ASSESSMENT OF GEOTHERMAL POTENTIAL IN THE AREA OF CITY OF KARLOVAC, CROATIA

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ABSTRACT

Geothermal field Karlovac is located in Karlovac depression, which is situated in central Croatia region, near the city of Karlovac, approximately 35 km southwest from the capital city of Croatia, Zagreb. In the 1980s geothermal reservoir was detected with two deep exploration wells (Ka-2 3.5 km deep and Ka-3 4.1 km deep; 2.6 km apart). The reservoir was in carbonates, between 1.8 and 3.3 km of depth and had measured temperatures of water approximately 140°C.

Looking at the paleogeographical situation, the area of Karlovac subdepression is a part of outermost southwest edge of Pannonian basin, which is characterised by substantial geothermal potential. Structural and tectonic conditions of Karlovac subdepression are direct consequence of compression and extension tectonic movements throughout geological history of wider area. Main role on today's structural and tectonic make up of the area had three crucial aspects. Firstly, the movements in Tertiary Alpine orogeny, more precisely Pyrenees tectonic phase (Upper Eocene - Oligocene) and Sava tectonic phase (Upper Eocene – Miocene). Today's geological relationships of this region are consequences of complex geological development of carbonate platform, as main reservoir rock, development and preservation of fractured and karstic structure and isolation by thick overburden made of basin sediment. On the other hand, second crucial aspect was development of increased regional geothermal inflow by the means of optimisation of thermal conduction through thinning of Earth's crust in the region of Pannonian basin. Last crucial aspect was the possibility of thermal convection of water/fluid into thousands of meters thick carbonate deposit, which, in respect, created the geothermal reservoir in question.

Seems as the most interested part of this geothermal reservoir in carbonates is its lowered part, almost completely elongated in north-south direction. The lowering occurred along the fault of the same north-south direction. That carbonate part has the depth of burial of top carbonate complex around 3 km, while it ranges around 1 km in elevated parts, with tendencies of shallowing, so its thickness and/or presence could be questionable.

Karlovac field is of interest for electric power production and high potential in the direct thermal use. It was recognised as one of the most perspective areas in Croatia for development of the first project of geothermal district heating, as concluded by Islandic experts. They were a part of feasibility study "Geothermal Energy Utilisation Potential in Croatia", made in cooperation with Energy Institute Hrvoje Požar, from April 2016 to June 2017, as a part of Bilateral fond of Norwegian financial mechanisms and EEA. Since the city of Karlovac is in close proximity from this significant geothermal reservoir, there is a large interest in combining the geothermal resource with the city's heating needs.

1. INTRODUCTION

In this paper, geothermal field Karlovac refers to geothermal aquifer in carbonate complex Rečica. It was discovered by two exploration boreholes Ka-2 and Ka-3 (made in 1983 and 1988 respectively) and confirmed by hydrodynamic testing. Hydrodynamic measurements were made during the drilling of the boreholes and later in repeated measurements in 2000. The boreholes themselves were located based on geological and geophysical interpretation of 2D seismic measurements of regional density.

Geothermal field Karlovac was divided in four blocks, i.e. four suggested areas of interest (PIP). They were excluded in a note of intent for administering public competing, made by the Ministry of Economy since 19th of July 2016. For the purposes of this paper, four areas of interest were combined as Rečica (area of interest 1,2 and 3) and Karlovac (area of interest 4) (Figure 1).

The most valuable aspect of Rečica, in geothermal sense, is down along a deep deviation of NNW-SSE orientation, under a roof layer of clastic sediment. The roof layer of the carbonate complex, in this area, is confirmed by drilling at the depth of 2 000 to 3 000 m. Boreholes Ka-2 and Ka-3 are in the suggested area of interest 2 and 3.

Karlovac, in its NE part, has a SW part of deep carbonate reservoir, with depths of 3 000 up to 4 000 m. This deeper part is separated from the shallower (Karlovac) by a fault area and it is in the faults elevated wing. The fault jump in the roof layer of mezozoic carbonate complex in around 2 000 m in the north, 1 000 in the inner part and 3 000 m in the south.

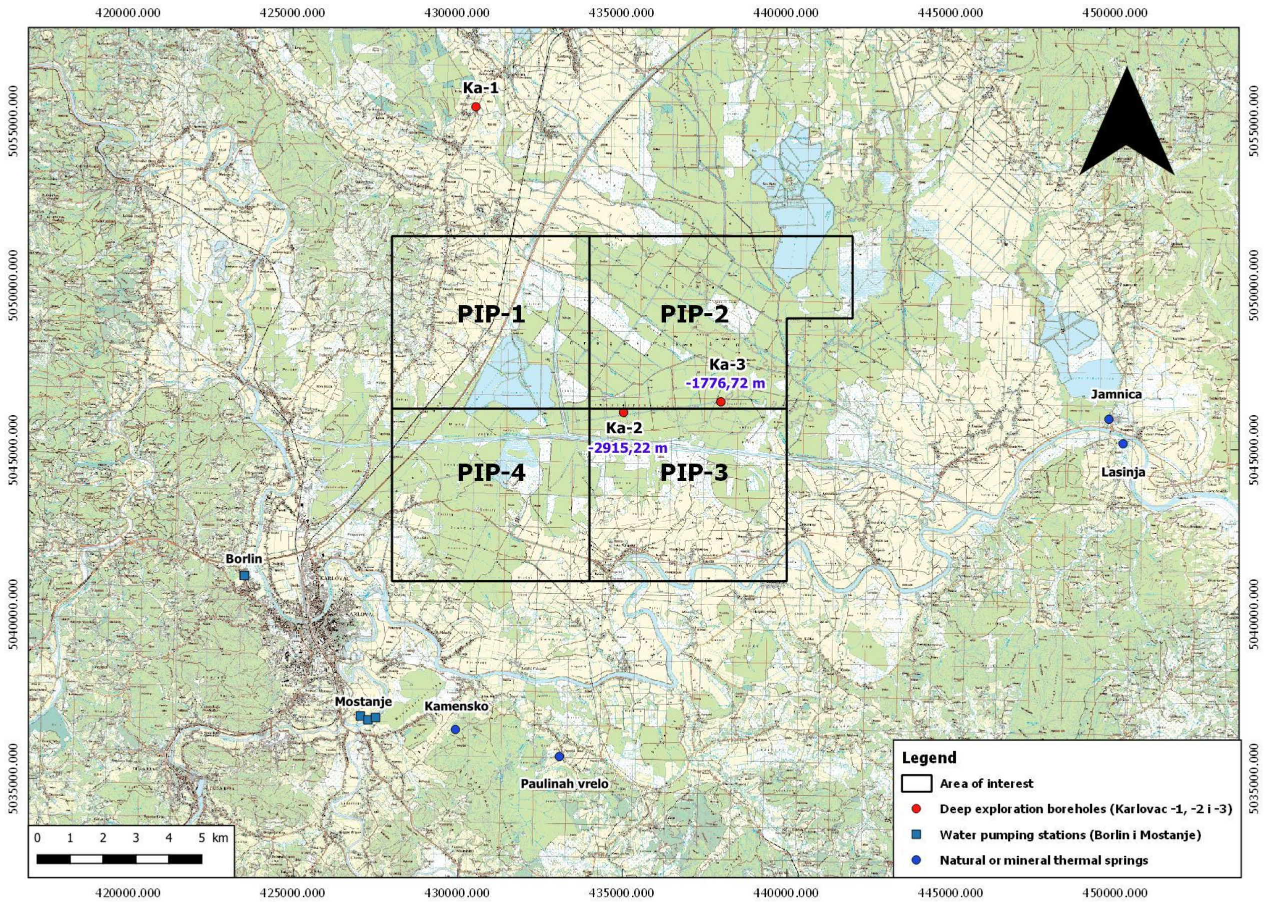

Figure 1: Topographic map of SW part of Karlovac subdepression with suggested areas of interest Rečica and Karlovac (HTRS96)

2. GEOLOGICAL CHARACTERSITCIS

Most significant data about geological framework of Karlovac subdepression were acquired during the drilling of exploration boreholes Ka-1, Ka-2 and Ka-2.

Geological and geophysical information of these boreholes were used for defining petroleum and geothermal potential of exploration area “Southwest Sava", (later “Sava-2”). This area was of some scientific interest and some papers were published dealing with that topic. (KOLBAH et al., 2000., KOLBAH et al., 2002., KOLBAH et al., 2006., ŠKRLEC et al., 2005.) (Figure 2).

2.1 Borehole Ka-1

Borehole Ka-1 was made in 1964 with a final depth of 1 615 m. All up to 1 545 m was clastic deposits and after 1 545 m, the borehole entered mezozoic limestones and limestone marl (Figure 2). The borehole was never tested and was liquidate as negative.

2.2 Borehole Ka-2

Borehole Ka-2 was made in 1983 with a final depth of 4 145 m. Until 3 025 m, the borehole passes only through clastic sediment deposits, and after through carbonate deposits of limestone and dolomitic breccias and heterogenous breccias. In an interval between 3 840 and 4 074 m, there is a clastic layer of marl and shale. Due to the lack of fossils, the age was determined as mezozoic, while the interval between 4 075 and 4 145 m as upper Triassic.

2. 3 Borehole Ka-3

Borehole Ka-3 was made in 1988 with a final depth of 3 523 m. Until the depth of 1 567 m, the borehole went through complex of paleogenic and neogenic clastic deposits made of clay, marly clay, sand and layers of coal in the upper parts and interchanging marls and sandstones in the deeper part (Figure 2). The interval between 1 567 and 1885 m is made of upper cretaceous carbonate sludges and sandy marls, and from that to the bottom of the borehole (3 523 m) of crystalline limestone dolomite with couple of interlacing layers of pure dolomite, dolomitic limestones and limestone breccias. The same problem of lack of fossils as for the previous borehole was observed here and the age was also determined as mezozoic.

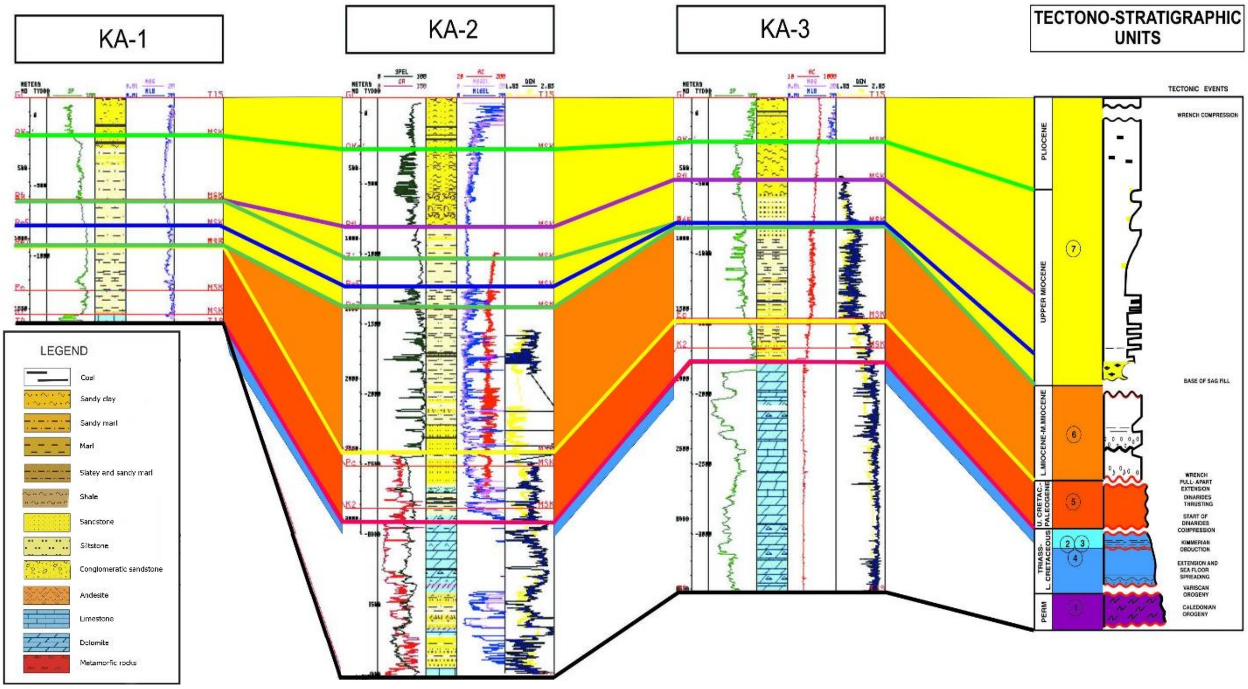

Figure 2: Correlation and geological column of boreholes Ka-1, Ka-2 and Ka-3 (as in Kolbah, 1998)

3. SUGGESTED AREA OF INTEREST REČICA

3.1 GEOTHERMAL CHARACTERISTICS OF THE RESERVOIR AND THE SURROUNDING AREA

The base element for the geothermal model are the data acquired by testing of specific layers during the drilling process and later by testing according to the program of Final testing for borehole Ka-2 and Ka-3 liquidation.

The temperature of the roof layer in borehole Ka-3 (at 1 884 m) was determined at 142°C by hydrodynamic testing DST-5. The measured temperature at 2 145 m was corrected for 11% to a value of 160°C and extrapolated to 261 m more shallow area, using an internal reservoir gradient of 23.66°C/100 m. Obtained geothermal gradient toward the surface, with an average annual surrounding surface temperature of 11°C, was 69.97°C/km. By that internal gradient of the reservoir, the temperature at the bottom of the borehole Ka-3 (at 3 523 m) was extrapolated to the value of 203.60°C. The same process was applied for the roof layer of Ka-2 at 3 354 m: the temperature of 191.82°C with a geothermal gradient toward the surface of 59.78°C/km and the temperature at the bottom of the Ka-2 borehole (at 4 145 m) of 218.32°C.

The order of magnitude of these values is supported by a few other measurements as, for example, hydrodynamic measurements of dynamic gradient pressure at the borehole Ka-3 (121°C at 1 782 m) or DST-5 measurement on the borehole Ka-2 (139°C at 3 354 m). Even thou these values are reduced over 20% (up to 40%), due to severe restrictions of the measurements themselves and degradation of formation temperature in a very porous reservoir, in a qualitative sense, they do bear witness to favourable geothermal conditions.

3.2 Assessment of production potential

The main characteristics of geological and geothermal makeup of Rečica were indicated and partly determined by deep boreholes Ka-2 and Ka-3 and, with available technology, they could be used for heat production for the city of Karlovac and other purposes. This prediction can be validated by the thickness of the massive carbonate deposit saturated with low-salinity water (expected thickness of 2 000 m) with probably the same unitary hydrodynamic regime. For now, there is a possibility of a hydrodynamic communication of this area with the elevated area across the fault zone.

Geological development and present structural and tectonic relationships define further screening or communication of the reservoir with any surrounding aquifers and technical possibilities of deep drilling. Besides the geological makeup of the aquifer itself, for the deposit of geothermal water in mezozoic carbonates in Rečica, other important factor is the regional geological build, especially Earth`s crust thickness, the rocks in the roof layer and the floor layer.

Regional characteristics of the Earth`s crust and interaction of massive carbonate reservoir and isolating roof layer of basin clastits has, according to present testing in boreholes Ka-3 and Ka-2, caused an increase in geothermal gradient towards the surface in floor rocks of the geothermal reservoir: at depths of over 4 000 m and 6 000 m to 45°C/km and 40°C/km.

So far, further growth of geothermal gradient was determined, due to the possibility of vertical convection of water, which helps the geothermal inflow towards the roof layer. Because of that fact, geothermal flow in the wells of around 140-170 °C is expected (Figure 3), which would result in geothermal gradient toward the surface of over 70°C/km (for a roof layer at 2 000 m depth) and 50°C/km (for a roof layer at 3 000 m depth). This conservative thermodynamical model, based on limited information, does predict a very high mobility of geothermal water in carbonate deposit with a low geothermal gradient, lower than 24°C/km. Other than some important indication during the drilling itself (caverns and the loss of drill-in fluid) and limited hydrodynamical testing, there is a high possibility of this geothermal aquifer having an inflow of around 100 l/s.

Rečica (with suggested area of interest 1, 2 and 3) consists of deeply lowered part of mezozic carbonate aquifer. The area between main fault systems takes up cca 12×6 km (where boreholes Ka-3 and Ka-2 are) could be a possible location for around 200 drainage production-injection zone with 1 000 m radius (Figure 3).

According to the structural layout (Figure 4), the depth of the roof of the aquifer varies significantly. The middle elevated and most easily assessable area (where Ka-3 and Ka-2 are) has the interested depths at around 2 000 m. The maximal depths of roof layer are around 3 700 m to the north and over 4 000 m to the south. Even thou the expected thickness of the aquifer is over 2 000 m, production wells would be in upper 500 m of the aquifer.

The main lowering along parallel faults, nowadays relaxing by movement, could make, because of possible horizontal shear, partly or in total a hydrodynamic barrier under stress. The answer to these questions should be given by further exploration.

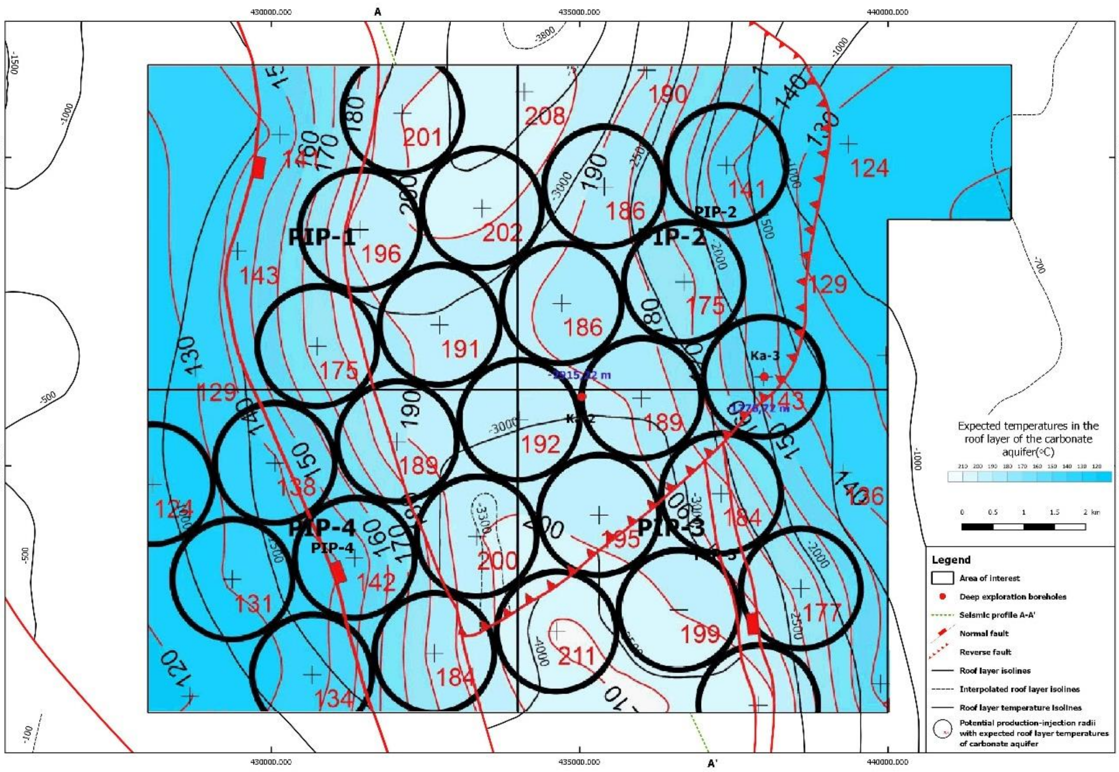

Figure 3: Scheme of expected lay out of production-injection drainage surfaces and the temperatures in the roof layer of carbonate aquifer (HTRS96)

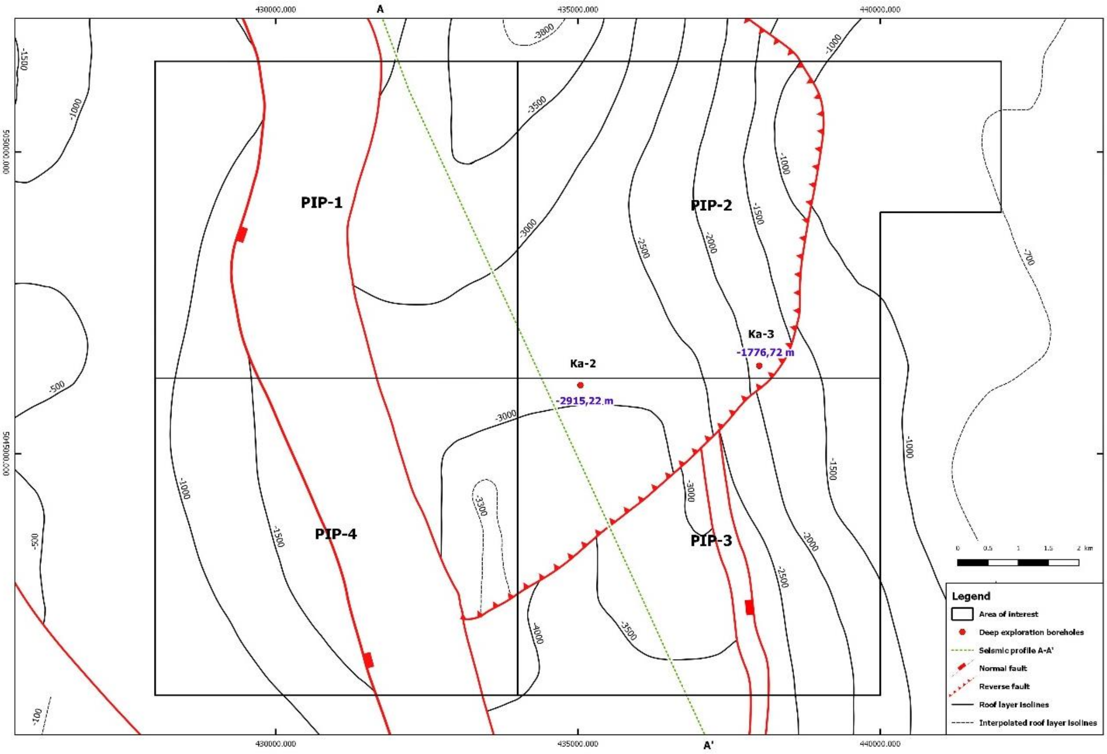

Figure 4: The map of structural and tectonic characteristics of roof layer (HTRS96)

3.2.1 Borehole Ka-2

Porosity of carbonate complex is significant, even extremely high at certain intervals. Date from DST and remote testing can only be taken as orientation values. The main goal of the testing was never to identify the amount of water that the boreholes could give.

3.2.2 Borehole Ka-3

Average depth of intervals with good porosity is 2 821 m and calculated hydrostatic pressure at that depth is 282 bars. Reservoir temperature is estimated based on geothermal gradient from DST data: T_{max} 120°C at 2 511 m. From that, the geothermal gradient was calculated as g1 = 4.32°C/100 m, with average annual temperature of environment at the borehole surface of 11.6 °C. That geothermal gradient was used to estimate the temperature t_{st} = 133°C at depth H_{sr} = 2 821 m.

During testing of certain intervals while drilling boreholes Ka-2 and Ka-3 and during further testing, water samples were taken. According to the analysis of water from clastic-carbonate complex (Ka-2) and carbonate complex (Ka-3), the salinity is under 1 g NaCl/dm^3. Even thou the rocks in this complex have a geochemical potential for hydrocarbon generation, there was no indication of any dissolved gas in any of the water samples.

Significant distance between tested intervals could indicate that the whole complex is hydrodynamically unitary.

4. SUGGESTED AREA OF INTEREST KARLOVAC

Seen as there is no borehole in this area, we can only assume that the build of this part of the subdepression is the same as the rest of it. In contrary to suggested area of interest Rečica, this area, in its NE part consist of SW deep carbonate reservoir with depths up to 4 000 m (Figure 4).

Rečica and Karlovac areas of interest are divided by a fault zone. Karlovac is on an elevated wing of the fault, whose jump in roof layer is 2000 m in north, 1 000 m in the middle and 3 000 m in the south (Figure 4). Lower SW part of Karlovac is developed in a platoe, where the depth of possible carbonate layers is somewhere between 1 500 and 1 000 m.

The other important tectonic zone, generally parallel to previous, is on the outer part of Karlovac area, almost touching its SW corner point (Figure 4). It raises the roof of the mezozic carbonate complex to very shallow depths, as can be confirmed from the drinking water wells in the area.

Hydrodynamic character of this tectonic zone should be further investigated. Carbonated complex located right under the city of Karlovac is also saturated with drinking water, used in one small part as a drinking water source of highest quality. The most elevated area consists of water-pumping station Borlin (2.5 km west of PIP-4, Figure 1). Drinking water from these two wells is used for cities water supply since 1915 with 13 l/s (Z-1) and 32 l/s (Z-2). Temperature of the water agrees with average annual temperature and varies 12-14°C. Even shallower depths of carbonates (10.4-20.5 m) were found at water-pumping station Mostanje (2 km south). In last three years, there have been three new wells: Mostanje MZ-1/14, Mostanje MZ-2/15 i MZ-3A/15. The depth of MZ-1/14 is 100 m and the depth to the roof dolomite layer is 10.4 m. The depth of MZ-2/15 is 100 m and the depth to the roof dolomite layer 12.8 m, and finally the depth of MZ-3A/16 is 120 m and the depth of carbonate roof layer 20.5 m. The wells are still not in exploitation stage, but testing showed inflow of 60 l/s (MZ-1/14), 70 l/s (MZ-2/15) and 90 l/s (MZ-3A/16), and the temperature of water is 12-14°C.70 l/s (MZ-2/15) i 90 l/s (MZ-3A/16), and the temperature of water is 12-14°C.

4.1 Geothermal characteristics of the reservoir

Geothermal model was made from the data collected and calculated for Rečica. In the first project stage, drilling and testing of exploration-production borehole is planned at the elevated edge of the main fault zone, to the depth of around 1 700 m. The purpose is to verify the existence and the quality of carbonate complex and the hydrodynamic character of the fault zone. Discovery at a possible shallower geothermal reservoir with expected water temperatures around 100 to 120°C and inflow of 100l/s, would satisfy the heating needs of the whole city of Karlovac. The additional advantage would be in less piping needed from the reservoir to the facility, than compared to Rečica.

Used thermodynamical model does not predict hydrodynamical communication with wells Borlin and Mostanje (Figure 4). Also, for now, we can only assume hydrodynamical relationship of deep reservoirs and parts of carbonate complex that can be found on the surface outside Karlovac subdepression and it should be further investigated.

The question of screening high value geothermal inflow from the deep geothermal aquifers is expected on another important tectonic line that almost touches SW corner point of suggested area of interest Karlovac and is mostly parallel to the main fault zone. With this tectonic deformation, the raise can be noted of the roof of carbonate complex on the SW of Karlovac from 1 000 m to almost the surface, with isolating layer of 12-15 m thickness. This most elevated part of carbonate complex, used for water- pumping stations with no temperature dependent sources, should be in a range of geothermal reservoir in Topusko (> 50°C). The problem of screening, if new exploration wells are not made, can be solved with measuring the drainage radius around the production well and additional testing between the wells and water-pumping stations. All that would give an idea for a location of injection borehole.

4.2 Assessment of production potential

Geological and physical characteristic of the reservoir and the geothermal fluid in Karlovac can only be discussed based on the data from Ka-2 and Ka-3 in Rečica area. Based on existing seismic profile (Figure 6) there is no visible difference in geological build of these two areas, so we can assume that most of the other characteristics are same or similar.

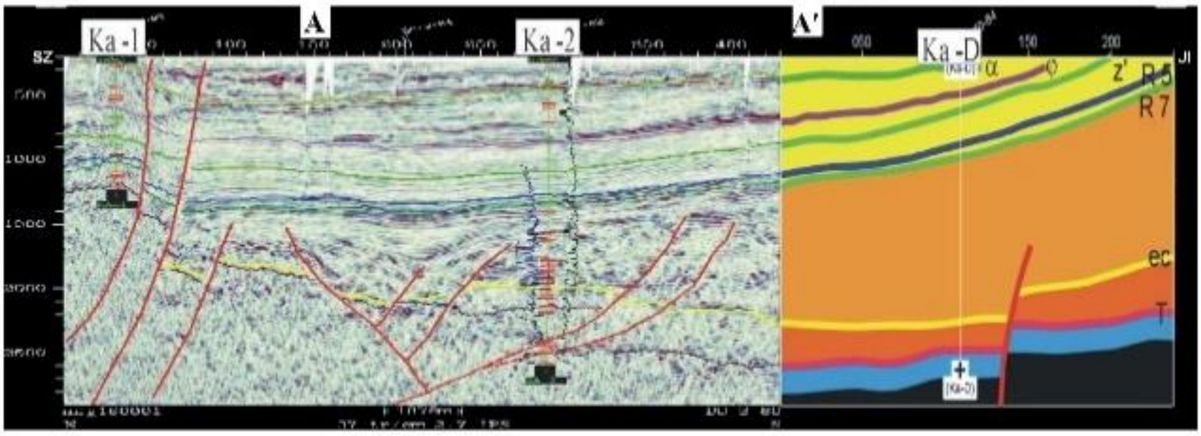

Figure 6: An example of interpretation of 2D seismic profile and deep boreholes (as in Kolbah, 1998)

The quality of water in the suggested area of interest Karlovac matches completely with the quality of water in other parts of the carbonate complex. For this project, the data about production possibilities of the reservoir is of value. The production possibility in this case is the amount of geothermal water and if they could supply the energetic need of the city of Karlovac. A very positive start is the date from the well inflows in the city area. Maximum capacity is around 90 l/s (around 8 000 m^3/d).

5. THERMODINAMIC CALCULATIONS OF THERMAL POWER AND PRODUCTION OF THERMAL ENERGY IN KARLOVAC AND REČICA

Thermal power related to temperature and the amount of geothermal water that can be acquired on the surface. That amount of water depends on the achieved conditions of technics used in drilling and production technology regime.

Average thermal power can be calculated as:

$$P_t = q_w \cdot (C \cdot \rho)_{wu} \cdot \Delta T \qquad [1]$$

where:

P_t – average thermal power, W
q_w – estimated amount of production, m^3/s
$(C \cdot \rho)_{wu}$ - specific heat of water at wellhead conditions, $4{,}076100 \cdot 10^6$, Jm^3 K-1 (from literature),
ΔT – the temperature difference, °C.

Calculations of thermal power for different productions and different temperatures of geothermal water used is shown in lower Table 1. Estimated amount of production of geothermal water varies from 4 000 to 10 000 m^3 per day, which are real values considering the expected reservoir parameters.

Thermal power (P_t) that could be acquired from geothermal water varies depending on the amount of production and used temperature of geothermal water.

The amount of energy (E_g) that could be collected in a time frame of a year can be calculated as:

$$E_g = 8\,760 \cdot P_t \qquad [2]$$

Where 8.760 is the total number of working hours a year.

Table 1: Calculation for thermal power for production of 4,000, 6,000, 8,000 and 10,000 m^3 per day and temperature used on temperature difference of 40°C, 50°C and 60°C

Production (m^3/day)	**Temperature difference** **ΔT** (°C)	**Thermal power** P_t (MW)
4,000	40	7.5
6,000	40	11.3
8,000	40	15.1
10,000	40	18.9
4,000	50	9.4
6,000	50	14.1
8,000	50	18.9
10,000	50	23.6
4,000	60	11.3
6,000	60	17.0
8,000	60	22.6
10,000	60	28.3

Annual production of energy depends on the amount of production of geothermal water, used difference in temperature and number of working hours. In Table 2. data for calculated possible production of energy with 4,400 working hours a year (6 months) are shown.

Table 2: Calculations of thermal power for production of 4,000, 6,000, 8,000 i 10,000 m3/day and possible production on temperature difference of 40°C, 50°C and 60°C

Production (m^3/day)	**Temperature difference** **ΔT** (°C)	**Thermal power** P_t (MW)	**Possible production for 6 months** (***E_g***) (MWh_t)
4,000	40	7.5	33,000
6,000	40	11.3	49,720
8,000	40	15.1	66,440
10,000	40	18.9	83,160
4,000	50	9.4	41,360
6,000	50	14.1	62,040
8,000	50	18.9	83,160
10,000	50	23.6	10,3840
4,000	60	11.3	49,720
6,000	60	17.0	74,800
8,000	60	22.6	99,440
10,000	60	28.3	124,520

Geothermal water (temperature 140°C and flow 100 l/s, 8 640 m^3 per day), after passes through heat exchange, shows a drop of temperature to 80°C.

6. CONCLUSION

Significant geothermal potential was identified in the wider area of city of Karlovac, as a part of petroleum-geological exploration which were made in the second half of the twentieth century.

Geothermal field Karlovac refers to geothermal aquifer in carbonate complex in the Karlovac vicinity. It was discovered by exploration boreholes Ka-2 and Ka-3 and confirmed by hydrodynamic testing. These two boreholes are located 12 km NW to the city of Karlovac, in the area of settlement Rečica.

During the borehole testing, high temperatures and significant water inflow with the potential for thermal and electric power production were found. In the deepest part of the Karlovac subdepression, in the outer parts of main fault zones, carbonate sediments are shallower as a result of tectonic movements in the geological past.

Observed area of the Karlovac subdepression was divided, for the purpose of this work, in blocks of four suggested areas of interest (PIP) according to the note of intent for administering public competing, made by the Ministry of Economy since 19th of July 2016. Both blocks on the north and one on the southeast (PIP-1, -2 i -3) were considered as suggested area of interest Rečica. The block on the SW was considered as suggested area of interest Karlovac.

In the area of interest Rečica, revitalization of the existing deep exploration boreholes Ka-2 and Ka-3 was considered, while in the area of interest Karlovac two new boreholes with the depth of about 1800 m were considered at the higher part of the fault zone which should determine and confirm the existence and the quality of the carbonate complex and hydrodynamic character of the dominant fault zone.

Besides suggested area of interest Rečica, geological setting and the hydrodynamic characteristics of the shallower part of carbonate aquifer in the suggested area of interest Karlovac, could also be interesting for geothermal energy utilization for the purpose of district heating of city of Karlovac.

Geological investigation indicate inflow of about 100 l/s at the borehole wellhead. Thermodinamical calculations result with about 19 MW_t on both locations with the total production of the 83 000 MWh_t/year. The analysis has confirmed that both locations have potential for the further development of the project.

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