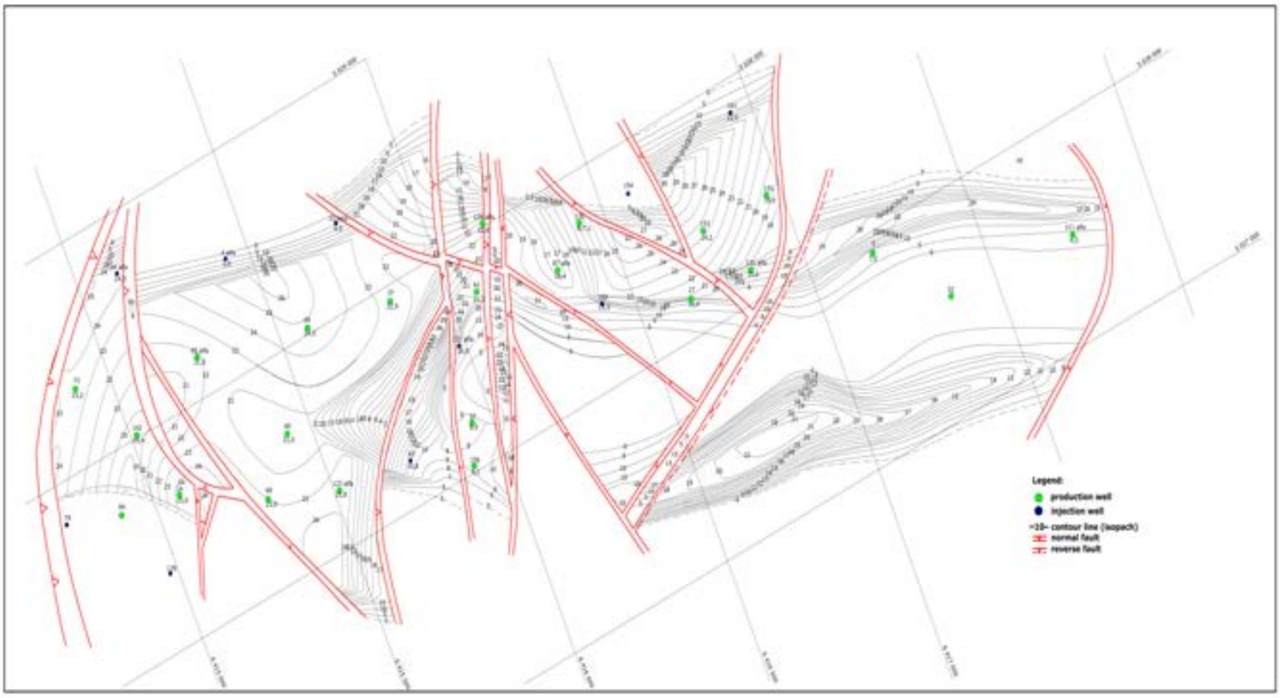

Figure 2.2: Thickness map for reservoir "L" (**from ***)

For the "L" reservoir, the average mean porosity for gas is 18.5%, for oil 20.0%, while the average permeability is 20.6 • 10^{-3} μm^2 (**from ***). From the "L" reservoir hydrocarbons are produced form 22 wells, and due to the large share of reserves in the "A" field, formation water injection is used since 1993 with 10 injection wells in order to increase oil recovery. Injection wells of field "A" will be analysed in the following chapters.

3. Interpolation methods for a small data set

The simplest interpolation methods for processing a small set of data are: nearest neighbourhood and inverse distance weighting (e.g., **Malvić, 2008; Mesić Kiš & Malvić 2014; Mesić Kiš 2017**). These methods contain simple mathematical models and are therefore suitable for processing a small set of data, such as the number of injection wells in field „A".

3.1. Nearest neighbourhood method

The nearest neighbourhood method is the simplest interpolation method that fills the value of a network, taking into account the value of the nearest adjacent data, and the result of the method is zonal distribution of values (e.g., **Husanović & Malvić 2014; Kitikidou et al., 2014**).

Space distance is calculated according to the expression for Euclid's distance (**Equation 3.1**):

$$d\ (x,T) = \sqrt{(x_1 - T_1)^2 + \cdots + (x_n - T_n)^2} \qquad \text{Eq. 3.1.}$$

Where are:
d - distance,
n - number,
x and T - points in space.

It is usable when there is a small number of data, i.e. when there are relatively large areas where there is no data, and they need to be schematic mapped (e.g., **Husanović & Malvić, 2014**).

3.2. Inverse Distance Weighting

The inverse distance method is simple interpolation methods, where the value of the variable is estimated by the value closest to the measured value. The number of points involved in the assessment is determined by the radius of the circle around the data. The particular data is inversely dependent on the distance of the input data and the location at which the value will be estimated. **Equation 3.2.** to estimate the inverse distance method (e.g., **Balić et al., 2008; Medved et al., 2010; Ly et al., 2011**) is:

$$z_{IU} = \frac{\frac{z_1}{d_1^p}+\frac{z_2}{d_2^p}+\cdots\frac{z_n}{d_n^p}}{\frac{1}{d_1^p}+\frac{1}{d_2^p}+\cdots\frac{1}{d_n^p}} \qquad \text{Eq. 3.2}$$

Where are:

z_{IU} - estimated value,
$d_1 \ldots d_n$ - distances of locations 1…n to the estimated location z_{IU},
p - distance exponent,
$z_1 \ldots z_n$ - real values at locations 1…n.

The result of the interpolation depends on the exponent of distance that is usually chosen with values between 1 and 3, and the most commonly used amount of 2, which has been empirically proven to be the most appropriate value for acceptable depth geo-mapping. The method is applicable if the input variables are not highly grouped and the data number is less than 15, because then mathematical more demanding methods are unable to develop a quality view (e.g., **Husanović & Malvić, 2014**).

4. Application of interpolation methods on field „A“

The methods were applied to mapping injection quantities are: the nearest neighbourhood and inverse distance, and maps are made in the program SURFER 15. Data on injected quantities were collected for the period from 1985 to 2015, and for this period were made maps of injected water quantities. Maps of injected amount of water in the Lower Pontian sandstone reservoir "L" in the period of twenty years is shown on **figure 4.1.**

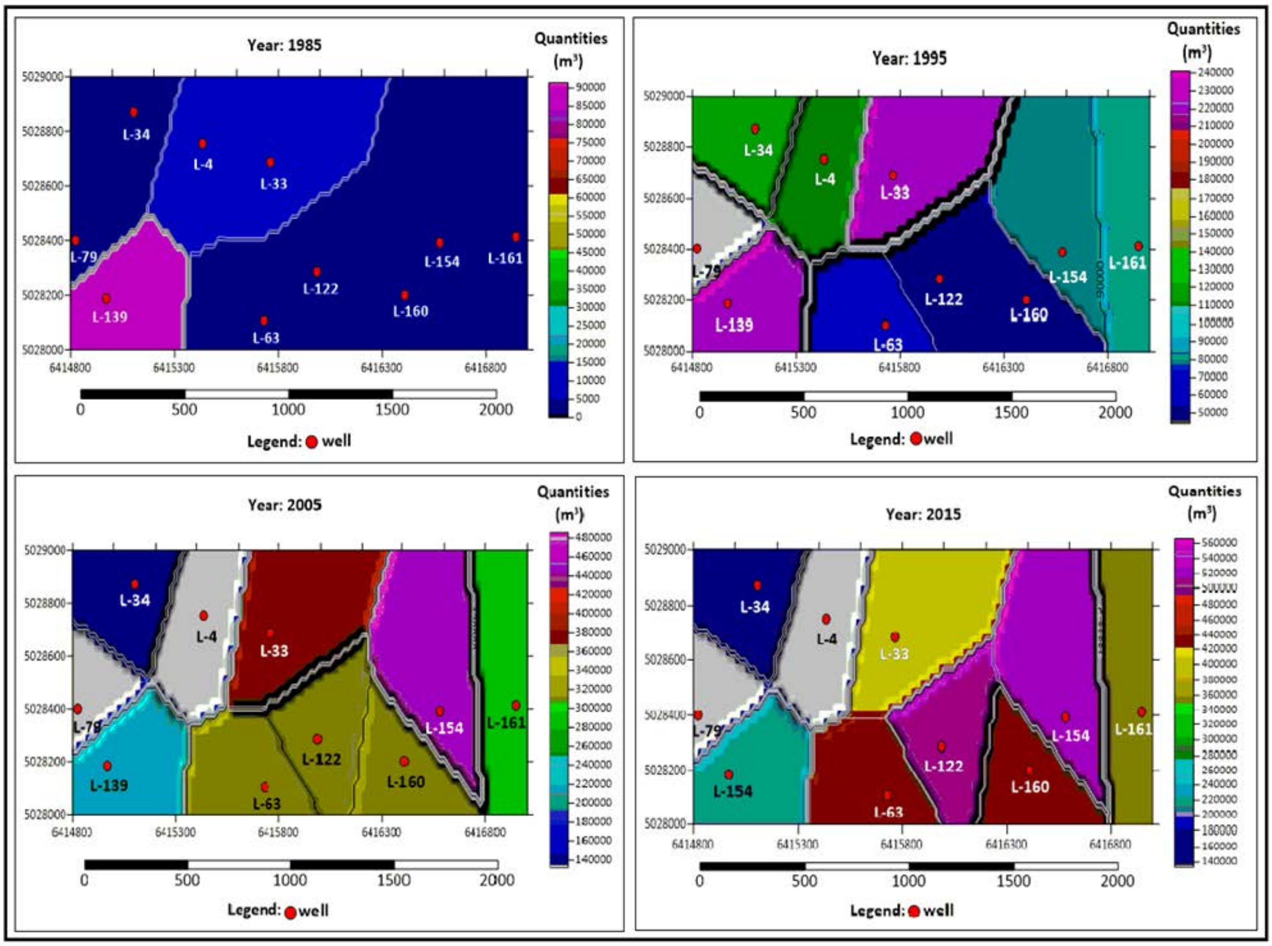

Figure 4.1: The map of injection water quantities obtained by the nearest neighbouring method

The map obtained by the nearest neighbouring method has defined the polygons (zones) from the input data of the reservoir, which is the characteristic of this method. During the injection of formation water, it can be noticed that the amount of injected water in some wells increased significantly, but the polygon appearance did not change from the original polygons, but the colors changed according to the amount injected. It can also be applied to the generated maps, there is no overlapping of individual zones (polygons), which makes this method applicable to this kind of mapping. The advantages of this method of mapping are getting rough image spread of water fronts in the mapped area, and polygons reflect the maximum range of individual water injection well. Such range can be prevented by impermeable fault, or change of lithological properties of the reservoir or block which is seen by the nonlinear polygon boundaries. The disadvantages of this method is the lack of a transition zone between the individual polygons. **Figure 4.2.** are shown maps injected amount of formation water in the Lower Pontian sandstone reservoir "L" in the period of twenty years, obtained by the method of inverse distance.

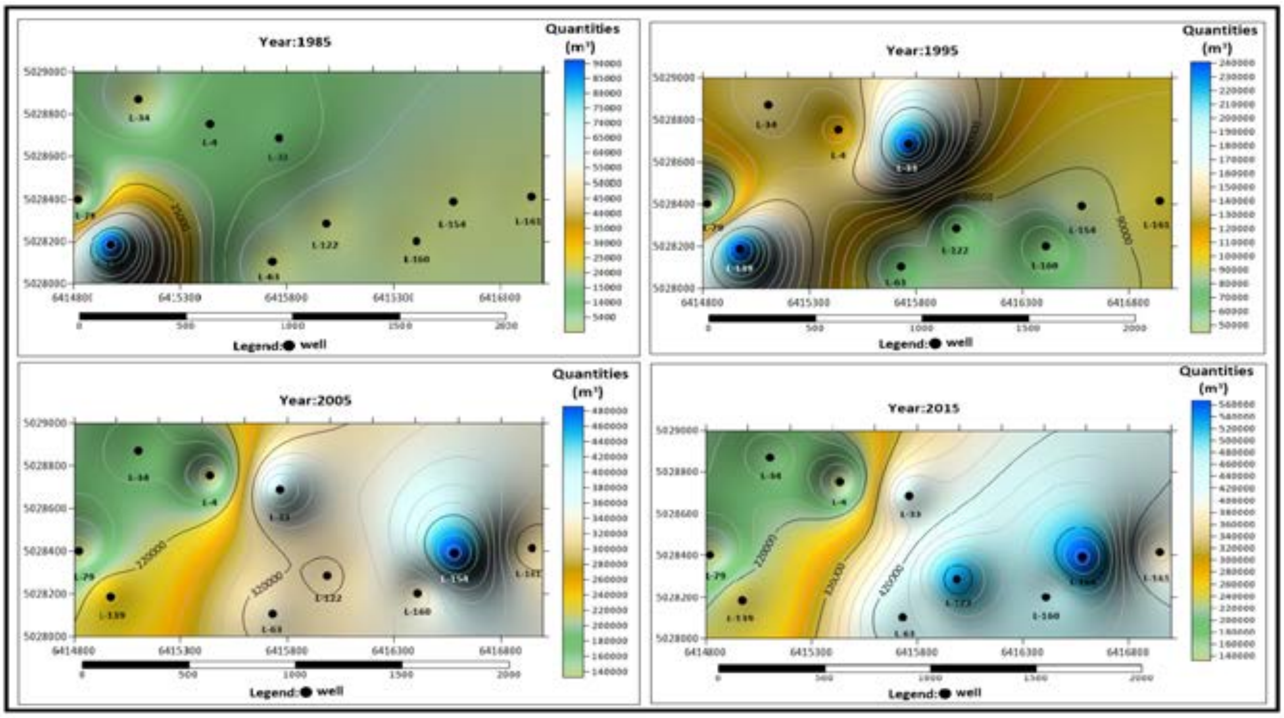

Figure 4.2: The map of injection water quantities obtained by the inverse distance weighting method

The maps obtained by the inverse distance method showed a clear spread of the waterfront across the mapped space, changing the colors depending on the amount injected. During a longer time injection of water, it can be noticed that the injected quantities of the eastern part of the mapped area are smaller, while in the west part larger, so it can be concluded that the lithological properties grow from the east to the west of the map area, or the persistence of a number of faults that are impermeable or poorly permeable ("sharper" transition zone). The advantage of this method is mapping of the quantitative transient zone between the injection wells. Transitional zones can be interpreted as a change of lithological properties within the map area, or in the case of a small or almost no transition zone to the possibility existence of impermeable faults. The disadvantage of this method is in of a large transition zone is the loss of the visual spatial reach of the waterfront for a single injection well.

5. Discussion and conclusion

In the case of a small number of data application methods nearest neighbours and inverse distance in example of the oil and gas field “A” are applicable and complement each other. The advantage of the nearest neighbouring method is to obtain a rough polygonal (zone) area, and can be taken as the extent of water expansion within a mapped area for a single injection well. The disadvantages of the nearest neighboring method are the lack of a transition zone between individual wells, and when there are several inside the same reservoir.

Then the advantages of the inverse distance method were observed, where maps were obtained with transient quantity zones between the individual injection wells. It can be seen clearly spreading water front through the mapped area and the ability to detect changes in these quantities, depend on the lithological composition of deposits and position the fault zones. In the case of multiple faults in the reservoir, more hydrodynamic units will be formed, which will significantly affect the ultimate appearance of the map obtained. For mapping injected amount of brine water, permeability or impermeability faults within the reservoir is the most important factor because it determines the spread of possible water fronts within the reservoir. This can be seen through a larger transition zone between different values of the injected amount on the map. The disadvantages of inverse distance methods is the loss of a "clear line" of the intersection range in the individual wells at larger transition zones between the wells, although it is arbitrarily set at polygonal methods.

When analysing the waterflooding of reservoirs, with the analysis of structural geological maps, effective thickness maps, hydrodynamic measurement data and well logging measurements, the application of geomathematical tools in the analysis of the reservoir is definitely of help to better understanding the reservoir, and thus achieving a greater final oil and gas recovery.

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Abstract in Croatian

Dubinsko kartiranje ležišta ugljikovodika u slučaju malog broja podataka na primjeru donjopontskih ležišta zapadnog dijela Savske depresije

Pridobivanje ugljikovodika iz donjopontskih ležišta Savske depresije je "zreloj" fazi, što podrazumijeva primjenu sekundarnih metoda (utiskivanje slojne vode). Zbog malog broja utisnih bušotina, u radu su primijenjene metode kartiranja: najbližeg susjedstva i inverzne udaljenosti. Oboje metode su primjene na naftno-plinskom polju A koje se nalazi u sekundarnoj fazi pridobivanja ugljikovodika. Parametar za kartiranje je količina utisnute slojne vode i dobivanje prostorne raspodjele u ležištu „L".

Ključne riječi: metoda najbližeg susjedstva, metoda inverzne udaljenosti, Savska Depresija, Hrvatska

Author contribution

Josip Ivšinović done all paper.

2nd Croatian congress on geomathematics and geological terminology, 2018

Professional paper

The relationship between sandstone depositional environment and water injection system, a case study from the Upper Miocene hydrocarbon reservoir in northern Croatia

Josip Ivšinović[1]
[1] INA d.d., Trg G. Szabe 1, 44310 Novska, HR;

Abstract
In the Sava Depression (in Northern Croatia), typical Lower Pontian (Neogene) sandstone reservoir "K", and the largest hydrodynamic units "K1" are present. The reservoir lithology has been strongly influenced by the regional geological settings, especially lacustrine depositional environments with periodically active turbidites. A contour (isopach) map and correlation section showed an increase of pelitic detritus into reservoir sandstones and/or pinching out. Moreover, marginal fault zones create strike-slip pull-apart during Lower Pontian, which have lately been inverted into present day faulted anticlines (pop-up). Such geological settings affected the entire production process and equipment for water injection and separation. An appropriate selection of technology has improved the hydrocarbon recovery in terms of absolute volumes as well as the oil - water ratio. A similar approach was very successful for long-term hydrocarbon production on other fields in the Sava Depression, i.e. in heterogeneous sandstone reservoirs, with a large portion of pelitic detritus.

Keywords: Neogene, sandstones, hydrocarbons, injection, dehydration, Croatia

1. Introduction

The hydrocarbon reservoirs, especially the sandstone ones, are mostly managed with water injection in the later phases of their recovery. Every such production system is unique, but there are some general rules for their management, mostly based on reservoir lithology. Sandstones are the most abundant hydrocarbon reservoirs in Croatia, especially in the northern part of the country. The Sava Depression in the historically famous petroleum province belongs to the southwestern branch (Croatian part, abbr. CPBS) of the Pannonian Basin System (abbr. PBS), located in Central and Eastern Europe. The history of hydrocarbon production is long, dating from the second part of 19th century (e.g., **Velić et al., 2012; Velić et al., 2016**). The majority of sandstone reservoirs in the CPBS belong to the Upper Miocene lacustrine environments, developed in several sub-lithofacies (e.g., **Vrbanac et al., 2010a; Velić et al., 2015**). During the Pannonian period, the area belonged to the southern part of the Lake Pannon. In the Pontian period, a large lake was disintegrated and its remains in Croatia eventually formed the Lake Slavonia, which lasted into the Pliocene period and finished with continental environments in the Quaternary period.

Analysed hydrocarbon reservoirs are saturated with hydrocarbons and formation water in different portions. Over time, the rate of produced water (free and bound water inside the oil or drops of water inside the gas stream) in the recovered fluid is variable, and mostly increased in a later phase. Such water is separated in the process of dehydration (e.g., **Ivšinović and Dekanić 2015**), removing also fine-grained sandy as well as silty and clayey particles. Such fine detritus is part of heterogeneous sandstones, and lithological heterogeneity is in the CPBS resulted from the Neogene depositional environments. In mature fields, the water injection system also includes separation, which is crucial for maintaining recovery. Results presented in this study are obtained from the selected field in the Sava Depression (part of the CPBS). That is a typical production system from Neogene sandstone reservoirs in Northern Croatia (e.g., **Gospić Miočev, et al., 2015; Ivšinović, 2016; Ivšinović et al., 2018**). This field is currently in the mature stage and produced from sandstone reservoirs (e.g., **Zelić, 1987; Zelić and Petrović, 1990**). The presented injection-separation system is the key for maintaining production and overall recovery in heterogeneous reservoirs with a large water front.

2. Notes about regional geological settings of the CPBS

In order to understand a typical Neogene sandstone reservoir in Northern Croatia, the basics of a depositional model are summarized. The CPBS is a unique part of the PBS, located in the south-western branch of that area (here "branch" is

Corresponding author: Josip Ivšinović
josip.ivsinovic@ina.hr

used as a term for a separated part of the system, with characteristic form). Its marginal position and regional pre-Neogene, Neogene and Quaternary tectonics caused the diversification of the CPBS into elongated (northwestern to south-eastern) regionally subsided depressions (Sava, Drava, Mura, Slavonia-Srijem; see **Figure 1**).

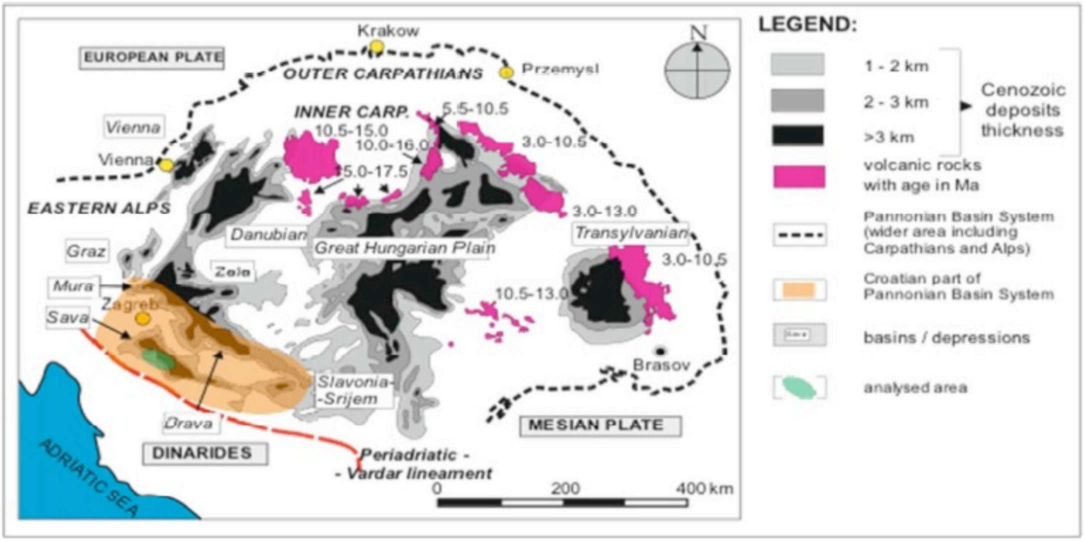

Figure 1: Geotectonic units of the Pannonian Basin System and its Croatian part (modified after **Malvić, 2012; Royden, 1988**)

As the position of those depressions is marginal regarding the central part of the PBS, they were mostly covered with shallow and periodically isolated water systems. Time scales of particular geological ages are taken after **Malvić and Velić (2011), Malvić (2012) and Ćorić et al. (2009)**. The Paratethys covered the CPBS during the Badenian and Sarmatian periods (approx. 16.0-11.5 Ma). It was followed by the isolated, large Lake Pannon (Early Pannonian; 11.5-9.3 Ma), followed by the smaller Lake Slavonia (which periodically may have been disintegrated into lakes like Sava, Drava, etc.). Lake Pannon probably also existed during the Late Pannonian (9.3-7.1 Ma) and part Pontian (7.1- 5.7 Ma) period, when it was followed by smaller lacustrine environments that lasted to the end of the Pliocene period. Pavelić and Kovačić (2018) defined single lacustrine, fresh-water, Lake Slavonia that developed from the middle Pliocene to the early Pleistocene period. The process of shallowing finished with dominant continental (inland) environments that lasted locally from the Late Pliocene and dominated during the Quaternary period. The main tectonic and depositional properties of the CPBS, regarding geological stages (see **Figure 2**), were published by **Malvić and Velić (2011)**. Also, for that area, all geological categories that could define hydrocarbon systems are described, with probabilities of their geological events, in **Malvić and Rusan (2009)**. Here it is also necessary to summarize present-day problems with the Pontian stage in the Pannonian Basin System or approximately the area that had been covered with the Central Paratethys during the Middle Miocene period. The Pontian had been defined with a typical locality in the realm of the Eastern Paratethys (Black Sea). Despite this, many authors accepted Pontian as a valid or assumed stage in the entire Pannonian Basin System (e.g., **Kázmér, 1990; Piller et al., 2007; Popov et al., 2004, 2006; Steininger and Wessely, 2000**). However, recently some authors published some new depositional models of the Upper Miocene period that could revise the Pontian as a stage applied in the CPBS (e.g., **Pavelić and Kovačić, 2018**), similar to when the Hungarian part of the PBS had been proposed to replace the "Pontian" succession with Upper Pannonian (e.g., **Sacchi and Horváth, 2002**). Just for simplicity, in this work the "classical" Pontian age and markers, were used in the same ways as they were used in the last decades in the CPBS (and cited works).

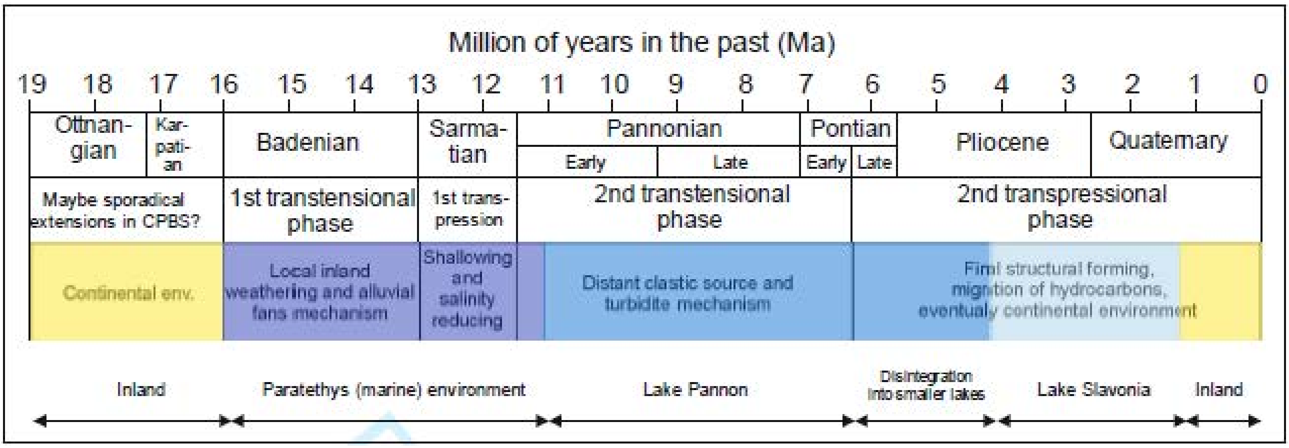

Figure 2: Time-scales of the main tectonic and depositional events in the Neogene and Quaternary in the CPBS (modified after **Malvić, 2012**)

The entire area of the CPBS from the Late Pannonian until the Late Pontian period is considered as a dominant clastic environment, with enormously large volumes of sandy and silty detritus deposited from turbidites. Lacustrine marls, from the same period, represent sediments from "calm" periods. Such a lacustrine environment (see **Figure 3**), with periodically active turbidites, characterised the entire CPBS during Upper Miocene (e.g., **Malvić, 2003, 2012**).

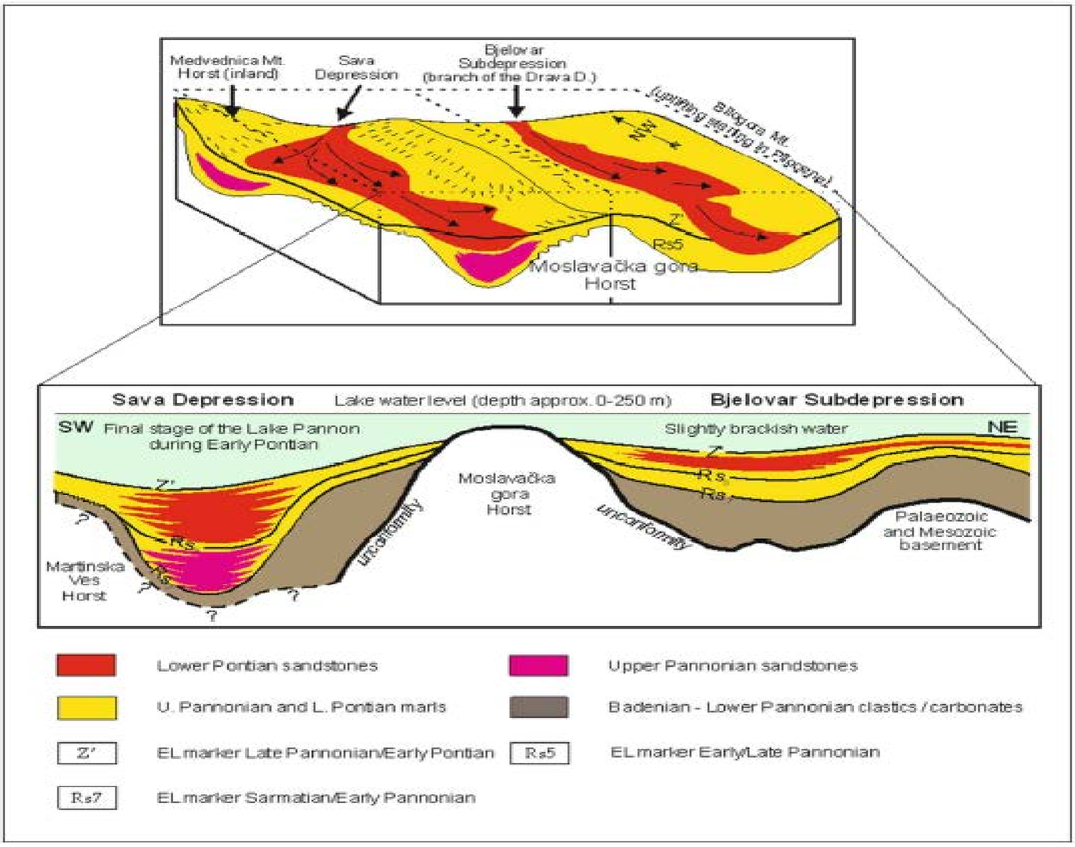

Figure 3: Schematic review of regional lacustrine environment and exchange of lacustrine pelitic and turbiditic deposits at the border between the Sava and Drava Depressions (taken from **Malvić, 2012**, compiled after **Vrbanac et al., 2010b; Malvić and Velić, 2011**)

Consequently, the hydrocarbon reservoirs discovered in the Upper Pannonian and Lower Pontian sandstones are of turbiditic origin. Such turbidites are characterised with transitional lithofacies, which varies from sand in the central part to clayey silt at the margins (see **Table 1**). Their depositional settings reflect the reservoir lithology, comprising "pure sandstones" only in the central part, with the domination of the heaviest, psammitic detritus. In the marginal parts, the reservoir lithology is represented with silty, clayey or even marly sandstone. All those lithological heterogeneities had strong reflections firstly in the hydrocarbon secondary migration and, today, in the production regime and recovery rate (see **Table 1**). Currently, the water injection is the most frequent secondary method in Croatia applied for increasing hydrocarbon recovery, exclusively into Neogene sandstones of the CPBS. It is highly influenced by reservoir lithofacies, fault zones and permeability distribution.

Table 1: Qualitative relation among field zones, lithofacies and recovery in the Neogene clastic environments active in the CPBS

Depositional sub-environment	Dominant lithofacies	Heterogeneity degree	Hydrocarbon recovery
The central part of fields, inside bottoms local depressional strike slips	Medium (rarely coarse) grained sands	Low	High, any post-primary regime production will, at least temporary, boost recovery.
Central part of fields, highly faulted structure	Medium (fine (in faulted zones) grained sands	Medium	Medium, strongly depends on fault's sizes and permeabilities
Marginal parts of fields, toward basin marls	Fine grained sands to silts (medium clay content)	High	Due to two or three lithotypes, the permeability is local, the recovery low

3. Geographic location and local geological settings of the analysed area (the "JM" Field, Sava Depression)

The analysed "JM" Field is located in the western part of the Sava Depression (see **Figure 4**). The field is located about 90 km south-east from the Croatian capital Zagreb. The southern part of the field zone is a valley with an average altitude of 120 m, which is increased to 231 m in its north-eastern part. The absolute depths of the Neogene reservoirs are between 1000 and 2000 m with the reservoir pressure about 10 % higher than hydrostatic and the average temperature gradient of 0.036 °C/m. The hydrocarbon production started in 1970 and 1971. According to **Brod (1945)** classification, the reservoirs are layered, trapped with overlaying strata, and laterally sealed with impermeable rocks or tectonic structures. Here, the largest "K" reservoir is analysed, considered also as an informal lithostratigraphic bed. The "K" reservoir is the most important Lower Pontian hydrocarbon reservoir in the analysed field. That reservoir, as well as all other Upper Miocene formations, in that field, are a result of turbiditic deposition in the lacustrine environment (the Lake Pannon, later the local Lake Slavonia).

The analysed reservoir includes more than 13 % of proven hydrocarbon reserves of the field "JM", with a 25.6 % recovery. The average porosity is 24 %, the permeability $10\text{-}250 \cdot 10^{-3}$ μm^2 and the effective thickness 9-10 m. Up to now, several recovering methods have been applied, i.e., gas cap, dissolute gas and water injection. All 26 wells are used for production, where currently 15 are still in production, and 9 are used for measuring. There are also 3 additional injection wells. The well section given at Fig. 5 has been selected as a typical well's lithological column in the field. The majority of wells reached the Lower Pontian (the Kloštar Ivanić Formation), due to the fact that hydrocarbon reservoirs were discovered inside that formation.

Figure 4: Enlarged position of the wider field zone inside the Sava Depression. The location of the Sava Depression inside the CPBS is given at **Figure 1**.

The complete Quaternary and Upper Miocene lithological sequence is given in **Figure 5**. The Quaternary deposits (the Lonja Formation) are 20-30 m thick and consist of grey and brown-grey clays, sands and humus. The Pliocene is represented by weakly consolidated sandstones, claystones and marls. Its thickness is about 600 m. The Upper Pontian (the Široko Polje Formation) includes mostly light grey marlstones, about 90 m thick. The Lower Pontian (the Kloštar Ivanić Formation) is represented with an alternation of sandstones and marls. Several sandstone layers are saturated with hydrocarbons, making them reservoirs. Such sandstones are well-sorted and medium grained with a thickness of 20-150 m. They are separated by marls, with an average thickness of 30-150 m.

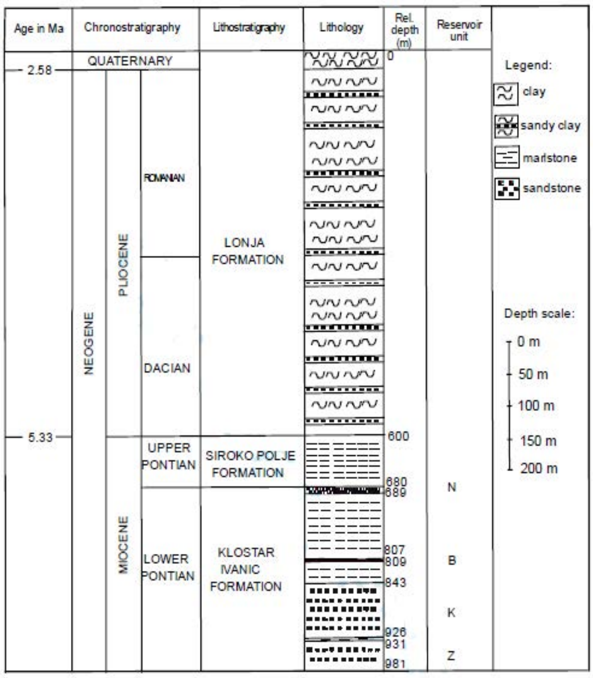

Figure 5: Typical geological section of the analysed field with formal (formations) and informal (reservoirs) lithostratigraphic units. Ages are according to International Commission on Stratigraphy (**Int. Chronostratigraphic Chart, v2017/02**).

The "K" reservoir borders are defined by marginal impermeable fault zones. That is also the main production target, which has several hydrodynamic units. The contour (isopach) map of the "K" reservoir such largest unit (the "K1" unit) is shown in **Figure 6**. The partially permeable, "middle" fault zone (strike ENE-WSW), divided the unit at approximately similar sandstone volumes. The "K1" hydrodynamic unit is the most important production volume inside the "K" reservoir, where the water flooding began in 1993.

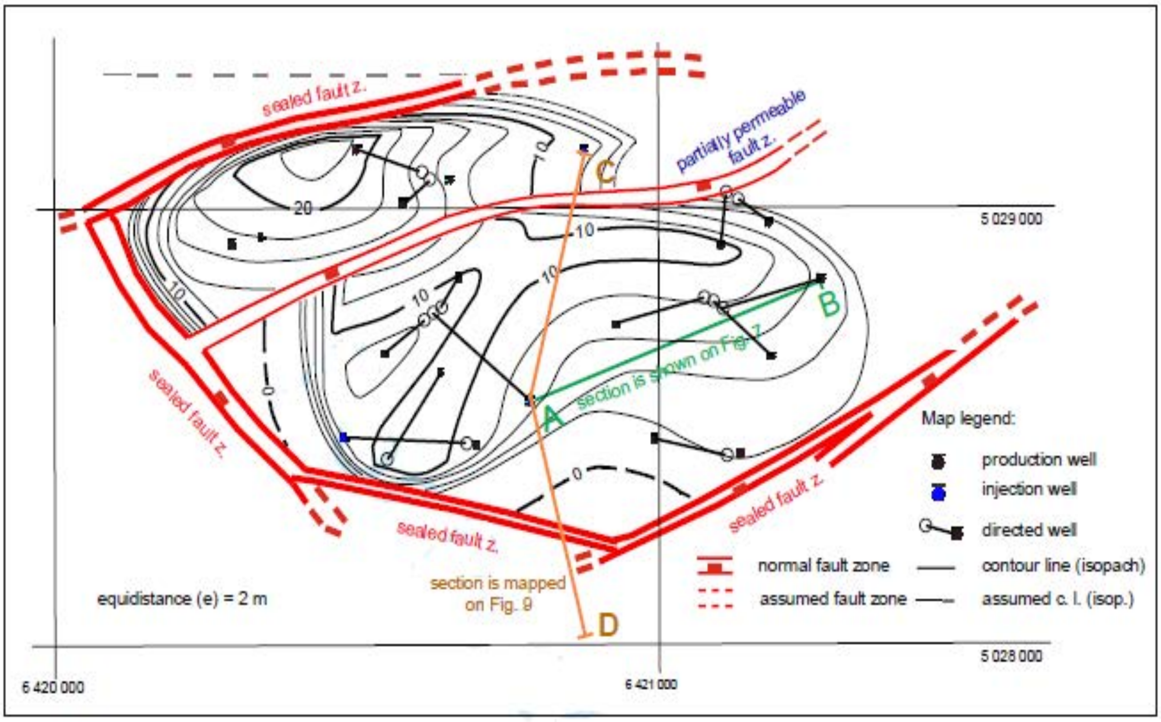

Figure 6: Isopach map of the "K1" hydrodynamic units, as the largest production volume inside the "K" reservoir (redrawn after data available with permission from archive of INA Plc.)

The areal extension of "K1" unit can be easily observed in Figures 6 and 7, where the isopach "0 m" mostly follows the sealed fault zones on margins. The thickest isopach ("22 m") in the NW part indicates the location of the depositional centre, where the largest volumes of psammitic detritus had been deposited. Oppositely, on the margins, especially ESE, the thicknesses are significantly lower, and sandy detritus included significant quantities of silt and clay. The entire structure had been defined by fault zones during its evolution, which created a strike-slip structure. Consequently, reservoir sandstones locally pinch out, caused by fault zones and/or transitional lithofacies at the margins (see **Figure 7**). In such systems, hydrocarbon recovery is not simple, even in the case of water flooding, because such injection plans and volumes can be validated only after some production period, i.e. based on «reservoir variable response» like pressure or water ratio.

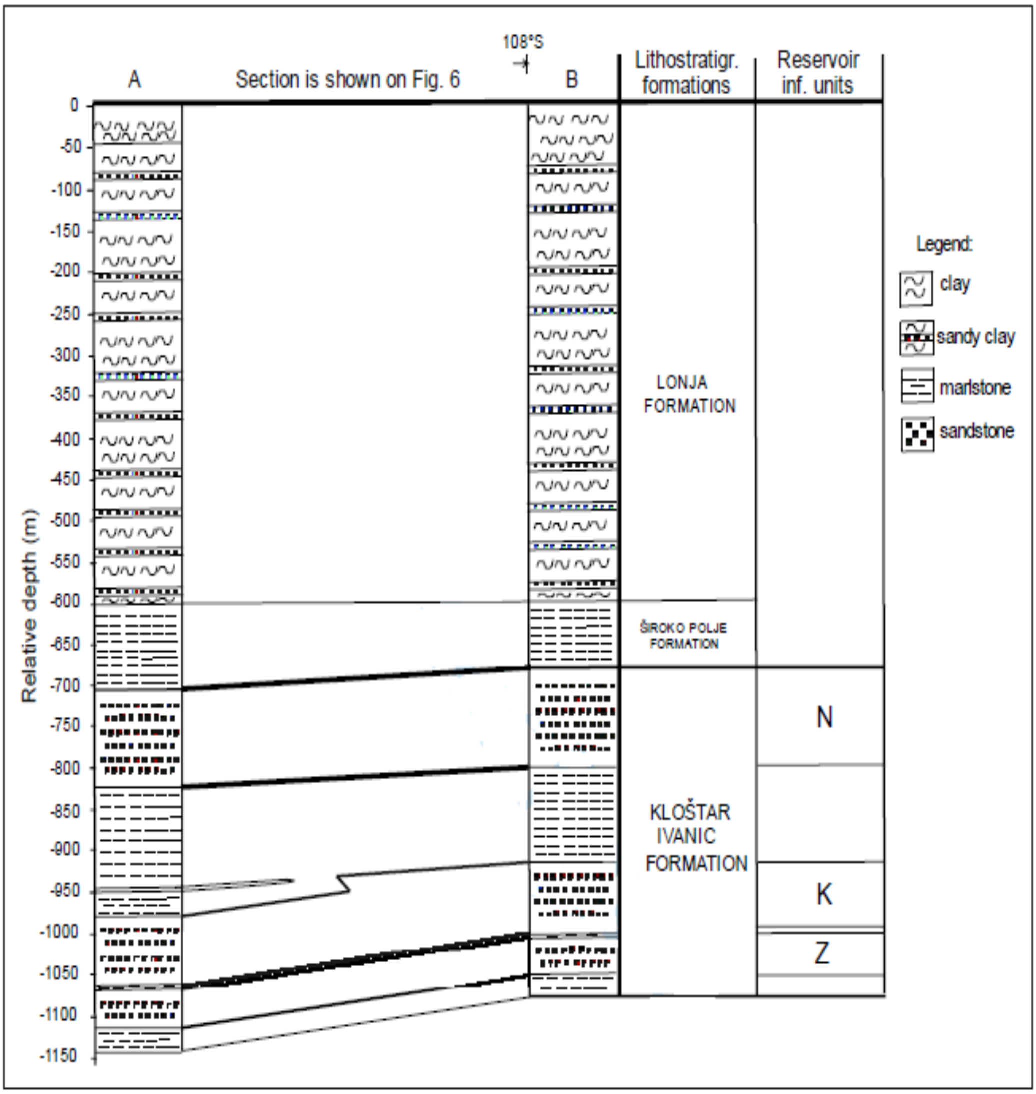

Figure 7: The geological section A (injection well) – B (production well). It is also shown on **Figure 6**

4. Water separation-injection system applied in the analysed sandstone reservoir ("K")

The production of hydrocarbons and water had been measured in five measuring stations and collected in the dispatching station (see **Figure 8A**). The dehydration process has been modified according to the reservoir characteristics and, especially, the issue regarding the sand in the produced fluids. Such a production process is crucial regarding the heterogeneity of the reservoir, because in produced fluid, the water content and portion of fine-psammitic and pelitic detritus are relatively high. Furthermore, some of the shallowest Upper Pontian reservoirs are weakly consolidated which resulted in a larger portion of detritus in fluid and represents an additional load for the desanding separator.

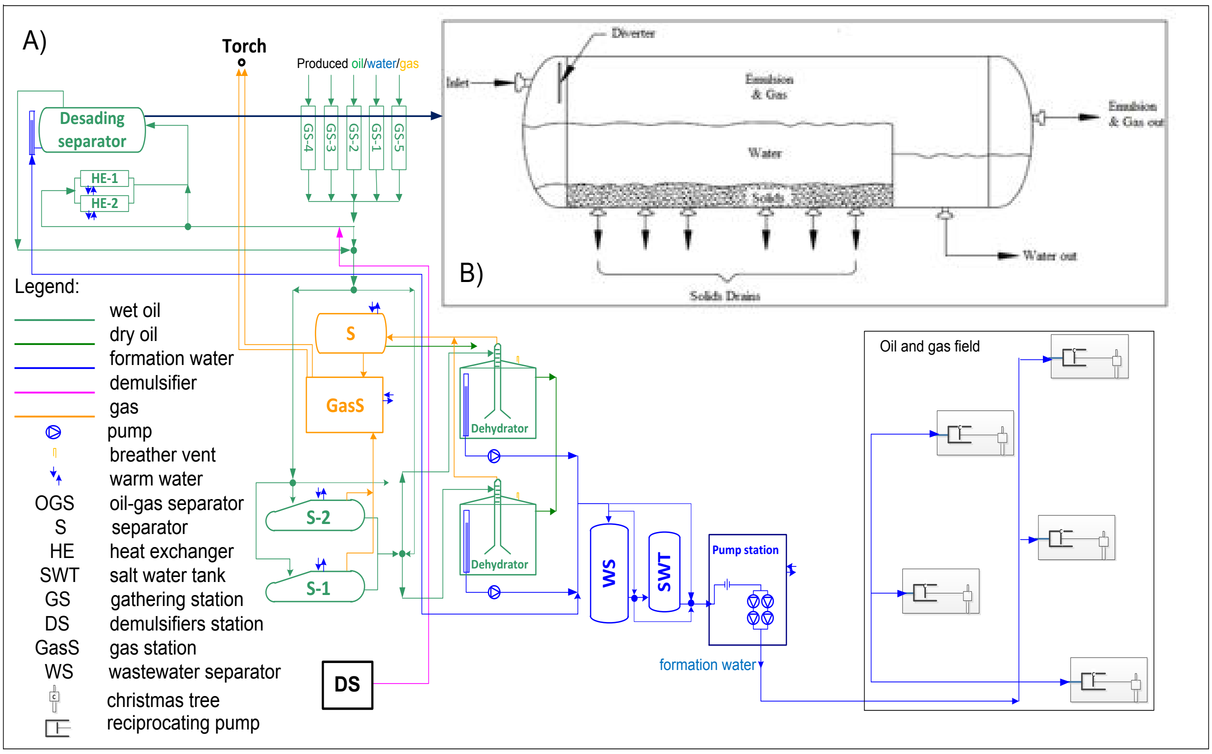

Figure 8: A) A schematic sketch of water separation and the injection process in the analysed reservoir (redrawn after data available with permission from archive of INA Plc.). B) Side view of the desanding separator applied for the "K" reservoir/"K1" hydrodynamic unit (modified after: **Stewart & Arnold, 2009).**

The applied separator type (**Figure 9B**) for processing of the "K" reservoir fluid, could be easily adapted for any lithologically similar Neogene reservoir in the CPBS. In such a separator, any fine-psammitic and pelitic detritus, has been deposited through a diagonal fluid flow. Solid residue is occasionally removed from the device using drains, but to prevent plugging, the entire separator needs to be cleaned periodically. Moreover, during the separation, fluids are also drained through special drainpipes; the emulsion (of oil and water) separately from the gas. Eventually, the emulsion is processed in a heat exchanger where demulsifiers are added. As a result, surface-active agents are absorbed at the oil–water interface, rupturing the tough film (skin) surrounding the water droplets, and/or displacing the emulsifying agent and forcing the emulsifying agent back into the oil phase (e.g., **Arnold and Stewart, 2008**). At the end, the fluid enters the dehydrator where the formation (field) water is separated from the inlet fluid.

By applying the previously described separation method, larger quantities (see **Table 2**) of oil (both in relative and absolute ration) were produced. Numerically, such a process made it possible to increase the oil ratio in the totally recovered fluid by approximately 25 %. Moreover, the solid particles had been efficiently removed from the processed liquid, maintaining the reinjection of processed field water. The efficiency of the "JM" field's dehydration is more than 99 %, i.e. it is the volume of the field water which is removed from the recovered oil. The process is controlled on a daily basis which proved it as a typical successful separation and dehydration method for Neogene sandstone reservoirs in the CPBS. Using such an approach, the economical production can be extended on a very late production stage of the mature fields in the CPBS (e.g., **Ivšinović and Dekanić, 2015; Ivšinović, 2016**).

Table 2: Results of the applied separation process in the gathering station of the "JM" Field

	Year						
	2009	2010	2011	2012	2013	2014	2015
Water	100*	0.96	0.94	0.96	0.95	0.91	0.93
Oil	50**	0.65	0.79	0.78	0.71	0.69	0.75
* referent relative value of produced water in the first recorded year							
** referent relative value of the produced oil in the first recorded year, also in absolute relation with water							

Such a system also reached the goal - to inject water into reservoir rock(s) without plugging or reducing permeability, which could happen because of particulates, dispersed oil, scale formation, bacterial growth or clay swelling (e.g., **Patton 1990, Bader 2007, Igunnu and Chen, 2014**). So, the formation water, after its separation from produced fluid, is distributed by a low-pressure pipeline to the injection wells. Every injection well is equipped with a reciprocating pump that ensures the pressure of the injected water be the same as the reservoir pressure (e.g., **Ivšinović, 2017**). The reciprocating pumps are constructed for working conditions under pressures higher than 200 bars and capacities up to 1000 m^3/d (**Sečen, 2006**). Such an injection well is housed in a container in order to protect the surface injection equipment, including three packers and a landing nipple for the storing of Instruments. However, the influence of each such injection well system is strongly restricted with reservoir lithology, i.e. heterogeneity. Even in the case that the injection fluid will not deteriorate reservoir petrophysics, lithological heterogeneity strongly determines the injected fluid penetration radius (see **Figure 9**).

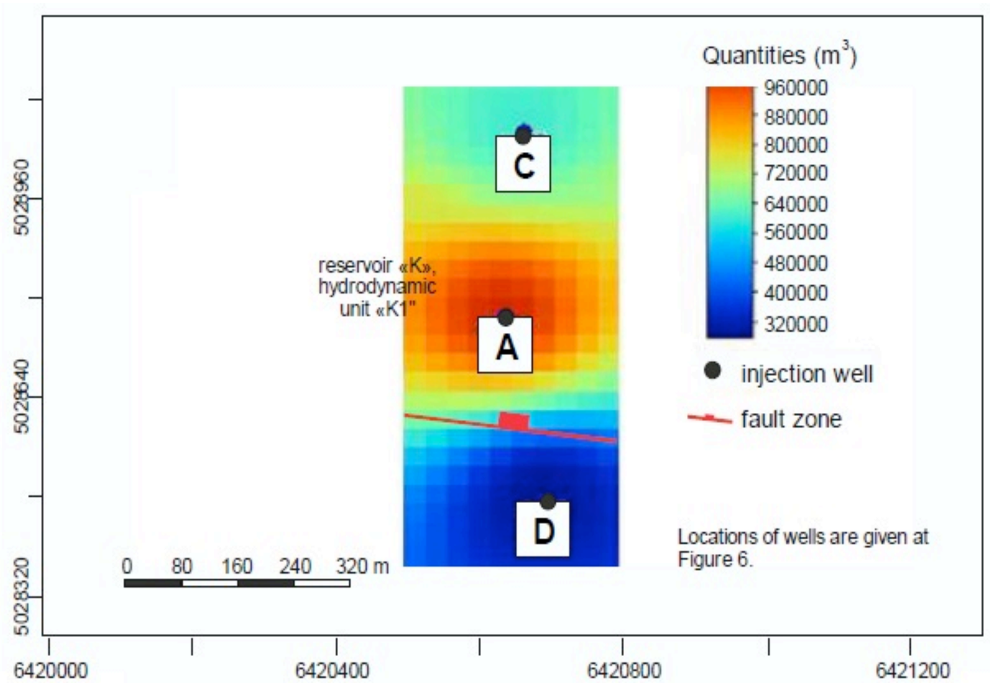

Figure 9: Injection volumes of particular wells are strongly influenced by local reservoir lithology fault zones. The map had been interpolated using the Inverse Distance Weighting method, due to polygonal methods do not consider appropriate lithology.

5. Conclusions

The presented case study, from the Sava Depression, Neogene (upper Miocene) hydrocarbon reservoir located in Northern Croatia led to the following conclusions:

• The entire area of the CPBS (Northern Croatian Upper Miocene subsurface deposits) is characterised by numerous turbiditic sandstones, where many of them are saturated with hydrocarbons.

• Due to the turbiditic origin, such reservoirs are often heterogeneous, especially in their lateral, marginal parts, where the portion of fine-grained sandstones and siltstones can be significant.

• This fact strongly affects the production from such reservoirs and, as seen from the largest "K" reservoir in the "JM" Field (Sava Depression).

• The production during the mature phase is supported with modified gravel packs, making it possible to produce even from poorly consolidates, Upper Miocene deposits, or from silty or clayey sandstones at the field margins.

• This is the reason for the application of another separation process, using special surface equipment (separator and dehydrator). Although the entire technology is well known, adaptations provided for the Neogene sandstone reservoirs in the Croatian part of the Pannonian Basin System are presented in this study.

• Lithological settings also influenced the water injection plan, i.e. the distribution of injection wells in a particular reservoir and/or hydrodynamic unit. They have cased and perforated injection intervals, which ensures the larger injection ranges into the reservoir. The application of the single injection system was especially efficient in the "JM" Field, although even there the injection radius is very local, due to lithological heterogeneity and pinch outs of reservoir beds.

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Abstract in Croatian

Odnos između taložnog okoliša pješčenjaka i sustava za utiskivanja vode, primjer ležišta ugljikovodika gornjeg miocena u sjevernoj Hrvatskoj

U Savskoj depresiji (Sjeverna Hrvatska) prisutno je tipično donjoponstko pješčenjačko ležište "K", a predmet istraživanja je hidrodinamička jedinica "K1". Litologija ležišta jako je pod utjecajem regionalnih geoloških postavki, osobito jezerskih sedimentnih okoliša s periodički aktivnim turbiditnim nanosima. Konturne karte i korelacijski profili pokazali su porast pelitnog detritusa u pješčenjaku i uz moguće progresivno isklinjavanje. Dodatno, granične zone rasjeda uzrokuju izduljene i raskomadane strukture ležišta tijekom Donjeg Ponta, koji su kasnije preokrenuti u postojeće antiklinale. Takve geološke postavke utjecale su na cijeli pridobivni sustav i opremu za utiskivanje i odvajanje vode. Odgovarajući izbor tehnologije unapredio je pridobivanje ugljikovodika u odnosu na apsolutne volumene kao i na omjer nafte i vode. Sličan pristup odabiru tehnologije je bio vrlo uspješan na duže vrijeme i na ostalim poljima u Savskoj depresiji, tj. u heterogenim pješčenjacima s velikim udjelom pelitnog detritusa.

Ključne riječi: neogen, pješčenjaci, ugljikovodici, utiskivanje fluida, dehidracija, Hrvatska

Author contribution

Josip Ivšinović done all paper.

2nd Croatian congress on geomathematics and geological terminology, 2018

Original scientific paper

Correction of the seismic attribute sweetness by using porosity-thickness map, Lower Pontian LP reservoir, Sava Depression

Kristina Novak Zelenika[1], Saša Smoljanović[1]
[1]INA-Oil Industry Plc.,Av. V. Holjevca 10, Zagreb

Abstract

The seismic attribute of sweetness is often used to define the quality of the hydrocarbon reservoir due to the ability to identify sandstone bodies, which have a stronger reflection compared to the surrounding marls. The quality of deposits can also be described by porosity-thickness maps. Coarser material in the center of the channel has higher values of porosity, but also greater thicknesses. By multiplying these two variables, depositional channels would be emphasised. The LP reservoir of the A field, located in the Sava Depression, has been analysed. The Lower Pontian LP reservoir is composed of sandstones, deposited by a regional transport of turbidite currents. The structure of the reservoir is an anticline with two maxima separated with the structural saddle. The LP reservoir was analysed with a seismic attribute of sweetness and with a porosity-thickness map. The m aps showed many similarities, but there were certain differences, especially in the central part of the southern maximum. According to the well data this part show lack of LP reservoir, and the seismic is of poor quality. Correlation of the mapped parameters is confirmed by correlation coefficients (medium correlation, for the whole analysed area and strong correlation only for the northern part with thicker sandstones). In the central part of the southern maximum, the correlation between the attributes of sweetness and the porosity-thickness map was not established. The seismic attribute correction is made by the ratio function of the sweetness attribute and the porosity-thickness values for the entire area and for the northern part. Corrected maps of seismic attribute are only slightly different than the original ones.

Key words: seismic attribute sweetness, porosity-thickness map, sandstones, Sava Depression, Croatia.

1. Introduction

Seismic interpretation is an important element, both in exploration and in the development of hydrocarbon reservoirs. Seismic attributes have become an indispensable tool in the description of the underground, and the attribute of sweetness is often used to define the quality of the deposit itself. Therefore, it is very useful in identifying isolated sand bodies due to their stronger reflection compared to surrounding marls. However, in the environment with sandstones and marls intercalations, it will not yield such good results (**Hart, 2008**). **Radovich & Oliveros (1998)** pointed out that the seismic attribute of sweetness, apart from the sandy bodies, also indicates their saturation with hydrocarbons due to high amplitude and low frequency. However, there are some examples of sweetness attribute interpretation where it has been proven that the same attribute values have sandstones saturated with oil and water.

The quality of the reservoir can also be described by the porosity-thickness map, starting from the fact that each of the mentioned variables is a direct result of the deposition itself. Suppose that in the centre of the channel, due to the stronger current, coarser material will be found, unlike the edges of the channel, where the current strength decreases and a fine grained detritus begin to deposit. Accordingly, coarser material in the centre of the channel will have higher values of porosity and thickness. Multiplication of these two proportional parameters will emphasize the quality of the reservoir and define the position of depositional channels in the analysed area. Of course, the precondition for such a method of interpretation is a large number of input data, required for quality geostatistical analysis and distribution.

Since both parameters (seismic attribute sweetness and porosity-thickness map) describe the quality of the reservoir, they can be correlated. Their correlation was made for the Lower Pontian LP reservoir of the A field in the Sava Depression. Numerous similarities are found in the output maps, but there are some differences. The highest differences are in areas where the sand body is very thin or even not present, which match with a very poor seismic. The similarities in the output maps are mathematically represented by the coefficient of correlation. Also, the ratio equations of the sweetness attribute and porosity-thickness values at well locations are also shown, for the entire field area and for

Corresponding author: Kristina Novak Zelenika
Kristina.novakzelenika@ina.hr

the area of the best map matching (northern part of the field). The same functions were used for the correction of the seismic attribute, since the porosity-thickness map more precisely describes the reservoir.

2. Geological settings of the Sava Depression

According to **Ćorić et al. (2009)** the oldest Miocene deposits in the Sava Depression are of the Badenian age, which discordantly lay on the Palaeozoic-Mesozoic basement. Extensional tectonic got stronger during Badenian and the main depositional depressions have been opening. Mechanisms that deposited siliciclastic material of local origin in the shallow sea were alluvial fans (**Tišljar, 1993; Malvić, 1998, 2006**).

The end of Badenian and the beginning of the Sarmatianis are characterized by the deposition of calcareous marls and clayey limestones. The area had become calmer due to weakening of the extension tectonic. During that time clayey marls and sandstones were deposited (**Vrbanac, 1996; Rögl, 1996, 1998**). The Lower Pannonian deposits are represented by rhythmic changes of clayey limestone, silty marl, marl and sandstone, which were filling brackish shallow area (**Rögl & Steininger, 1984; Vrbanac, 1996; Rögl, 1996; 1998; Magyar & Geary, 1999; Magyar et al., 1999; Muller et al., 1999**).

On the Lower Pannonian, Upper Pannonian is followed. In the Sava Depression, sandstones of that time have significant amount of hydrocarbons. Lithologically, they are presented with marls, silts and sandstones. Sedimentation at the time of the Upper Pannonian indicates the beginning of a significant change in the depositional environment when the turbid currents mechanism began to dominate (**Vrbanac, 1996; Rögl, 1996, 1998**). The material transport was regional with a source in the Eastern Alps (**Šimon, 1980; Malvić et al., 2005**).

The Lower Pontian sandstones were deposited through turbid currents, and the material transport direction was also regional. In calm periods, when the turbid currents were not active, marl, as a sediment typical for the deep water environment, was deposited.

During Upper Pontian, the sedimentation mechanisms become local. The depositional area continued to fill with material. The Upper Pontian deposits are clayey marls, marly clays and clays and the appearance of lignite (**Rögl & Steininger, 1984; Vrbanac, 1996; Rögl, 1996, 1998**).

During Pliocene and the part of Pleistocene, the remaining shallow parts were filled with marly clays, marls and sporadically sandy marls. Coarse grained material followed (gravel, sand) and clay with the appearance of lignite. The final inversion of the structure and sedimentation of sediments characteristic of glacial and interglacial periods is typical for Quaternary (**Velić & Saftić, 1991, Velić & Durn, 1993, Velić et al., 1999, Bačani et al., 1999**). The youngest sediments are represented by loess, clay, humus, gravel and sand. Chronostratigraphic units, as well as transport and depositional mechanisms in Sava Depression are given in **Figure 1**.

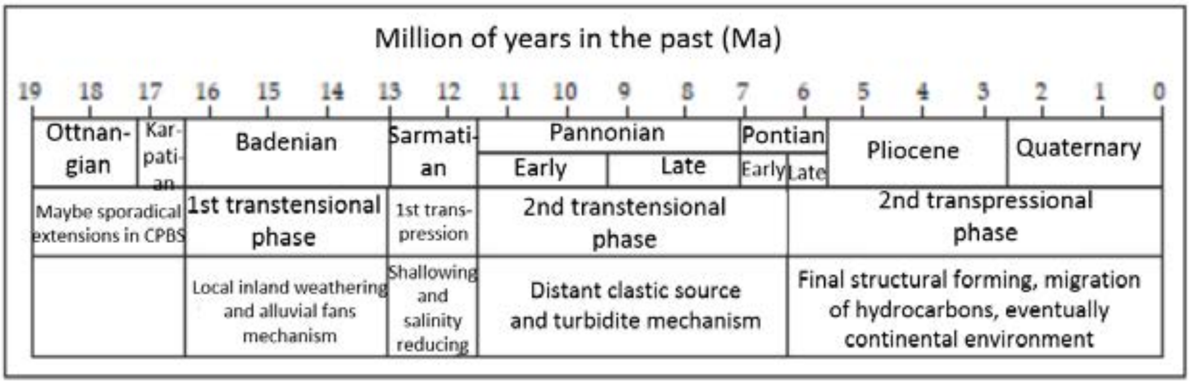

Figure 1: Chronostratigraphic units and transport and depositional mechanisms (**Malvić and Velić, 2011**)

Neogene sediments can be divided into three depositional megacycle (**Velić et al., 2002**). The first is represented by the sin-rift extension, with the high influence of tectonics on sedimentation, when pull-apart structures were formed. The Badenian is marked by the first transtension, and the Sarmatian by the first transpression phase (**Figure 1**). Sediments of the second megacycle were deposited at the time of re-extension of the basin (**Horvath & Tari, 1999**) during Pannonian and the Pontian (**Figure 1**) (**Velić et al., 2002**). The deposits of the third megacycle belong to the second transpression (**Figure 1**), with the structure inversion. Normal faults, which were active during the extensional phase, reactivate and change the character. In the uplifted parts numerous transitional structures were formed.

2.1. Geological settings of the analysed area

Field A is located about 50 km east of Zagreb in the area of the Sava Depression. It fits into the development of the Sava Depression. Based on the deep wells data, a normal sequence of chronostratigraphic units (Sarmatian, Lower Pannonian, Upper Pannonian, Lover Pontian, Upper Pontian, Pliocene and Quaternary) was established.

Sarmatian sediments were proven only in four wells of the A field. They were represented with calcareous and sandy marls, marly sandstones and conglomerate sandstones. Lower Pannonian deposits are more or less calcareous marls. Lithologically, Upper Pannonian is represented by grey sandy and low calcareous marls intercalated with fine-grained quartz-mica sandstones. Upper Pannonian and Lower Pontian sandstones are the main hydrocarbon reservoirs of the A field. The Lower Pontian sediments consist of clayey and sandy marls and fine to medium-grained sandstones. Analysed LP reservoir is located within these deposits. Clayey and marly sediments and sandy intervals of small horizontal distribution are characteristic for Upper Pontian deposits. Lithologically Pliocene consists of sandy clay and clayey sandstones. There is vertical and horizontal interlayering of clay, sand and gravel. Sandstones occur in the form of limited lenses and are sometimes filled with gas. The Quaternary is represented by humus, sandy clay, fine-grained sand and gravels of different granulations. The lithostratigraphic column of the field A is shown on **Figure 2**.

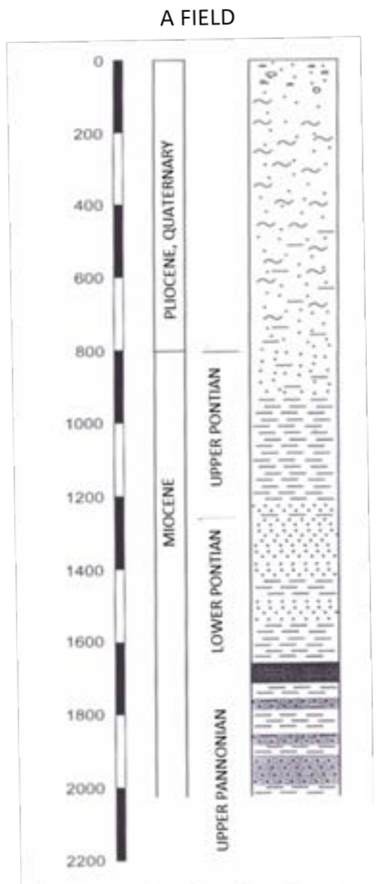

Figure 2: Lithostratigraphic column of the A field

The field structure is an anticline with two maxima, north and south, with a structural saddle between them (**Figure 3**). The main direction of the structure is northwest-southeast. In the area of the north and south maximum, the LP reservoir is gas prone. From the shallower and deeper sand intervals, it is divided by continuous marls with an average thickness of 10 to 15 m. There are good reservoir properties in the northern part of the reservoir and in the edge of the south maximum. The basic physical parameters of the reservoirs were determined based on the quantitative interpretation of the well logging and the results of core analysis.

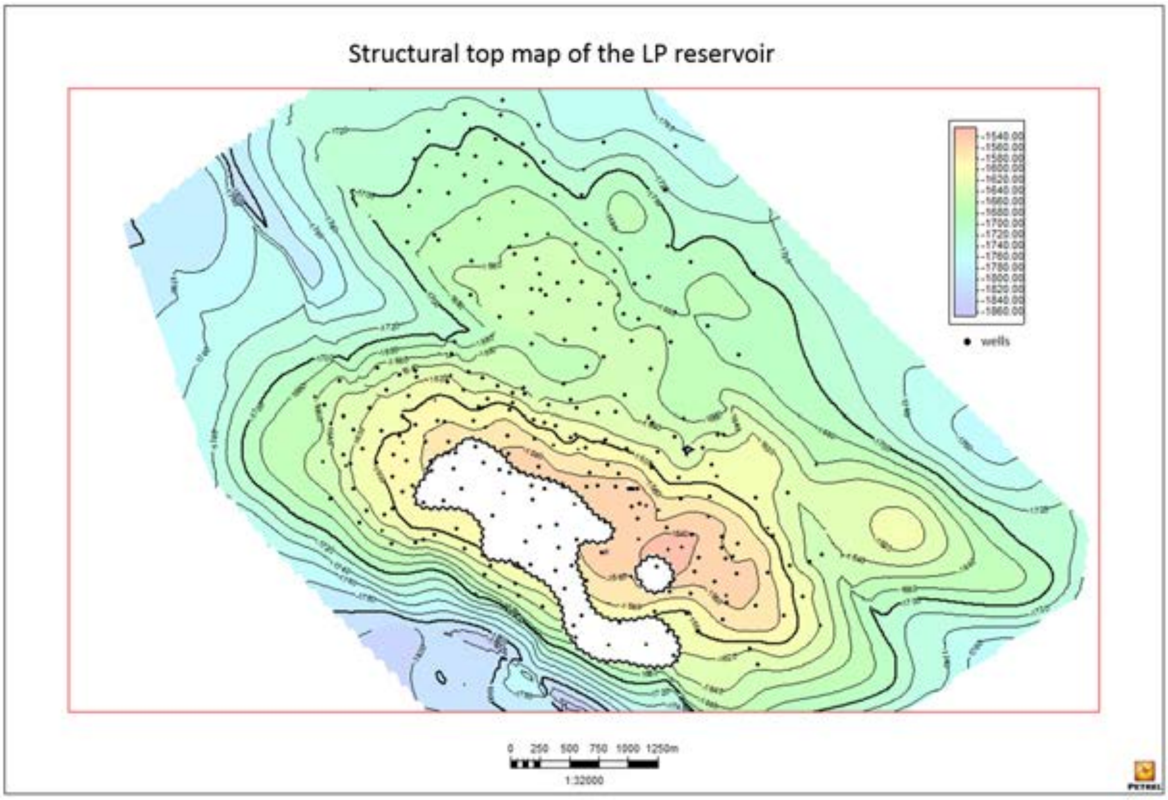

Figure 3: Structural top map of the LP reservoir

3. Correlation between seismic attribute sweetness and porosity-thickness map of the LP reservoir

The seismic attribute sweetness is interpreted in a 16 ms interval (8 ms above and 8 ms below) of the interpreted horizon (**Figure 4**). The problem is the central part of the field with poor seismic. The well data show very thin or even lack of the LP reservoir in the central part. So, it is possible that the interval of +/- 8 ms is actually affected by the sand bodies above or below the reservoir itself. Therefore, in some parts, attribute show higher values than expected. Of course, the seismic interpretation of the analysed horizon is also questionable in this area. However, regardless of the seismic quality, the map can generally point to depositional channels of the regional NW-SE direction.

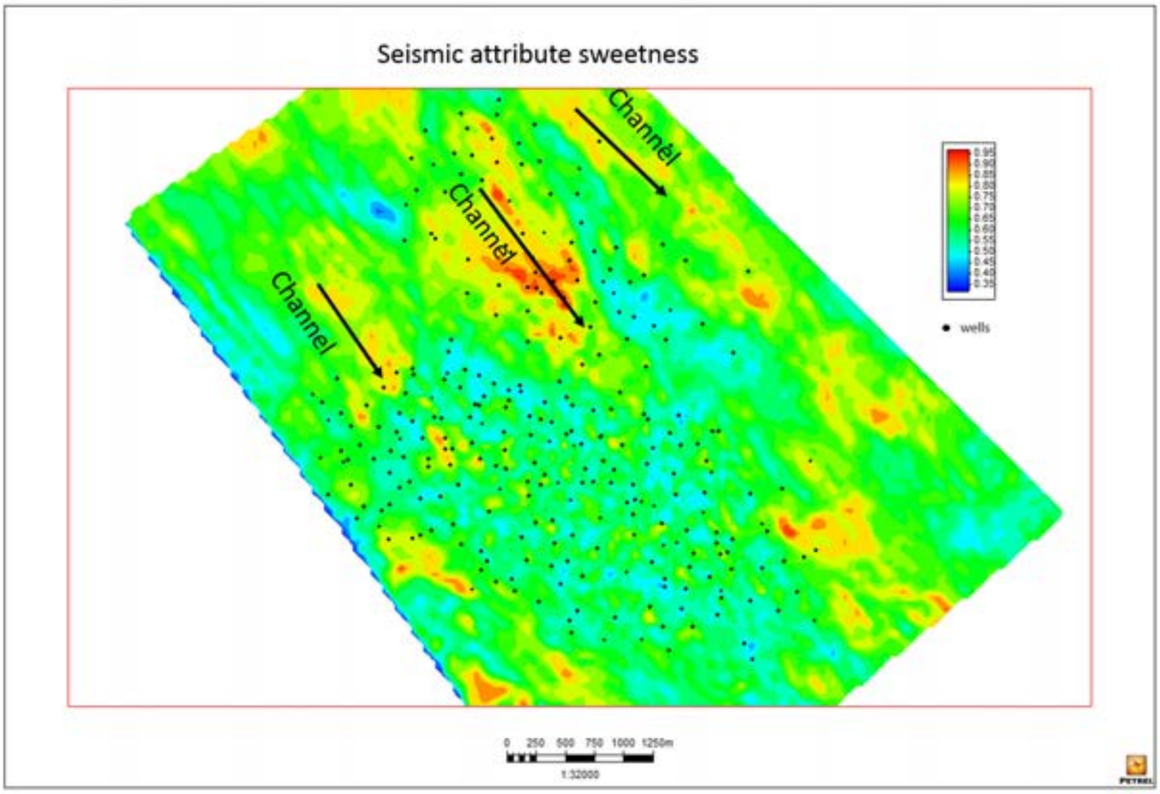

Figure 4: Seismicattributesweetnessinthe interval of 8 ms above and below the interpreted LP horizon

Due to the huge amount of data, detail variogram analyses were made for the porosity distribution. Porosity was distributed by the Ordinary Kriging method. Thickness represent the total thickness of the zone from the top to the bottom of the reservoir. Considering the assumption that higher values of porosity and thickness have sandstones in the central part of the channel, two variables (porosity and thickness) are multiplied to emphasize sand bodies, i.e. depositional channels distribution. Average map of distributed porosity multiplied with total thickness is shown in **Figure 5**. Visually, there is great similarity with the seismic attribute sweetness map. However, there are some differences. The southern sedimentation channel is visible only on the seismic attribute. It is not visible on the porosity-thickness map due to the lack of well data. Furthermore, porosity-thickness map clearly show lack of the LP reservoir in the central part of the south maximum, where the seismic attribute shows certain values, but the sedimentation bodies are not visible. Therefore, in the case of a sufficient number of well data, it can be assumed that porosity-thickness map more precisely describes the distribution of depositional channels.

Compared multiplied porosity-thickness and sweetness values were normalized. Correlation has been proved mathematically, with a medium correlation for the whole area and strong correlation in the northern part, where sandstones have higher thicknesses (**Figure 6**). However, there is no correlation between the seismic attribute and the porosity-thickness map in the central part of the southern maximum (**Figure 6**).

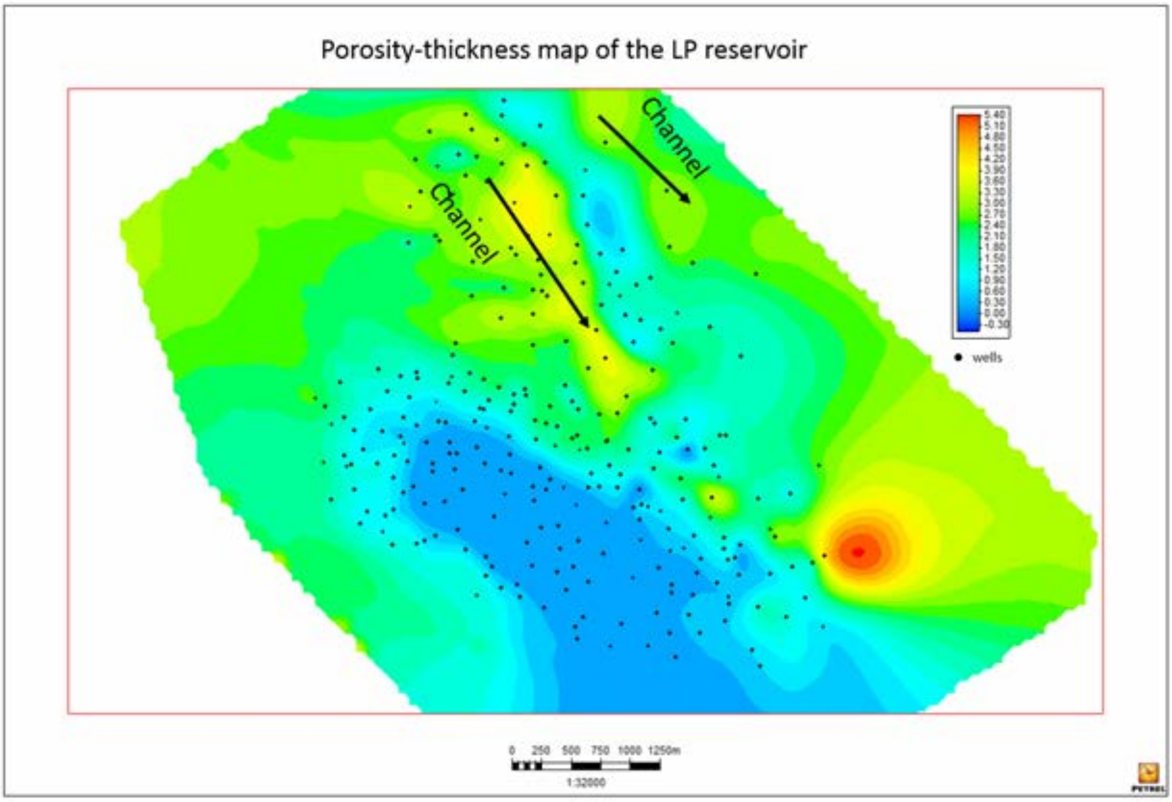

Figure 5: Porosity-thickness map of the LP reservoir

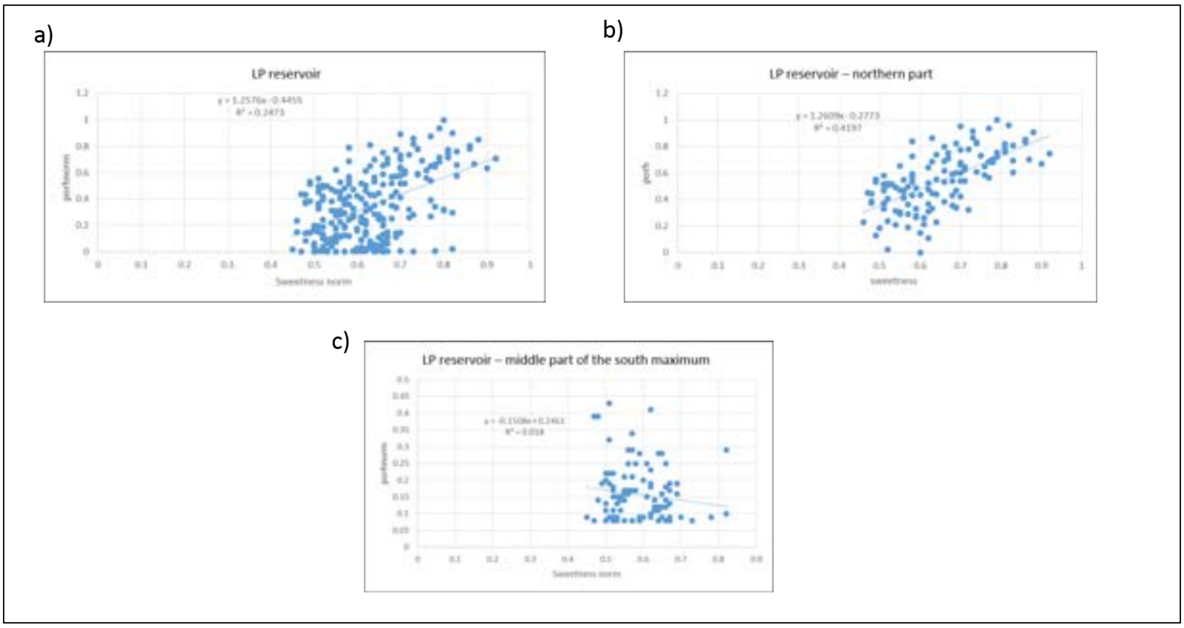

Figure6: Correlations of sweetness attribute and porosity-thickness normalized values for a) whole analysed area, b) northern part and c) central part of the south maximum

4. Correction of the seismic attribute sweetness

Considering that the porosity-thickness map of the LP reservoir is more representative in distribution of sand bodies, since it was made exclusively on the well data, the seismic attribute was corrected by the function of sweetness and porosity-thickness ratio for:

a) The entire field area, including all well data, with a medium correlation

$$y=1.2576x-0.4455 \tag{1}$$

b) Northern part of the field with a strong correlation

$$y= 1.2609x-0.2773 \tag{2}$$

Figures 7 and 8 show the comparison of the seismic attribute corrected by function for the entire area and function for the northern part. In both cases no significant change of attributes is noticed, especially for the central part of the south maximum, where correction is most needed. Only a minor change can be observed in the north and central channel, with slightly lower attribute values (less orange on the map).

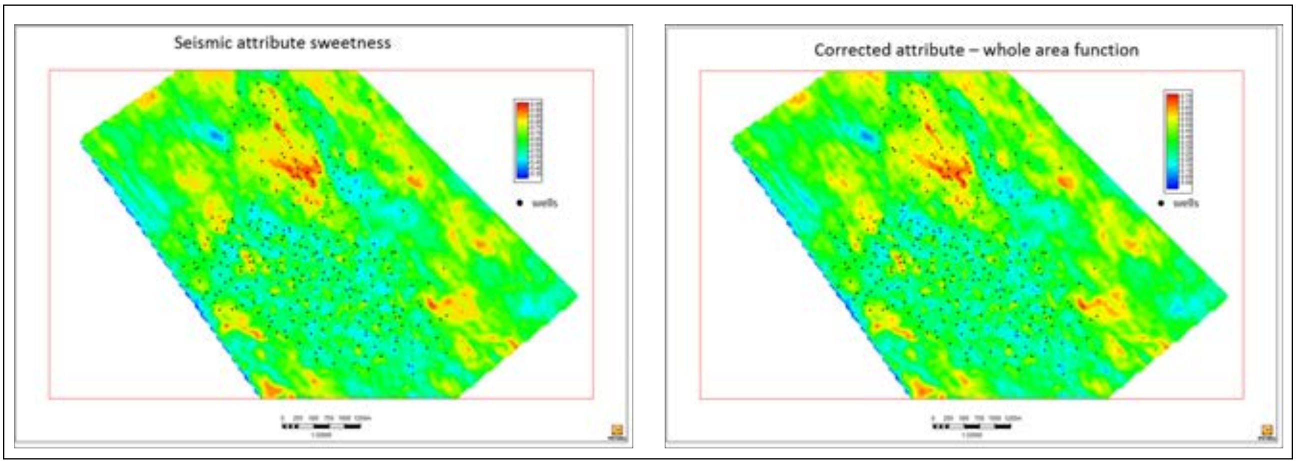

Figure7: Comparison of the seismic attribute of sweetness and corrected attribute by function for the whole area

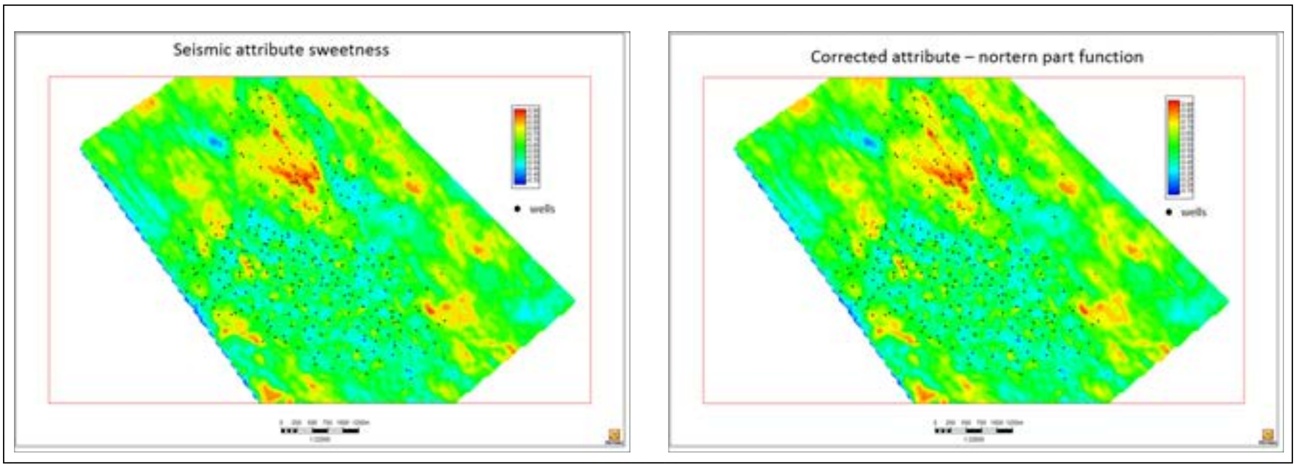

Figure8: Comparison of the seismic attribute of sweetness and corrected attribute by function for the northern part

5. Conclusion

The analysed LP reservoir of the A field is located in the Sava Depression. Sedimentologically it fits in the development of Sava Depression. The LP reservoir is Lower Pontian age. It is composed of material from the regional detritus transport through turbid currents from the Eastern Alps. The reservoir structure is an anticline with two maxima with structural saddle between them. The reservoir is composed of quartz-mica sandstones, which pinch-out in the central part of the southern maximum. It is separated from the shallower and deeper reservoirs by continuous marl, deposited in calm periods, when turbid currents were not active.

The LP reservoir was analysed by seismic attribute of sweetness and by porosity-thickness map in order to confirm depositional channels locations. Similarities in the sweetness and porosity-thickness maps were established. Interdependence of the mapped parameters is confirmed by the correlation coefficients; a) medium correlation, if all wells of the analysed area are involved, and b) strong correlation only for the northern part, with sandstones of greater thicknesses. Data used for correlation are normalized values of variables in well locations. In the central part of the southern maximum the correlation between the attributes of sweetness and the porosity-thickness map was not established. Visually, that part show the most significant differences in the maps. The porosity-thickness map clearly show lack of the LP reservoir, while the map of the seismic attribute show areas with even high values. Such high attribute values are dispersed, and sandy bodies are not visible.

The correction of the seismic attribute was performed by the ratio function of the seismic attribute and the porosity-thickness maps for the whole area, with the medium correlation and by the function for the northern part, where strong correlation of the parameters was established. The result is a corrected map of seismic attributes, which is only slightly different than the original.

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Extended abstract in Croatian

Korekcija seizmičkog atributa sweetness pomoću umnoška karata šupljikavosti i debljine, donjopontsko ležište LP, Savska depresija

Interpretacija seizmike važan je element, kako u istraživanju, tako i u razradi ležišta ugljikovodika. Seizmički atributi su postali neizostavni alat u opisu podzemlja, a atribut sweetness često se koristi za definiranje kvalitete samog ležišta. Stoga je vrlo koristan prilikom identifikacije izoliranih pješčanih tijela, zbog njihove jače refleksije u odnosu na okolne lapore.

Jednako tako, kvalitetu ležišta mogu opisati i karte umnoška šupljikavosti i debljine, polazeći od činjenice da je svaka od spomenutih varijabli direktna posljedica samog taloženja. Naime, pretpostavimo li da će se u središtu kanala, zbog jače struje taložiti krupniji materijal, za razliku od rubova kanala, gdje se jačina struje smanjuje te se počinje taložiti i sitniji detritus. Krupniji materijal u središtu kanala će sukladno tome imati veće vrijednosti šupljikavosti, ali i veće debljine. Umnožak tih dvaju proporcionalnih parametara dodatno će naglasiti kvalitetu ležišta te definirati položaj taložnih kanala u prostoru. Naravno, preduvjet za ovakvu metodu interpretacije je veliki broj ulaznih podataka potrebnih za kvalitetnu geostatističku analizu i prostornu distribuciju.

Analizirano ležište LP polja A nalazi se u području Savske depresije. Sedimentološki se potpuno uklapa u sliku razvoja Savske depresije. Ležište LP je donjopontske starosti. Sastavljeno je od materijala regionalnog donosa turbiditnim strujama iz područja Istočnih Alpi. Struktura ležišta je antiklinala s dva nadsvođenja između kojih se nalazi sedlo. Kolektorske stijene su kvarc-tinjčasti pješčenjaci, koji u središnjem dijelu strukture južnog nadsvođenja isklinjuju. Od plićih i dubljih ležišta dijele ga kontinuirani lapori, taloženi u dubljevodnim mirnim uvjetima, kada turbiditne struje nisu bile aktivne.

Ležište LP analizirano je seizmičkim atributom sweetness te kartom umnoška šupljikavosti i debljine, kako bi se utvrdilo rasprostiranje taložnih kanala. Budući da oba parametra (seizmički atribut sweetness i karta umnoška debljine ležišta i šupljikavosti) opisuju kvalitetu ležišta, oni se mogu međusobno uspoređivati. Utvrđene su sličnosti u kartama sweetness atributa i umnoška šupljikavosti i debljine. Međusobna ovisnost kartiranih parametara potvrđena je koeficijentima korelacije i to srednjom korelacijom, ukoliko se uključe sve bušotine analiziranog područja i snažnom korelacijom samo za sjeverni dio, gdje su pješčana tijela većih debljina. Podaci korišteni za korelaciju su normalizirane vrijednosti varijabli na lokacijama bušotina. U središnjem dijelu južnog nadsvođenja nije utvrđena korelacija atributa *sweetness* i umnoška šupljikavosti i debljine. Upravo taj dio i vizualno ima najveće razlike u kartama. Na karti umnoška

šupljikavosti i debljine jasno se uočava nedostatak ležišta, dok se na karti seizmičkog atributa uočavaju područja s čak visokim vrijednostima. Takve visoke vrijednosti atributa su raspršene, a pješčana tijela nisu vidljiva.

Korekcija seizmičkog atributa napravljena je pomoću funkcije odnosa atributa i umnoška šupljikavosti i debljine za cijelo područje, sa srednjom korelacijom i po funkciji za sjeverni dio, gdje je utvrđena snažna korelacija parametara. Rezultat su korigirane karte seizmičkog atributa koje se tek neznatno razlikuju od originala.

Ključne riječi: seizmički atribut *sweetness*, karta umnoška šupljikavosti i debljine, pješčenjaci, Savska depresija, Hrvatska.

Authors contribution

Kristina Novak Zelenika (PhD, reservoir modelling expert) provided part of theoretical background, provided distribution maps and conclusions. **Saša Smoljanović** (reservoir geology senior expert) provided parts of theoretical background.

2nd Croatian congress on geomathematics and geological terminology, 2018

Original scientific paper

Statistical analyses of Late Cretaceous clastic deposits from Mali Potok Creek (Medvednica Mt., Northern Croatia)

Jasenka Sremac[1]; Davor Kudrnovski[1]; Josipa Velić[2,4]; Marija Bošnjak[3]; Ivo Velić[4,5]

[1] University of Zagreb, Faculty of Science, Department of Geology, Horvatovac 102 a, 10000 Zagreb, Professor and M.Sc.

[2] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia, professor emerita

[3] Croatian Natural History Museum, Demetrova 1, 10000 Zagreb, Croatia, senior curator

[4] Croatian Geological Summer School, Pančićeva 5, Zagreb, Croatia

[5] Croatian Geological Institute, Sachsova 2, Zagreb, Croatia

Abstract

Statistical analyses were applied to the Late Cretaceous clastic deposits exposed along the flanks of the Mali Potok creek in Medvednica Mt., as an auxiliary tool in order to help determining the source of pebbles, depositional processes and position within the sedimentary basin. Particularly interesting is the comparison of the conglomerate matrix with the overlying sandstone. Matrix grain size exhibits normal distribution, with most abundant fractions between 0.125 and 0.5 mm and sorting coefficient 2.14. Sandstones are grain-supported, well sorted, with coefficient value 1.55. Asymmetrical distribution, with domination of small-sized clasts between 0.032 and 0.125 mm in diameter characterizes these deposits. Such distribution is in concordance with interpretation of sandstones as synorogenic turbidites. Clastic succession from Mali Potok Creek can be well compared with contemporaneous deposits in the wider area, particularly with recently studied clastic succession in the vicinity of the Medvedgrad Castle.

Keywords: Clastic deposits, statistics, Santonian-Campanian, Medvednica Mt., Croatia

1. Introduction

Late Cretaceous clastic deposits near the Medvedgrad Castle in the Medvednica Mt. (Northern Croatia) were recently studied in order to estimate their reservoir potential (**Sremac et al., 2018, submitted**). Contemporary clastic deposits crop out in Mali Potok Creek, south from the Medvedgrad succession (**Figure 1**). Clastic succession transgressively lies over the Palaeozoic low-metamorphic rocks. A continuous transition from conglomerates into sandstones, shales, and finally pelagic argillaceous limestones at this outcrop was first studied by **Kudrnovski (1993)**, while the neighbouring clastic deposits of the same age were described by several authors (**Crnjaković, 1979; Marinčić et al., 1995; Pavelić et al., 1995**).

Conglomerates are polymictic, clast- to matrix-supported with clasts of cobble, pebble and even boulder size, upto 75 cm in diameter. Clasts are commonly elongated in shape, well-rounded and often arranged parallel to the bedding plane. Most of the clasts originate from the nearby uplifted land, but some carbonate clasts are derived from skeletons of contemporary benthic biota. Matrix is of similar composition as the overlying sandstones.

The main purpose of this research was to compare the modal composition and size distribution of conglomerate matrix and overlying sandstones, and to find differences and similarities with the recently studied neighbouring locality near Medvedgrad.

Corresponding author: Jasenka Sremac
jsremac@geol.pmf.hr

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Figure 1: Position of exposures of Late Cretaceous conglomerates in the vicinity of Medvedgrad Castle. Locality Mali Potok Creek encircled (Google Earth, August 2018).

2. Methods

A detailed sedimentological log was reconstructed in the field (**Figure 2**). Pebbles were counted, sorted by lithology and measured in the field. Their lithology was more detailed studied after the preparation of thin sections. Heavy minerals probes and roentgen analysis were performed in the Department of Geology, Faculty of Science. Grain size distribution in conglomerate matrix and in sandstones was calculated and presented by simple Microsoft Excel tools. Sorting coefficient was obtained from the simple **Equation 1**:

So=SQRT(Q3/Q3) (1)

with SQRT as square root function, Q_1 being the smallest grain size and Q_3 being the largest grain size.

Figure 2: Details from the studied succession in the Mali Potok Creek: **a.** conglomerates; **b.** sandstones; **c.** overlying Scaglia limestone. Hammer size 33 cm.

3. Results

Conglomerates comprise clasts varying in size from 0.4 to 75 cm. According to the granulometric analysis provided in the field, by counting the 10 largest clasts in a layer (**Bluck, 1967**), pebbles (4-64 mm in diameter) and cobbles (64-256 mm) prevail. Average maximum clast size varies from layer to layer. It can be concluded that conglomerates comprise all size-groups of clasts, from pebbles, through cobbles, up to the boulders. Most of the clasts are well-rounded, although there are also angular fragments (**Figure 2a**). Smaller clasts are generally less rounded. Rounded clasts are in most cases elongate in shape, with longer axes parallel to the bedding planes. Exceptionally, in some layers longer axes are obliquely positioned towards the bedding planes. In basal horizons conglomerates are clast-supported, but the amount of matrix soon reaches 15%.

Terrigenous siliciclastic material prevails over the carbonate clasts. Green-coloured rocks were observed as the most abundant among the clasts. Microscopic analyses have shown the lithologies of low-metamorphic schists (quartz-chlorite, quartz-epidote and epidote-chlorite schists), spilites and, sporadically, diabases. White quartz clasts are clearly visible in the field, and other clasts belong to the quartzites, cherts, shales and siltites. Carbonate grains are autigenic, mostly comprised of skeletons of corallinaceans, corals, bivalves, echinoderms and large benthic foraminifera. Matrix is of sand to silt size. Sand-sized clasts make up to 98% of matrix (**Table 1, Figure 3**). Average diameter of matrix grains (median) is 0.26 mm (**Figure 4**). Sorting coefficient is 2.14, pointing to the poor sorting (**Müller, 1967**).

Table 1: Conglomerate matrix and sandstone grain size from Mali Potok Creek

	CONGL. MATRIX	SANDSTONE
GRAIN SIZE [mm]	PERCENTAGE OF GRAINS	PERCENTAGE OF GRAINS
2-4	1.1	0.5
1-2	9	1.2
0.5-1	19.1	0.5
0.25-05	21.9	2.2
0.125-0.25	31.6	8.4
0.063-0.125	15.1	40.1
0.032-0.063	2.2	39.2
0.016-0.032	0	7.9
	100	100

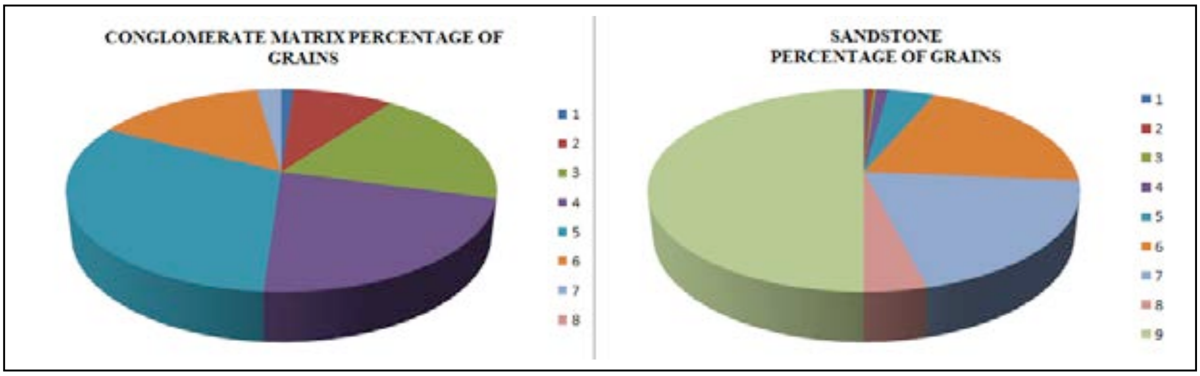

Figure 3: Comparison of grain size distribution in Late Cretaceous conglomerates and sandstones of Mali Potok Creek: Fractions: 1. 2-4 mm; 2. 1-2 mm; 3. 0.5-1 mm; 4. 0.25-5 mm; 5. 0.125-0.25 mm; 6. 0.063-0.125; 7. 0.032-0.063; 8. 0.016-0.032 mm.

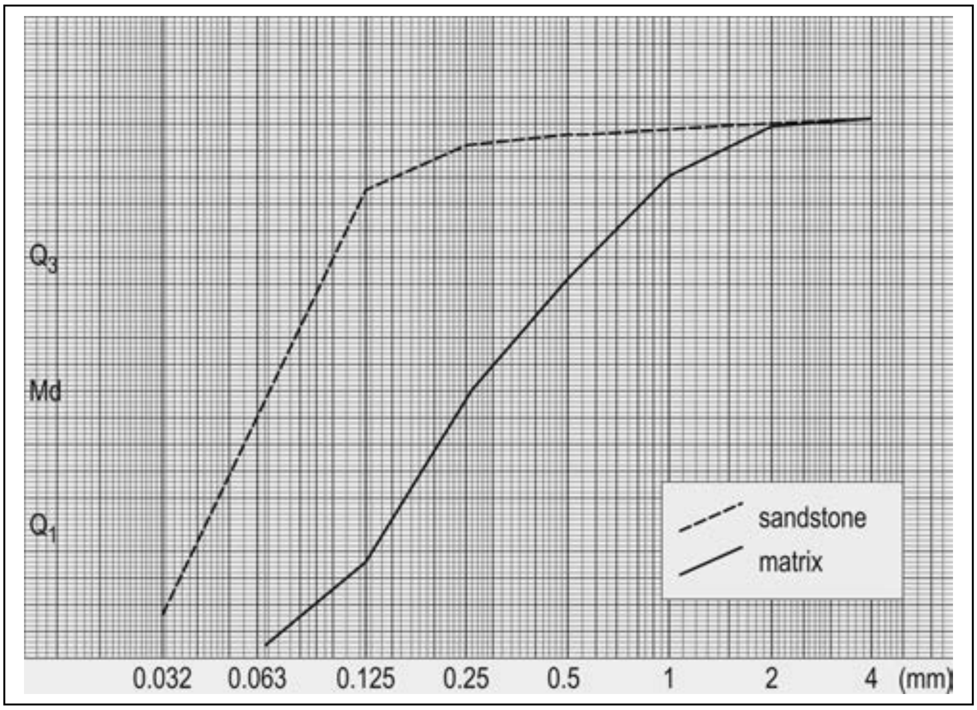

Figure 4: Results of granulometric analyses of conglomerate matrix and sandstones of Mali Potok Creek (**Kudrnovski, 1993**).

Sandstones overly the conglomerates forming a ca. 2.5 m thick horizon. Freshly cut, sandstones are dark-brown in colour. They are strongly tectonized and break up into irregular platty particles parallel to bedding planes (**Figure 2b**). Some layers are cross-lamminated (**Kudrnovski, 1993**). Sandstones are clast-supported, with fine-grained detritic matrix. Silt-sized grains dominate (**Table 1, Figure 3**). Grain size median is 0.067 mm (**Figure 4**), and sorting coefficient is calculated as 1.55, defining the rock as medium-sorted (**Müller, 1967**). Larger clasts are better rounded, while sand-sized clasts are angular or semi-rounded.

Modal composition of sandstones exhibits high percentage of quartz and rocks, with addition of feldspar and plagioclase (**Table 2, Figure 4**). Rock fragments comprise spilite, quartz-chlorite schist, quartzite and shale (**Kudrnovski, 1993**).

Table 2: Modal composition of Late Cretaceous sandstone from Mali Potok Creek.

GRAIN TYPE	%
QUARTZ	44.45
PLAGIOCLASE	1.7
FELDSPAR	1.7
ROCKS-VOLCANIC	8.8
ROCKS-METAMORPHIC	27.4
ROCKS-SEDIMENTARY	17.6

Heavy minerals compose 4.93% of the total sample weight (**Kudrnovski, 1993**). Epidote and opaque minerals are the most common, also with significant amount of chlorite (**Table 3, Figure 5**). Roentgen analyses proved the presence of visually determined epidotes and recorded the presence of titanite, not previously recognized among transparent heavy minerals (**Kudrnovski, 1993**).

Table 3: Composition of heavy minerals in Late Cretaceous sandstone from Mali Potok Creek.

HEAVY MINERALS	
GRAINS	PERCENTAGE
OPAQUE	37.5
CHLORITE	13.4
EPIDOTE	43.2
UNKNOWN	5.9
	100

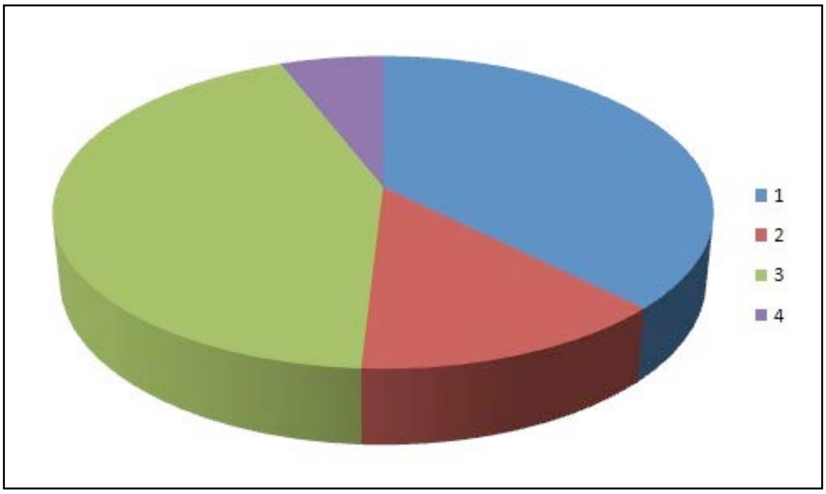

Figure 5: Distribution of heavy minerals in Late Cretaceous sandstone from Mali Potok Creek.1. opaque minerals; 2. chlorite; 3. epidote; 4. unknown.

A combined matrix and cement supports are present in sandstones. Matrix is silt-sized, composed of quartz and phylosilicate minerals (mostly micas). Mica grains are folded, indicating the compaction processes during the diagenesis. Deformed grains originate from shales, slate an phyllites, present as common clasts in underlying conglomerates. Carbonate cement occurs sporadically. According to the common classification (**Pettijohn et al.1972**), sandstones can be classified as lithic greywackes. In upper horizons, sandstones are overlain by shales and, finally, by pelagic Scaglia limestone, comprising the pelagic foraminifera of Late Cretaceous age (**Kudrnovski, 1993 and references therein**).

4. Discussion and conclusions

Terrigenous component of the studied clastic deposits in Mali Potok Creek in most cases originates from low-metamorphic Palaeozoic bedrocks, widely present in the studied area. These rocks are also the source of the mineral grains present in sandstones. Less frequent clasts composed of magmatic rocks are derived from the Mesozoic ophiolitic complex, also present in the wider area.

Lithological features and modal composition of conglomerates indicate their deposition from debris flows, as previously suggested by several authors (e.g., **Crnjaković, 1979; Marinčić et al., 1995; Pavelić et al., 1995**). A possible alluvial and/or deltaic palaeoenvironment was discussed by these authors, but **Sremac et al. (2018, submitted)** rather suggest short-term flows, transporting the material from the uplifted proto-Medvednica along collapse zones into the shelves and surrounding depressions.

Sandstones and shales are generally considered as synorogenic flysch deposits (e.g. **Lužar-Oberiter et al., 2012 and references therein**) reflecting the sinking of the Gosau-type basin (**Borojević Šoštarić et al., 2012**). Such interpretation is in accordance with modal composition of the studied clastic deposits, with rather common grain-size distribution within the conglomerate matrix, and asymmetrical distribution in overlying sandstones (**Figure 6**).

Sremac et al. (2018, submitted) consider the age of the clastic sequence as the Upper Santonian, as the pelagic Scaglia limestone comprise the Uppermost Santonian to Early Campanian microfauna. They also discuss the porosity and permeability of conglomerates and point to the possible importance of Cretaceous clastic deposits as reservoir rocks.

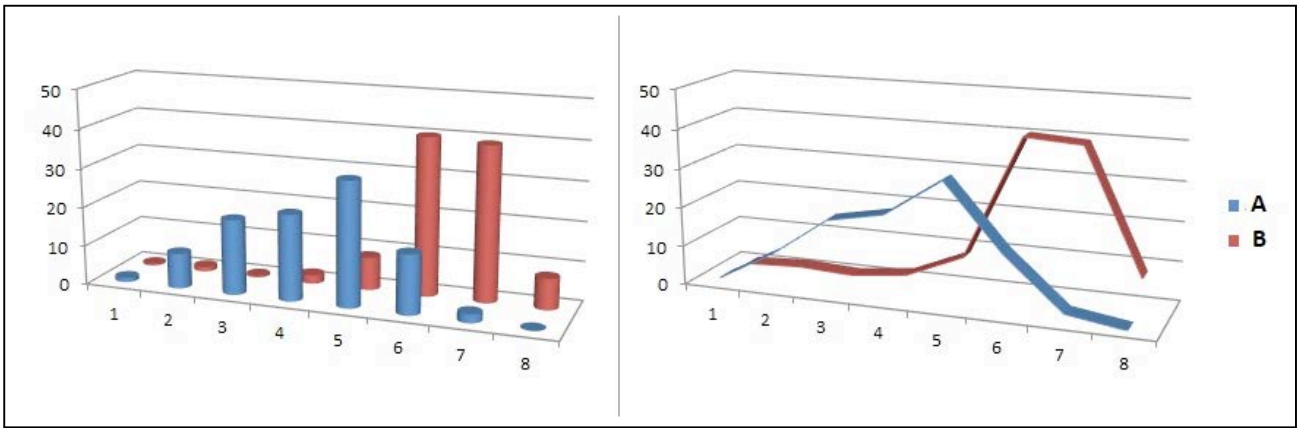

Figure 6: A comparison of grain size distribution (size categories 1-8 vs. percentage 0-50) in conglomerates (A, blue colour) and sandstones (B, red colour). Rather normal distribution is present in conglomerate matrix, while significant assimetry, with higher percentage of fine-grained fraction is visible in sandstones. Size categories as in **Figure 2**.

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Abstract in Croatian

Statistička analiza gornjokrednih klastičnih naslaga iz Malog Potoka na Medvednici (Sjeverna Hrvatska)

Statistička analiza načinjena je za gornjokredne klastične naslage na području Malog Potoka u Medvednici. Slijed naslaga pokazuje postupni prijelaz iz konglomerata u pješčenjake i šejlove, na kojima leže glinoviti Scaglia vapnenci. Konglomerati su polimiktni, klast- do matriks-potporni, s klastima veličine šljunka, valutica, sve do gromada. Klasti su izdužena oblika, dobro zaobljeni, često orijentirani paralelno slojnoj plohi. Većina klasta potječe iz naslaga okolne izdignute podloge, no ima i karbonatnih skeleta morskih organizama. Konglomeratni matriks je slična sastava kao pješčenjaci, koji leže u krovini. Veličina zrna pokazuje normalnu distribuciju, s najviše zrna u frakcijama između 0,125 i 0,5 mm i koeficijentom sortiranosti 2,14. Pješčenjaci imaju zrnsku potporu i dobro su sortirani, s koeficijentom 1,55. Asimetrična raspodjela, uz dominaciju sitne frakcije, između 0,032 i 0,125 mm, karakterizira ove naslage. Takva je raspodjela u suglasju s interpretacijom njihova postanka, kao sinorogenetskih turbidita. Na temelju planktonskih foraminifera iz najmlađeg dijela slijeda, Scaglia vapnenaca, određena je starost naslaga od santona do kampana. Slijed se može dobro usporediti sa sličnim naslagama na širem području, a osobito s nedavno istraženim profilom u okolici Medvedgrada. Na temelju dobivenih vrijednosti poroznosti i propusnosti konglomerata i nepropusne krovine zaključeno je da bi ove naslage trebalo detaljnije istražiti kao moguće ležišne stijene.

Ključne riječi: klastične naslage, statistika, santon-kampan, Medvednica, Hrvatska.

2nd Croatian congress on geomathematics and geological terminology, 2018

Original scientific paper

Biostatistic analyses of newly found pteropods (Mollusca, Gastropoda) in the Middle Miocene (Badenian) deposits from the southeastern Medvednica Mt. (Northern Croatia)

Ivana Derežić[1]; Marija Bošnjak[2]; Jasenka Sremac[1]

[1] University of Zagreb, Faculty of Science, Department of Geology, Horvatovac 102 a, 10000 Zagreb, Student, Professor

[2] Croatian Natural History Museum, Demetrova 1, 10000 Zagreb, Senior curator

Abstract

Fossil Pteropoda (Gastropoda, Thecosomata) have been recorded in the Badenian marine deposits of the Medvednica Mt. in the area of Čučerje and Marija Bistrica. During the new research of the Middle Miocene deposits in the southeastern part of the Medvednica Mt., new pteropods were found at the Goranec locality. They are preserved as casts and molds, jug shaped and determined as genus *Vaginella* Daudin, 1800. Biostatistics is a crucial tool in vaginellid species-level determination, which is often problematic due to their similar shell morphology and poor preservation. Based on the height, width and apical angle measurements of the collected casts and molds, biostatistical analysis were made and compared with the previous analysis of vaginellids from the Čučerje area. Majority of the specimens belong to *Vaginella austriaca* Kittl, 1886, which is the most abundant pteropod species in the Miocene deposits of the Paratethys. Here presented pteropod records point to the maximum of the Badenian marine transgressions, and contribute to the further palaeoecological and palaeogeographical research in the southwestern part of the Central Paratethys, Pannonian Basin System.

Keywords: Biometry, Pteropoda, *Vaginella austriaca*, Badenian, Medvednica Mt.

1. Introduction

Holoplanktic gastropods, pteropods, have wide horizontal marine distribution and represent an important group in palaeoclimatic, palaeoecological and palaeoceanographic research. Their rapid morphological evolution makes them excellent index fossils (**Pierrot-Bults and Peijnenburg, 2015**). Miocene pteropods are known from various localities from the Pannonian Basin System area, and some of them are index fossils widely used in biostratigraphic research of the Middle Miocene deposits of the Paratethys area (e.g. **Bohn-Havas and Zorn, 1993, 1994, 2002; Bohn-Havas et al., 2004; Zorn, 1991, 1995, 1999**). Their time appearance is also connected with the peaks of the Middle Miocene marine transgressions in the Paratethys (e.g. **Bošnjak et al., 2017 and references therein**). In the Northern Croatia area, which represents the southwestern margin of the Pannonian Basin System (e.g. **Pavelić & Kovačić, 2018 and references therein**), pteropods are recorded in the marine Middle Miocene (Badenian) deposits of the Medvednica Mt. (**Gorjanović-Kramberger, 1908; Kochansky, 1944; Bosak, 2017; Bošnjak et al. 2017**). During the new research of the Badenian deposits in the southeastern part of the Medvednica Mt., new pteropods were found at the Goranec locality (**Figure 1**) (**Derežić, 2018**). They are preserved as casts and molds, belonging to families Cavoliniidae Gray, 1850 and Limacinidae Gray, 1840, which are recorded in this area of the Medvednica Mt. for the first time. Most of the collected specimens belong to the family Cavoliniidae, genus *Vaginella* Daudin, 1800. Biostatistics is a crucial tool in vaginellid species-level determination, which is often problematic due to their similar shell morphology and poor preservation. Based on the height, width and apical angle measurements of the collected casts and molds, biostatistical analyses were made and compared with the previous analyses of vaginellids from the Čučerje area.

Goals of this research were to analyse and describe new pteropod findings on the Medvednica Mt. and to compare them with previous findings from this area in order to contribute to the knowledge of the Badenian marine environments and biostratigraphy of the Middle Miocene in northern Croatia.

Corresponding author: Jasenka Sremac
jsremac@geol.pmf.hr

Figure 1: Location map of the investigated area near Goranec locality (**Google Earth**, September 2018). Yellow pins mark here presented investigated outcrops.

2. Methods

During the field research in 2017 the Miocene deposits of the Goranec locality near Čučerje on the SE slopes of the Medvednica Mt. were analysed. Pteropods were collected from three outcrops of the Badenian „pteropod marls“ (**Figure 1**), marked as G1 (coordinates 45°53'48.74"N, 16°4'7.58"E), G2 (coordinates 45°53'51.94"N, 16° 4'3.56"E) and G3 (coordinates 45°53'52.12"N, 16° 4'7.94"E).

Collected material was analysed in the Department of Geology and Paleontology, Faculty of Science, University of Zagreb. Laboratory work included wet sieving technique. From each of the three collected samples, 30 dag was crushed and soaked into water with H_2O_2. After 24 hours' samples were sieved through meshes sizes 1000, 500, 250, 125 and 63 µm. Dry specimens were analysed under the stereomicroscope Olympus-SZX10 and photographed with Canon EOS 1100D camera. Photographs were saved in the Quick PHOTO CAMERA 3.0 programme.

Pteropods were analysed in the Croatian Natural History Museum in Zagreb. Vaginellids collected at localities G2 and G3 were chosen for the biostatistical analysis due to the numerous well preserved casts and molds. Specimens were cleaned, photographed, marked with temporary inventory numbers: G-2_L1 to G-2_L15 and G2-D1 to G2-D23 from locality G-2, and G3-1 to G3-38 from locality G3. Collected pteropods are housed in the Croatian Natural History Museum in Zagreb. Height, width and apical angle of the well preserved casts and molds were measured for the biostatistic analyses (**Figure 2**). All measured data were analyzed in the MS Excel program and biostatistic analyses of pteropods was based on the shell height/width ratio and apical angle histograms. Pteropod determination was based on the available literature (**Kittl, 1886; Janssen, 1984; Zorn, 1991, 1999; Janssen and Zorn, 1993, Cahuzac and Janssen, 2010**).

Associated fauna comprised foraminifera, calcareous nannoplankton, ostracods, spicules, echinoids, scaphopods and macrofossils (crustaceans, bivalves, dwellers, fish remains and fossil flora remains). More detailed analysis of associated fauna can be found in **Derežić (2018)**, and for the purpose of this paper only pteropod analyses are presented.

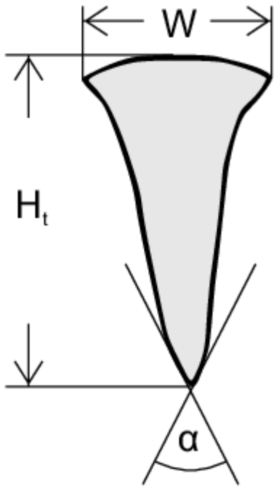

Figure 2: Measured elements of the vaginellids casts and molds from localities G-2 and G-3, Goranec area; W-shell width, H-shell height, α-apical angle (modified after **Bošnjak et al., 2017**).

3. Results

Pteropods on localities G2 and G3 were collected form marls, and total 74 casts and molds of *Vaginella* species were determined (**Figure 3**). Also, other representatives of the family Cavoliniidae were found on the investigated localities G2 and G3, and the representative of the Limacinidae on localities G1 and G3. Vaginellid specimens were the most abundant and for that reason chosen for the biostatistical analyses.

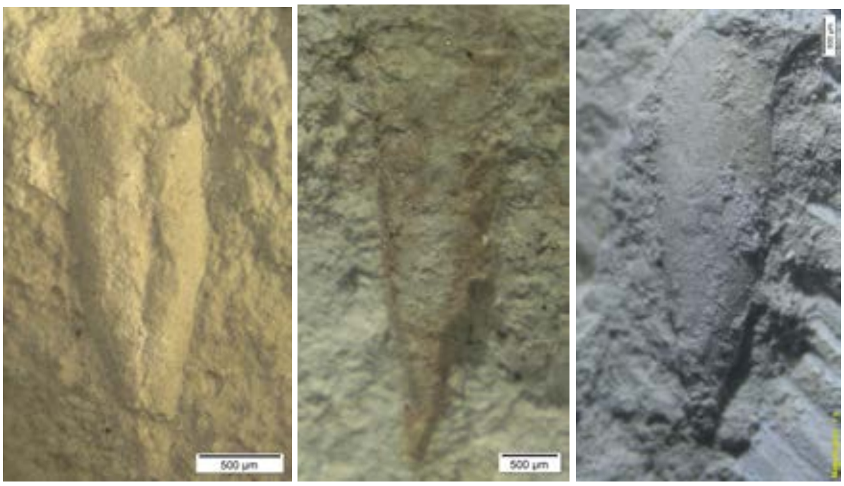

Figure 3: Part of the collected specimens of *Vaginella austriaca* Kittl, 1886 from investigated outcrops: a) specimen G2-L13, outcrop G2; b) specimen G2-L7, outcrop G2; c) specimen G3_20, outcrop G3. Position of the outcrops is shown on **Figure 1**.

Vaginellids have a similar shell morphology, mostly straight, elongated and jar shaped (e.g., **Kittl, 1886; Janssen, 1984; Zorn, 1991; Cahuzac and Janssen, 2010**). In the analysed material most of the vaginellid casts and molds are poorly preserved, and their complete shell is missing. Protoconch is rarely preserved and aperture is missing, it is damaged or not visible, as well as shell ornamentation of the collected specimens. Vaginellid species-level determination is problematic due to the poor preservation and similar shell morphology, making the biostatistics an inevitable tool in vaginellid determination. Based on the here presented biostatistics analyses and comparation with previous research (e.g. **Bošnjak et al. 2017**) majority of the specimens were determined as *Vaginella austriaca* Kittl, 1886 (**Figure 3**), which is the most abundant pteropod species in the Miocene deposits of the Paratethys.

In analysed specimens shell height (H), width (W) and apical angle (α) were measured (**Figure 2**). **Table 1 and 2** show measured elements of vaginellids, and on **Figure 4 and 5** are shown their shell height/width ratio and apical angle ranges. The abovementioned elements could be measured in all specimens, except for the apical angle in two specimens (**Table 1**, locality G-2) due to the poor preservation, but the specimens were included in biostatistics because of their shell preservation.

Table 1. Measured vaginellids elements, outcrop G2.

SAMPLE	WGTH, W (mm)	HEIGHT, H (mm)	APICAL ANGLE, α (°)
G-2_L1	1,14	3,25	27
G-2_L2	1,05	3,02	23
G-2_L3	1,3	3,84	20
G-2_L4	1,4	2,44	30
G-2_L5	1,14	1,53	35
G-2_L6	1,4	2,86	37
G-2_L7	1,07	3,75	31
G-2_L8	1,05	3,45	35
G-2_L9	0,89	2,25	21
G-2_L10	2,14	4,02	34
G-2_L11	1,65	4,12	40
G-2_L12	1,25	2,55	31
G-2_L13	1,51	3,4	28
G-2_L14	1	2,02	23
G-2_L15	1,19	1,79	21
G-2_D1	1,57	4,19	21
G-2_D2	0,98	2,43	22
G-2_D3	1,15	2,53	30
G-2_D4	1,93	4,09	32
G-2_D5	1,7	3,32	12
G-2_D6	0,98	2,66	33
G-2_D7	1,33	2,15	29
G-2_D8	0,91	2	28
G-2_D9	0,77	1,53	28
G-2_D10	1,64	3,36	18
G-2_D11	1	2,95	26
G-2_D12	1,2	2,06	/
G-2_D13	1,09	1,93	27
G-2_D14	0,8	2,25	31
G-2_D15	1,05	2,59	25
G-2_D16	0,94	2,86	25
G-2_D17	1,3	2,63	28
G-2_D18	0,74	1,86	12
G-2_D19	0,7	1,81	/
G-2_D20	1,25	3	32
G-2_D21	1,77	3,79	39
G-2_D22	2,55	3,05	25
G-2_D23	0,99	2,52	32

Table 2. Measured vaginellids elements, outcrop G3.

SAMPLE	WGTH, W (mm)	HEIGHT, H (mm)	APICAL ANGLE, α (°)
G-3_1	0,93	3	25
G-3_2	1,4	4,23	37
G-3_3	1,16	4,44	14
G-3_4	1,65	4,14	34
G-3_5	0,86	2,2	21
G-3_6	1,07	2,75	26
G-3_7	1,91	3,79	37
G-3_8	1,23	3,81	29
G-3_9	1,44	3,21	35
G-3_10	0,77	3,09	18
G-3_11	1,14	2,21	11
G-3_12	1,21	2,79	32
G-3_13	1,26	2,6	19
G-3_14	0,9	2,09	21
G-3_15	1,27	4,26	20
G-3_16	0,86	2,72	22
G-3_17	0,68	4,11	14
G-3_18	0,72	2,59	27
G-3_19	1,02	2,93	27
G-3_20	1,58	5,51	24
G-3_21	1,14	2,88	34
G-3_22	1,16	3,16	27
G-3_23	1,26	3,53	20
G-3_24	1,02	3,77	31
G-3_25	1,48	3,86	30
G-3_26	1,07	2,72	24
G-3_27	1,23	3,19	25
G-3_28	1,26	3,37	28
G-3_29	0,89	2,91	17
G-3_30	1,09	2,65	20
G-3_31	0,91	2,67	19
G-3_32	0,88	3,12	23
G-3_33	0,93	3,07	25
G-3_34	1,16	3,95	22
G-3_35	1,19	3,17	32
G-3_36	0,79	1,84	35
G-3_37	0,77	2,86	24
G-3_38	0,82	2,61	22

Shell height/width ratios of vaginellids (**Figure 4a and 5a, Table 1 and 2**) show their similar height and width range, which fits well with previous research on vaginellids from Medvednica Mt. and the Central Paratethys area as well (**Bošnjak et al., 2017 and references therein**). Apical angle values are in the range typical of vaginellid species, and it can be seen on **Figures 4b and 5b** that most of the specimens have values between 20° and 40°, typical for *Vaginella austriaca* species (e.g. **Cahuzac and Janssen, 2010**).

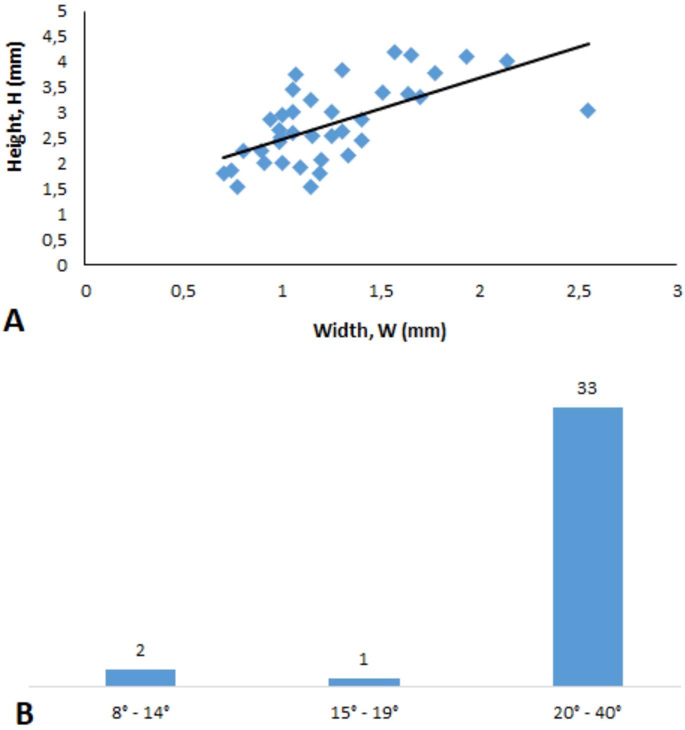

Figure 4: Biostatistical analysis of *Vaginella austriaca* Kittl, 1886 from locality G-2. **a)** shell height and width ratio; **b)** apical angle values.

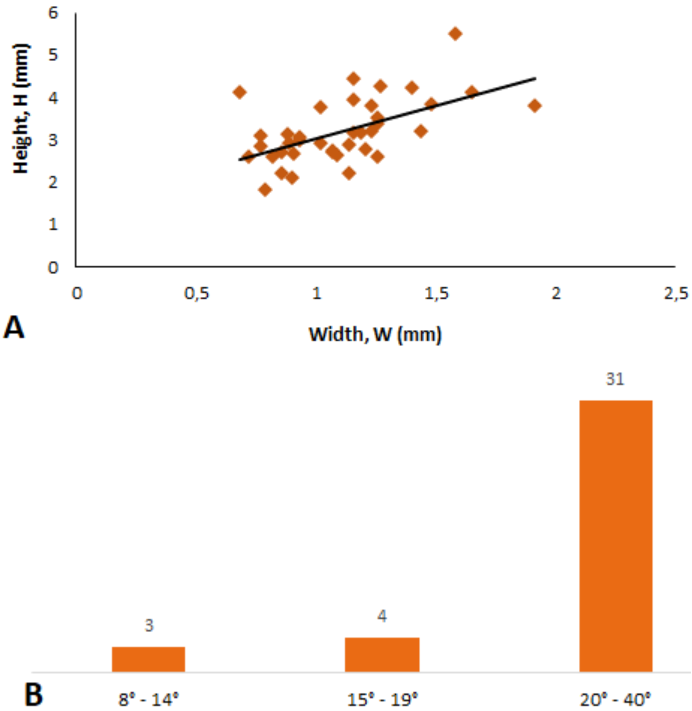

Figure 5: Biostatistical analysis of *Vaginella austriaca* Kittl, 1886 from locality G-3. **a)** shell height and width ratio; **b)** apical angle values.

4. Discussion

Vaginella species have variable morphology, on the species level and on the inter-species level, which together with their poor preservation mostly as casts and molds makes their species-level determination difficult (e.g. **Zorn, 1991; Janssen and Zorn, 1993; Cahuzac and Jannsen, 2010**). During the vaginellid evolution in Miocene their shell became more elongated, and several *Vaginella* species have a similar shape. Therefore, their determination can be based on statistics of shell morphology, taking the apical angle value as one of a distinguishing characteristic. However, that can be the case only in very well preserved specimens. Although the here presented vaginellids are poor preserved, apical angle values were additional diagnostic element for part of the collected specimens which could be determined. **Cahuzac and Janssen (2010)** describe apical angle values for *Vaginella* species, and here present specimens (**Table 1 and 2, Figure 4 and 5**) comprise ranges of *V. austriaca* (20°-40°), *V. acutissima* (c. 15°-18°) and *V. lapugyensis* (c. 8°-13°). As seen on **Figures 4b and 5b** most specimens show apical angle values typical for *Vaginella austriaca* species. Several specimens have apical angle values which correspond to *V. acutissima* and *V. lapugyensis* species (e.g. **Cahuzac and Janssen, 2010**) (**Figures 4b and 5b**), but they were determined as *V. austriaca* as well. Vaginellid casts and molds can be altered due to the diagenetic processes, and their shape and dimensions could be changed. That could be one of the reasons why several specimens have lower apical angles than 20° (**Figures 4b and 5b**), the lower limit for *V. austriaca* species, and the morphology and height/width ratio of the shell similar as the other specimens. These results are also in accordance with previous research from Medvednica Mt. (e.g. **Bošnjak et al., 2017**). Bearing all that in mind, specimens were determined as *Vaginella austriaca*.

The oldest pteropod findings have been found in the Middle Eocene deposits, and the most abundant pteropod records are in the Middle Miocene deposits connected with the timing of the marine transgressions (e.g. **Zorn, 1991; Bohn-Havas and Zorn, 1993, 194; Bohn-Havas et al., 2004**). Most various and numerous pteropods from the Miocene deposits of the Central Paratethys are *Clio* Linnaeus, 1767, *Limacina* Bosc, 1817 and *Vaginella* Daudin, 1800. *Vaginella austriaca* species is considered as the most widespread geographical and stratigraphical pteropod species in the Badenian of the Central Paratethys (**Janssen, 1984; Zorn, 1991, 1995, 1999; Bohn-Havas and Zorn, 1993, 1994; Bohn-Havas et al., 2004**). Time range of recorded *Vaginella austriaca* in the Miocene deposits of the Paratethys area corresponds to the peak of the Middle Miocene marine transgressions (e.g. **Rögl et al., 2007; Zorn, 1991; Bohn-Havas et al., 2004; Bošnjak et al., 2007 and references therein**).

Vaginella austriaca was recorded on the Medvednica Mt. in Čučerje area by **Gorjanović-Kramberger (1908)**, **Kochansky (1944)**, **Basch (1983)**, **Avanić et al. (1995)**, **Bosak (2017)** and **Bošnjak et al. (2017)**. In the area of the Paratethys Sea, this species is recorded in the Middle Miocene deposits of Austria (Karpatian, Badenian; after **Janssen 1984; Bohn-Havas and Zorn 1993, 1994; Janssen and Zorn 1993; Zorn 1991, 1999**), Bulgaria (Badenian after **Zorn, 1999** and **Nikolov, 2010**), Czech (Karpatian and Lower Badenian after **Zorn 1991, 1999**), Poland (Lower and Middle Badenian; after **Zorn 1991, 1999; Bohn-Havas and Zorn 1993, 1994; Janssen and Zorn 1993**), Hungary (Lower Badenian after **Zorn, 1991; Bohn-Havas and Zorn, 1993, 1994; Bohn-Havas et al. 2004**; and NN5 nannozone after **Bohn-Havas and Zorn, 1993; Bohn-Havas et al., 2004 and Selmeczi et al., 2012**), Romania (Lower Badenian after **Zorn 1991, 1999; Janssen and Zorn 1993; Bohn-Havas and Zorn 1994**), Slovenia (**Mikuž et al. 2012 and references therein**), Serbia (**Stevanović 1974**). Outside Paratethys this species is known from the Miocene deposits of the Mediterranean area (e.g. **Zorn, 1991; Janssen and Little, 2010**), North Sea Basin (e.g. **Cahuzac and Janssen, 2010; Janssen, 2012 and references therein**) and the Aquitaine Basin (e.g. **Cahuzac and Janssen, 2010 and references therein**).

5. Conclusions

Simply shaped tests of cavoliniid pteropods are not easy to determine on the species level. Simple statistic methods, taking into consideration height/width ratio and apical angle value can be of great help in this process.

High abundance of cavoliniid specimens collected in the research area (Goranec near Čučerje, Medvednica Mt.), similar to the other parts of the Paratethys Sea, provide a good foundation for statistical analyses. On the other side, poor preservation and plastic deformation complicate the biometrical analyses.

Biostatistical research has shown that most of the collected specimens belong to the cavoliinid species *Vaginella austriaca*, making it the most abundant pteropod during the Miocene in the research area, similar to the whole Paratethyan pelagic realm.

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Google Earth, https://www.google.com/intl/hr/earth/

Abstract in Croatian

Biostatistička analiza novih nalaza pteropoda u srednjomiocenskim (badenskim) naslagama jugoistoične Medvednice (sjeverna Hrvatska)

Fosilni mekušci iz skupine pteropoda (Gastropoda, Thecosomata) do sada su bili zabilježeni u morskim badenskim naslagama Medvednice u okolici Čučerja i Marije Bistrice. Daljnjim istraživanjem srednjomiocenskih naslaga u jugoistočnom dijelu Medvednice, na lokalitetu Goranec, prikupljeni su novi brojni uzorci pteropoda vrčastog oblika, sačuvanih u obliku kamenih jezgri i otisaka. Na temelju njihove morfologije zaključeno je da pripadaju rodu *Vaginella* Daudin, 1800. U određivanju vrsta ove skupine često se primjenjuju biostatističke metode zbog slične morfologije kućice i lošeg fosilnog očuvanja, kada je razlikovanje vrsta otežano. Na temelju mjerenja visine i širine te apikalnog kuta kućice obrađenih primjeraka napravljena je biostatistička analiza, te usporedba s ranije zabilježenim nalazima ovoga roda u okolici Čučerja. Zaključeno je da većina primjeraka pripada vrsti *Vaginella austriaca* Kittl, 1886, koja je i inače najbrojnija vrsta pteropoda u miocenskim naslagama Paratethysa. Nalazi zabilježenih fosilnih pteropoda upućuju na maksimum morskih transgresija tijekom badena što doprinosi daljnjim paleoekološkim i paleogeografskim istraživanjima jugozapadnog ruba Centralnog Paratethysa, odnosno Panonskog bazenskog sustava.

Ključne riječi: biometrija, pteropodi, *Vaginella austriaca*, baden, Medvednica.