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Preliminary communication

Preliminary estimate of CO_2 storage capacity by petrophysical modelling in Upper Miocene Poljana Sandstones in the western part of the Sava Depression

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Abstract
A preliminary assessment of the capacity of regional geological storage in the western part of the Sava Depression was based on data obtained from several deep exploration wells. The Poljana Sandstones represent a regional deep sandstone body, in most parts saturated with water, with promising underground facilities for the storage of CO_2 in the study area. Poljana Sandstones (member of Kloštar-Ivanić Formation bounded between E-log markers Rvand Z') have favourable petrophysical properties and are situated at reasonable depths. According to previous investigations, at depths greater than 800 meters supercritical conditions of temperature and pressure CO_2 are achieved, which ensures easy and safe injection into storage underground facilities. For the creation of a model in Petrel software, various data was used, including the distribution of CO_2 density, porosity, effective thickness and the relative depth of sandstone. Spatial distribution of porosity was made regarding neutron porosity logs. The most important parameter in the estimate of storage capacity is effective thickness, defined by the interval between E–log markers Rv and Z'. Hence, the effective thickness was used for top and bottom surface of sandstones. Density of CO_2 was created according to their spatial distribution regarding the depth and the temperature. The capacity of CO2 storage was calculated by the volumetric method. The use of a calculated Petrel model can subsequently determine the amount of CO_2 storage in the underground facilities of the study area.

Keywords
Petrel model, Poljana Sandstones, estimate of CO_2storage capacity, porosity, Sava Depression

1. Introduction

In this paper, data from several deep wells was used for the preliminary assessment of the capacity of regional geological storage in the western part of the Sava Depression. Porosity, the density of CO_2, the relative depth and effective thickness of Poljana Sandstones, defined from exploration wells, were input data for the Petrel model. Also, it should be noted that similar approaches of this methodology for the estimate of CO_2 storage capacity were already used for some parts of the Sava Depression (**Vulin, 2010; Kolenković, 2012; Novak et al., 2013a; Novak et al., 2013b; Kolenković and Saftić, 2014; Novak, 2015; Podbojec, 2015**).

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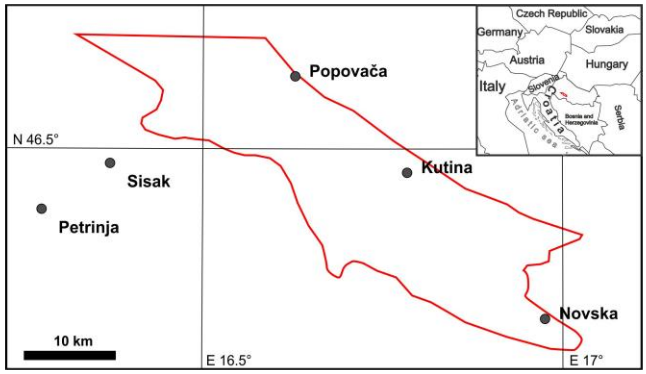

Figure 1:Area of explorationbounded by a red polygon

An area of geological modelling is situated between Moslavačka gora Mt. (in the North), Ravna gora and Psunj Mountains (in the East) and Sunja and Lonja Fields in the South and West. The Sava and partly Sunja and Lonja Rivers flow in the area. The study area mainly encompasses the Sisak– Moslavina County and covers an area of around 610 square kilometres. Also, the gas and oil field Okoli is located in this area, and is used for the regional geological storage of natural gas. The area of exploration for subsurface modelling and storage capacity determination is shown in **Figure 1**.

2. Geological storage of CO_2

Carbon dioxide as a greenhouse gas is considered as a major growing threat in the conservation of the existing climatic conditions on Earth. Its increased concentration is the result of burning fossil fuels and their derivatives and its releasing into the atmosphere. Therefore, as an alternative and "clean" way to reduce CO_2 emissions is its capture and permanent storage underground or use in enhanced oil recovery. CO_2 capture takes place at large stationary sources (e.g. power plants, refineries) and then dehydrated and compressed, it is transported by a pipeline or shipped to underground storage and finally injected into the corresponding body of rock with characteristics of long-term and safe storage.

2.1. Methods of geological storage/sequestration of carbon dioxide

Suitable storage/sequestration facilities are the most common sedimentary rocks - sandstone and carbonate deposits which must satisfy the requirements for the long-term and safe storage of CO_2. According to previous investigations, the injection of CO_2 and capacity can be realized at depths greater than 800 m where pressure and temperature conditions allow the supercritical state of CO_2. Fluids that are supercritical have properties of a liquid and a gas at the same time, i.e. they have a viscosity similar to a gas and a density closer to a liquid. In its supercritical state, CO_2 is a liquid which is more easily pressed into the underground due to minor differences in the density of the formation water and also, supercritical CO_2 fluid is reducing the effects of buoyancy. Above all, impermeable rocks have a necessary presence above the reservoirs and serve as an insulator for preventing the migration of CO_2 into the shallower layers or to the surface. Carbon dioxide can be permanently stored in several ways: in almost depleted oil and gas reservoirs, where CO_2 is used as a displacing fluid for residual oil from the pores of rocks, in enhanced oil recovery operations, in deep saline aquifers and coal layers which cannot be exploited for the coal itself **(IPCC, 2005)**. In the last case, where CO_2 is injected into coal seams it was regarded as Coal Bed Methane recovery which is a method where the CO_2 is injected into the micropore system of the coal layers. CO_2 displaces methane and thus comes to its permanent storage. The majority of underground storage options can be seen in **Figure 2**.

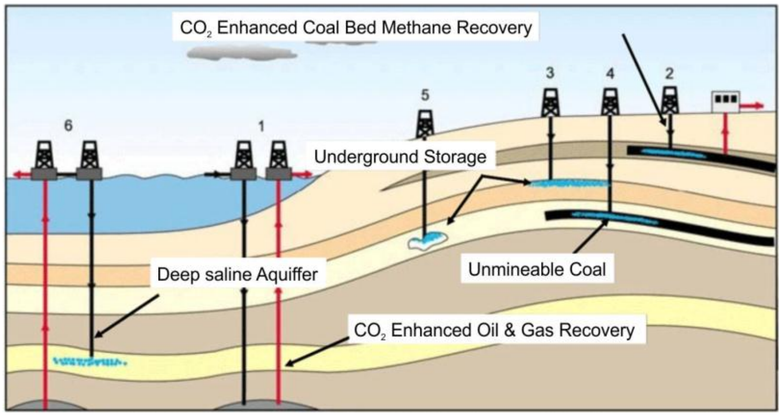

***Figure 2**: Schematic representation of geological storage/sequestration options (http://www.kgs.ku.edu/PRS/publication/2003/ofr2003-33/P1-03.html)*

2.2.Storage in deep aquifers

The most suitable underground facilities for the storage of anthropogenic CO_2 are so called deep saline aquifers whose pores are water saturated with high concentrations of dissolved minerals making them unusable for water supply. In most cases, they have increased salinity and are in most cases referred to deep (as the depths are much larger than aquifers used for water supply) saline aquifers. Since the characterization of such large rock volume requires a large amount of data, it creates an uncertainty factor when assessing the capacity of storage of CO_2. Processes which comprise CO_2 injection, the creation of its stable state and permanent storage into underground facilities, are collectively called trapping mechanisms (**Figure 3**) because they virtually act as traps that will capture CO_2 in underground "objects".

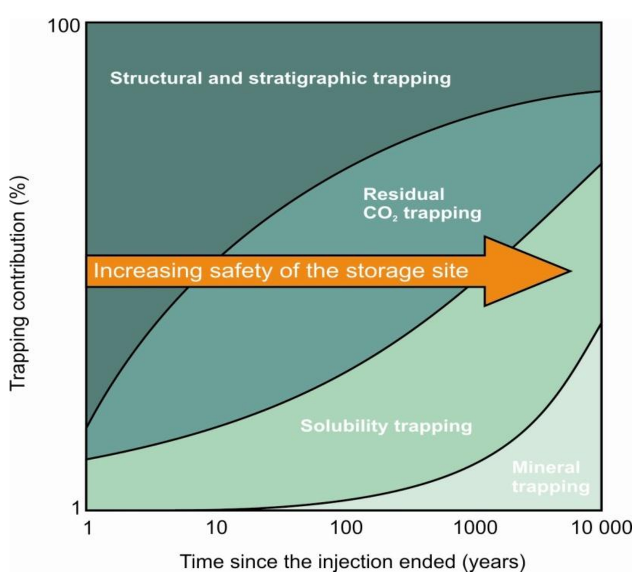

Figure 3: Graph of trapping mechanisms of CO_2 in deep saline aquifers (*http://grrebs.ete.inrs.ca/en/csc/csc_surveillance/, modified from IPCC, 2005)*

There are four groups of these processes (**Figure 4**), of which some become active immediately, while others will not have a significant share until many years after injection. Hydrodynamic trapping mechanism - the first process starts to develop while CO_2 slowly flows through the rock whose pores are filled with layered water. The force of buoyancy causes the CO_2 to flow upward near the injection well (no.1 on **Figure 4**).When it reaches the limit of proper overlying layer, then it continues to migrate as a separate phase, but still in the direction of buoyancy - to the top of the anticline (no. 2). There it partially becomes trapped in the space between rock grains due to surface tension or adsorption on the surface of minerals (no. 3) (residual and adsorption trapping mechanism); **White et al., (2003)**; **Saftić & Kolenković, (2008).** While migration is still in the upward direction (e.g., at the top of the anticline) CO_2 begins to concentrate in the pore space, thus creating an artificial cavity, depending on the state of CO_2 (in analogy to hydrocarbon reservoirs). Over a longer period (100-10000 years; **(IPCC, 2005)**), the stratified water dissolves more CO_2 and then chemical trapping mechanism starts (no. 4). Dissolved CO_2 in stratified water no longer represents a separate phase, so CO_2 starts to flow by gravity in to the deepest parts of the transmissive layer (no. 5). A solution of CO_2 in this way can react with mineral sand form stable carbonate minerals (no. 6) (mineral trapping mechanism) **Saftić & Kolenković (2008)**. The efficiency of the geological storage of CO_2 and the period of stability depends upon different factors, including the buoyancy of CO_2, formation water density, lithological heterogeneity and the mineralogical composition of a the underground storage “object”. The trapping security has to be evaluated within a risk analysis that has to be carried out for each storage site (Wildenborg et al, 2005; Oladyshkin et al., 2011). The main geological criteria for the selection of a suitable aquifer for the storage of CO_2 include the depth of burial, the effective thickness, porosity, permeability, continuity of collector and seal rocks and the salinity of formation water.

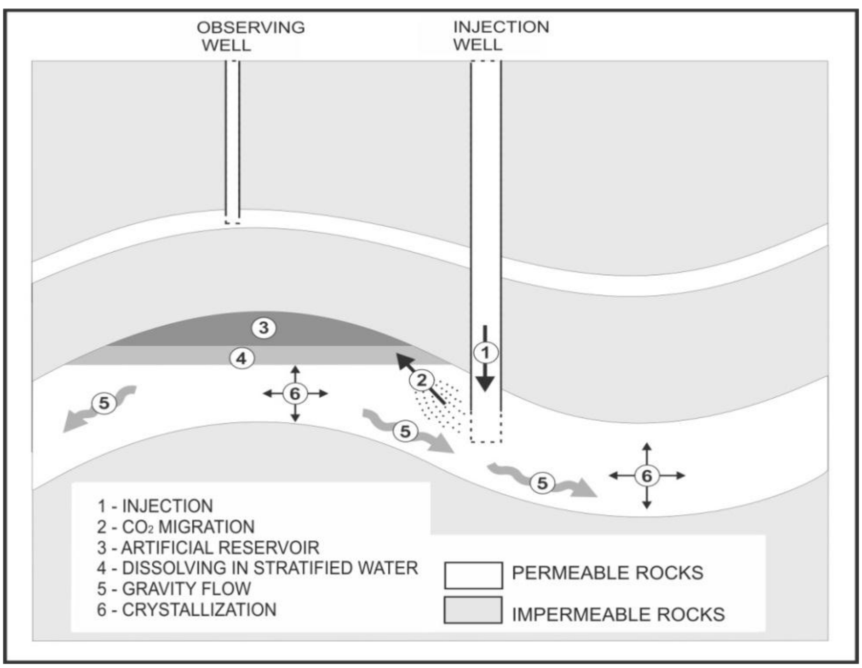

Figure 4: Processes of trapping mechanism *(Saftić and Kolenković, 2008)*

A problematic feature regarding subsurface modelling of aquifers for CO_2 sequestration, especially when dealing with petrophysical modelling, is the lack of well log data i.e. modern well logs in the depth intervals favourable for CO_2 storage. These include radioactive well logs in most of the wells for porosity and lithology definition (only a few wells there in have the favourable intervals) as well as fluid properties as these were not wells made specifically for testing the Poljana Sandstones, but deeper, possibly oil saturated Okoli and Iva Sandstones.

3. Geological settings in the Sava Depression

The Sava Depression belongs to the southwestern part of the Pannonian Basin System, with a very complex tectonic structure. The basement of Neogene – Quaternary sediments consists of magmatic-metamorphic and partly sedimentary complex rocks of the Palaeozoic, Mesozoic and Paleogene age. Sedimentary infill of the Sava Depression is formed from sedimentary rocks with some volcanoclastic of Neogene and Quaternary age, thus creating a sedimentary sequence whose thickness in the Sava Depression reaches about 5000 m **(e.g., Šimon, 1980; Velić et al, 2002; Saftić et al. 2003)**. In this paper, the aim of the explorations were Upper Miocene Poljana Sandstones which are a member of the Kloštar-Ivanić Formation. Time deposition of Kloštar-Ivanić Formation approximately corresponds to the Lower Pontian. These sediments are more often biostratigraphically regarded as Abichi-layers and they were named according to the typical fossil shell *Paradacna abichi* **(Ožegović, 1944)**. Poljana Sandstones represent an interval between E – log markers R*v* and Z'. Moreover, these are sandstone bodies with interbeds of marly and silty components. The review of chronostratigraphic and lithostratigraphic units for the Sava Depression is given in **Figure 5**.

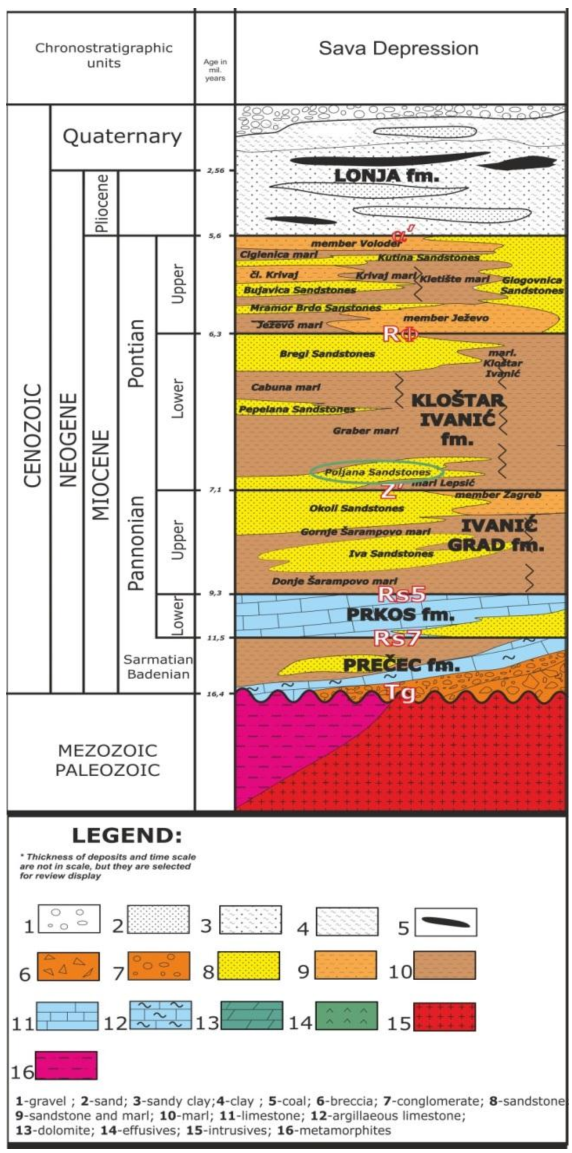

Figure 5: Chronostratigraphic and lithostratigraphic units in the Sava Depression **(Velić, 2007;Cvetković,2013)**

Structures are developed during Miocene, starting with transtensional tectonics in opening of the Pannonian Basin System and uplifting of the Apennines and the Dinarides **(Prelogović et al., 1998; Lučić et al., 2001;Velić & Malvić, 2011)**. The effect of two phases of transtension and transpression enabled the opening of the Pannonian basin. Transtensions were periods of main sediment accumulation and transpression of uplifting and structural forming **(Velić & Malvić, 2011)**. The faults are mostly normal, but there are also reverse whose fault character changed recent tectonic events **(Saftić et al., 2003)**.

4. Methodology

This chapter explains the procedure of the analysis and the method of calculating the parameters required for the assessment of capacity storage of carbon dioxide in the deep saline aquifer of Poljana Sandstones. First of all, it was necessary to set up the boundary of the Poljana Sandstones (their lateral pinch out) in order to precisely define the area of research/geological modelling as well as the area with favourable petrophysical properties for the storage of CO_2. Moreover, according to **Šimon (1980)** the boundary of the Poljana Sandstones is set regarding Dinaric orientation of the Sava Depression, which also marks the trend of sandstone's sedimentation deposited from the Eastern Alps. Determination of features of Poljana Sandstones (namely the surface, the effective thickness, depth of burial and porosity) was defined by using analysed data obtained from several exploration wells in the study area. The depth of regional aquifers is approximated by a mean depth of sandstone layer, or for deep saline aquifer Poljana to the value of depth by mid-depth interval bounded by the E - log markers Rν and Z'. Afterwards, it was necessary to determine conditions of pressure and temperature. CO_2 injection into underground storage facilities includes supercritical state of CO_2, i.e. pressure greater than 73.8 bar. Pressure on the mean depth of sandstones was calculated assuming hydrostatic gradient. With the known pressure gradient, pressure values at mean depth of sandstones are determined according to the mathematical expression (4-1):

$$p = \frac{G_h \cdot d_{avg}}{100} \qquad (4\text{-}1)$$

where:
p – pressure [bar]
d_{avg} - mean depth of sandstones [m]
G_h- hydrostatic pressure gradient [bar/100m]

The temperature at mean depth of deep saline aquifer Poljana can be calculated with the known geothermal gradient according to the expression (4-2):

$$T_{avg} = T_{avg.an} + \frac{G_t \cdot d_{avg}}{100} \qquad (4\text{-}2)$$

where :
T_{avg}– average annual temperature [ºC]
G_t - geothermal gradient [ºC/100 m]
d_{avg} - mean depth of deep saline aquifer [m]

The average annual temperature is the sum of all the mean values of the measured temperature in the nearest weather station (in this case the weather station is Sisak and the value is 11.7 ºC), and geothermal gradient values (average valueof geothermal gradient 4.69°C/100 m) were read form regional map of the geothermal gradient in the western part of Sava Depression **(Jelić et al., 1995)**.The density of carbon dioxide depends on pressure and temperature. Based on the estimated pressure and temperature at the mean depth of Poljana Sandstones, density values were read from the corresponding diagram in **Figure 6.**

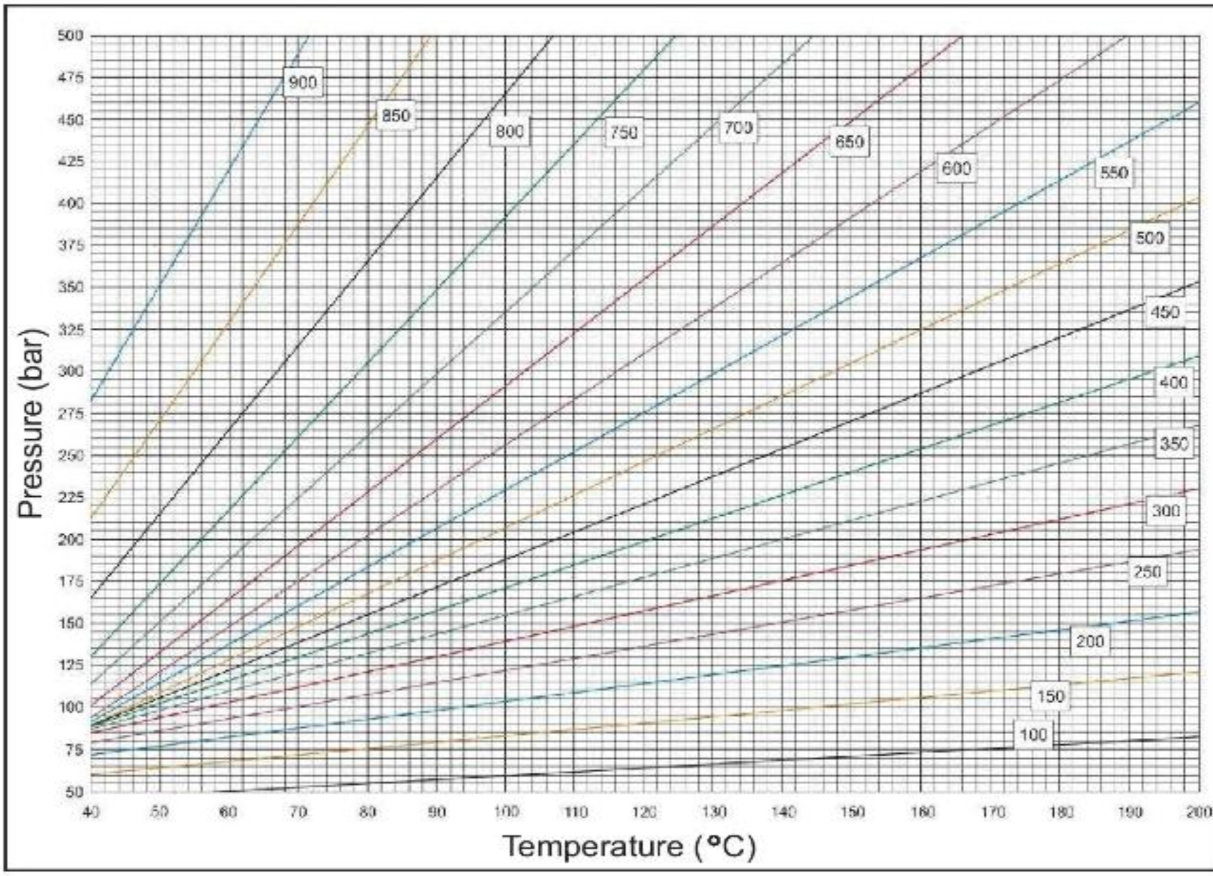

Figure 6:Diagram of CO_2 density as a function of pressure and temperature (**Vulin, 2010 according to Span & Wagner, 1996**)

Accordingly, suitable positions of underground storage facilities are related to the depths of 800-2500 m where a supercritical state of CO_2 is achieved **(Chadwick et al., 2008)**. Storage of CO_2 at greater depths of 2500 m requires increased investment and technical problems because of possible geomechanical instability of reservoir and cap rock caused by increased pressure injection **(Chadwick et al., 2008**). Effective thickness – cumulative thickness of permeable layers, is one of the most important parameters of the regional aquifer of Poljana Sandstones, a member of the Kloštar-Ivanić Formation. Values of porosity were obtained by the interpretation of neutron porosity logs from 16 wells which were later upscaled in Petrel during the modelling process. The boundary of the study area was made as a closed polygon by using the *Make/edit polygon s*tool. Parameter effective thickness was utilized for the surface of top and base of sandstones by using the *Make simple grid* tool. Maps of distribution of porosity and density CO_2 were made by the *Property modelling* tool. CO_2density values were upscaled based on well point data and spatially distributed with the *Petrophysical modelling* (Gaussian random function simulation) for them to be able to be used directly in the volume calculation. The *Volume calculation* tool calculated a total capacity of storage of CO_2 for the whole area of investigation.

5. Results

The finalised Petrel model encompasses: Top and bottom maps of Poljana Sandstones, a map of effective thickness of sandstones, as well maps of distribution of the density of CO_2 and porosity. On the map of effective thickness (**Figure**

7) higher values (around 120 to 160 m) can be noticed in the central part of an area of research, while lower values are related to the peripheral areas of Poljana Sandstones.

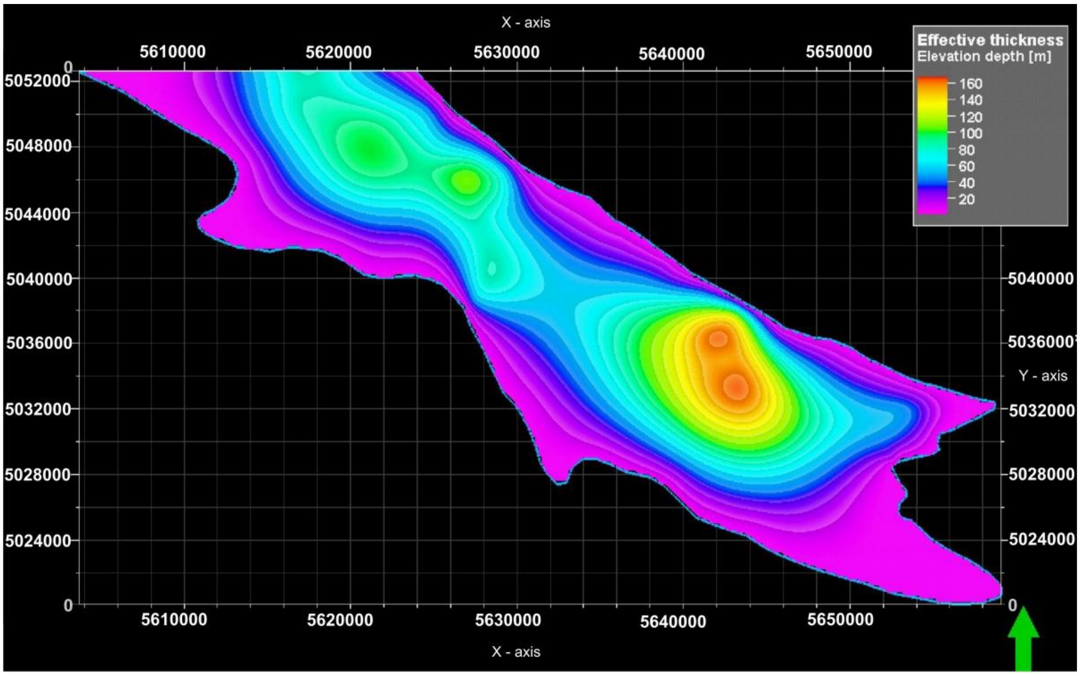

Figure 7: Map of effective thickness of Poljana Sandstones

Top and bottom maps of Poljana Sandstones (**Figure 8** and **Figure 9**) were made from effective thickness. According to the span of colours for proper depth, it can be noted that the deepest parts are situated in the centre (bluish and purplish coloured), while the shallowest parts are at the edge of the boundary of Poljana Sandstones (yellow or red colour).

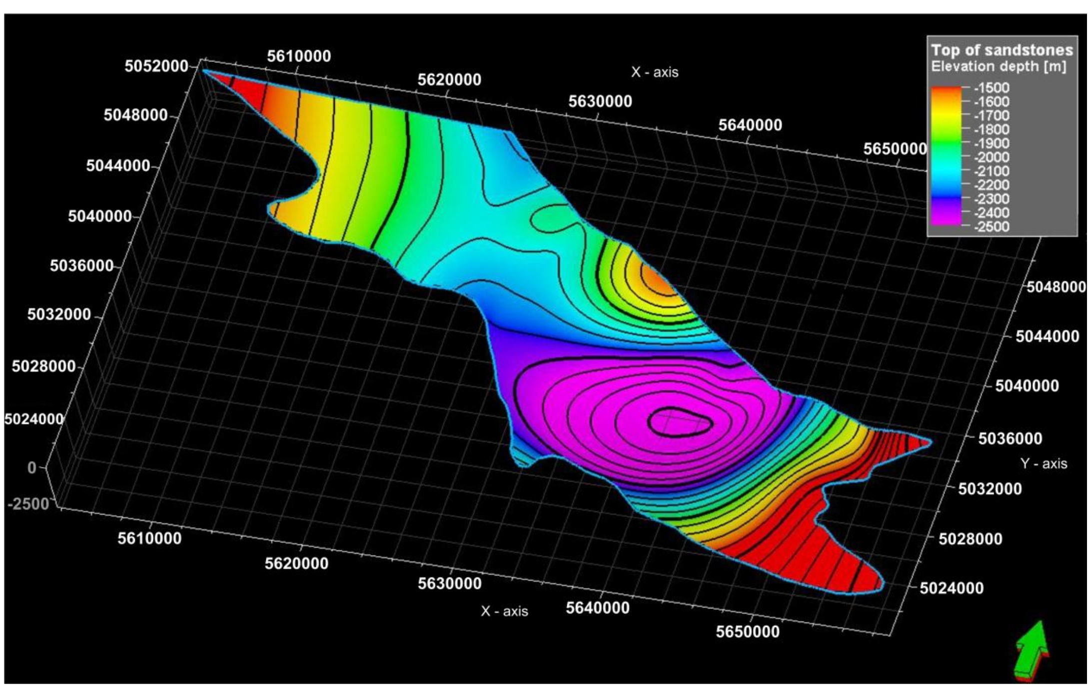

Figure 8: Contour map of Poljana Sandstones top surface

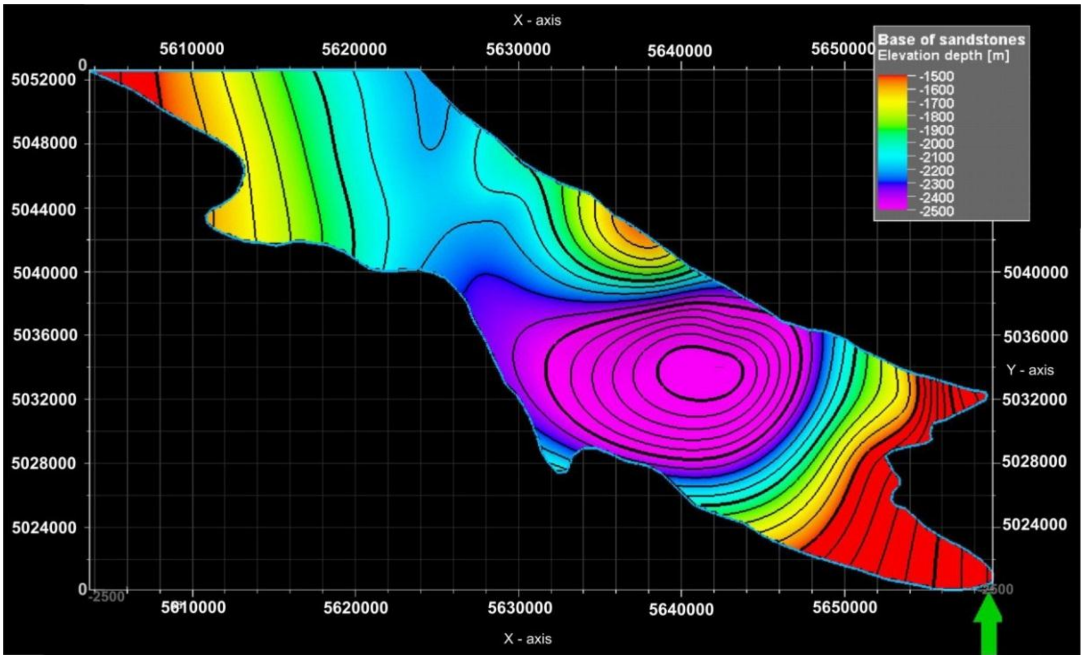

Figure 9: Map of the bottom surface of the Poljana Sandstones

In **Figure 10** a map of the distribution of density of CO_2 is shown. It is necessary as it is one of parameters for correctly calculating the capacity of storage of CO_2 considering its spatial distribution at proper depth. The overall distribution of the density of CO_2 is shown on a histogram, set up beside the legend, and it can be seen that the most common values are from 0.435 to 0.450 g/cm^3.

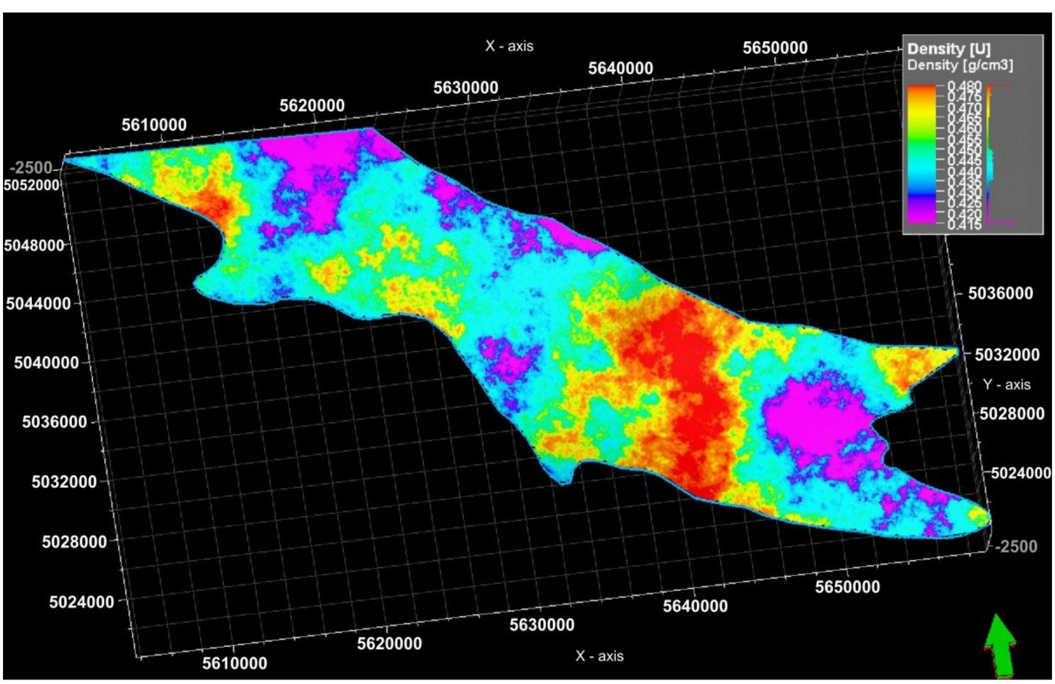

Figure 10: Map of spatial distribution of density of CO_2

The map of distribution of porosity measured by neutron logging of sandstones gives a unique value for each point of there search area and it is shown in **Figure 11.** The largest values of porosity (around 30%), marked with an orange and red colour, refer to the central part of area. It partly depends on the compound, heterogeneity, compaction and depth of burial of sandstones. Considering the above said, minimum values are also related to the edge of the boundary of Poljana Sandstones (greenish and bluish coloured). As a matter of fact, in this figure, the histogram of porosity distribution can be observed, so it can be concluded that the most frequent value range of porosity is from 21 to 25%.

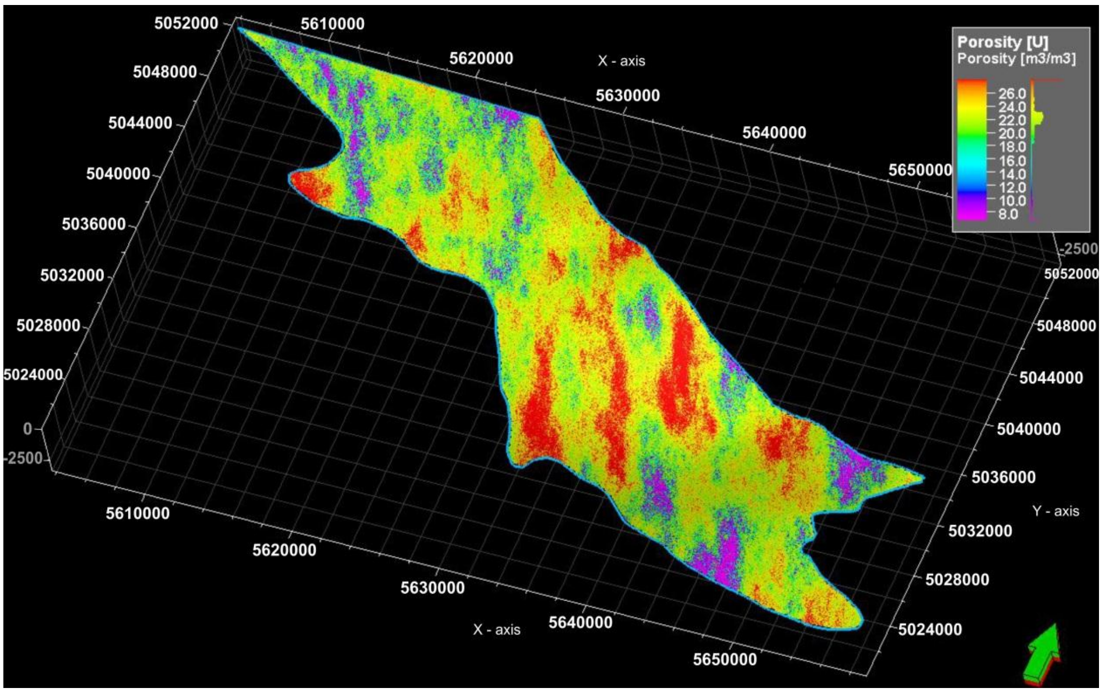

Figure 11: Map of distribution of neutron porosity

For calculating capacity storage of CO_2 the volumetric method was used which requires knowledge of the geometry of the aquifer (its surface, the effective thickness, porosity and coefficient of efficiency storage). In the framework of the project GeoCapacity **(EU GeoCapacity, 2009)** the volumetric expression (5-1) is given:

$$M = A \times h_{eff} \times \Phi \times \rho \times S_{eff} \qquad (5\text{-}1)$$

where :
M- total storage capacity of the regional aquifer [kg]
A- surface of the studied aquifer [m^2]
h_{eff} -effective thickness of the studied aquifer [m]
Φ- average porosity [m^3/m^3]
ρ- density at reservoir conditions [kg/m^3]
S_{eff}- coefficient of efficiency of storage [%]

In this case, the volume of storage was calculated for each cell of the model similar to the bulk volume calculations **(Slavinić & Cvetković, 2016)** but with added parameters for CO_2 storage from expression (5-1) for each cell. The calculated value of the quantity of CO_2 which can be injected into the aquifer for the study area is $58.040 \cdot 10^{6}$ t. This result describes Poljana Sandstones as an advantageous underground facility regarding the possible storage values. For reference, the yearly amount of emission of CO_2 from all sources for the Republic of Croatia in 2012 was 13.310^{6}t **(Novak, 2015)**.
According to **Kolenković (2012)**, the coefficient of efficiency of storage, with the defined amount of 2%, represents parameters which only partially cover the complex issue of efficiency, i.e. trapping mechanisms, geological structure and properties of heterogeneous aquifers. It needs to be pointed out that only a fraction of the pore space within any

saline aquifers will be available or amenable to CO_2 storage. The purpose of a storage coefficient is to assign a volume value to pore fraction in which CO2 can be effectively stored The coefficient of efficiency of storage is determined on the basis of the results of statistical data processing (Monte Carlo simulation) for saline aquifers of the United States and Canada **(US DOE, 2007)**. Thus, the major problem is that the same mean value of the coefficient of efficiency of 2% is used in the calculation and assessment of storage facilities in the Pannonian Basin System which could be revised in further studies regarding cases from within the Pannonian Basin System.

6. Discussion

The aim of this created Petrel model was the calculation of the amount of CO_2 storage capacity for the entire study area by using the volumetric method. Considering the calculated value of the capacity storage of CO_2 and described factors, it can be concluded that Poljana Sandstones have a potential to have large volumes of CO_2 stored within them. However, the exact amount of storage capacity has a certain amount of uncertainties. This primarily refers to the deficiency and unavailability of certain well data. Another part of the uncertainty estimate is attributed to the lack of knowledge about the coefficient storage efficiency, because it is not defined regarding deep saline aquifers of the Pannonian Basin System. Also, it is necessary to mention the lack of knowledge about the duration and interaction between various trapping mechanisms in deep saline aquifers. The described procedure is applied in spatial planning and in directing research to local assessments to be carried out in the later stages of research.

7. Conclusions

In the explored area Poljana Sandstones have favourable geological settings for CO_2 storage. Their depth is in the favourable range (800-2500 m) while petrophysical characteristics, mainly porosity, pressure at depth and temperature gradient can allow a storage capacity of 58.040 10^6 t of CO_2. The calculated amount would be sufficient for the sequestration of more than a four year value of the entire CO_2 emissions of the Republic of Croatia (13.3 10^6 t CO_2). This preliminary evaluation of CO_2 storage capacity has only approximate character and therefore does not provide the exact location of provision for injection and storage of carbon dioxide. Seen from an environmental point of view, in the future these safe underground storage facilities will represent the best geological option for anthropogenic CO_2, meaning a permanent reduction in carbon dioxide emissions from large industrial sources.

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Sažetak

Preliminarna procjena kapaciteta skladištenja ugljičnoga dioksida u gornjomiocenskim pješčenjacima Poljana u zapadnome dijelu Savske depresije na temelju petrofizičkoga modeliranja

Preliminarna regionalna procjena kapaciteta geološkoga skladištenja u zapadnome dijelu Savske depresije provedena je na temelju podataka dobivenih iz dubokih istraživačkih bušotina. Kao perspektivan podzemni objekt za skladištenje CO_2 na istraživanome području utvrđen je regionalni litostratigrafski član Poljana, u najvećemu dijelu zasićen vodom različite slanosti. Pješčenjaci Poljana (litostratigrafski član formacije Kloštar-Ivanić omeđen EK markerima *Rv* i *Z'*) kao ležišne stijene povoljnih su petrofizičkih svojstava e zaliježu na odgovarajućim dubinama za skladištenje CO_2. Prema prijašnjim istraživanjima, na dubini većoj od 800 metara postižu se superkritični uvjeti temperature i tlaka CO_2, čime se osigurava njegovo jednostavno i sigurno utiskivanje u podzemne geološke objekte. Definirani parametri pješčenjaka Poljana (dubina zalijeganja, efektivna debljina, poroznost i gustoća CO_2) korišteni su kao ulazni podatci za izradbu modela Petrel. Šupljikavost pješčenjaka Poljana izračunana je prema podatcima dobivenim iz dubokih istraživačkih bušotina u kojima je bila obavljena kompenzirana neutronska karotaža (CNL). Najvažniji parametar u procjeni kapaciteta za geološko skladištenje jest efektivna debljina definirana iz intervala između EK markera *Rv* i *Z'*. Gustoća CO_2 utvrđena je u skladu s njegovom prostornom distribucijom glede dubine i temperature. Kapacitet skladištenja CO_2 izračunan je pomoću volumetrijske metode. Uporaba dobivenoga modela Petrel može odrediti količinu CO_2 za skladištenje u podzemne objekte istraživanoga područja. Ovaj model može naći primjenu u prostornome planiranju i usmjeravanju skladištenja ugljičnoga dioksida u odabrani duboki vodonosnik.

Ključne riječi: model Petrel, pješčenjaci Poljana, procjena skladištenja CO_2, šupljikavost, Savska depresija