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Utilization of Vintage Hydrocarbon Exploration Data in Geothermal Research: the Case Study of Zagreb Geothermal Field (Croatia)

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ABSTRACT

The interest of scientific and stakeholder communities on the exploration of deep carbonate geothermal resources is rapidly increasing due to their widespread occurrence and the possibility of local scale uses for hydrothermal heat and power generation. Within the framework of the HotLime and GeoTwinn projects, funded by the Horizon2020 program, the pilot area of Zagreb (Croatia) was chosen for detailed geological and thermal reconstructions of the thermal reservoir hosted in up to 400 m thick Miocene and Triassic carbonate rocks at a depth of approximately 1 km. Despite promising temperatures (up to 82 °C) and a significant number of wells drilled during the 1980s (27 wells in a 54 km^2 area), geothermal exploration of this area did not continue in the following decades. Notwithstanding the number of wells, some of which are fully equipped for production and reinjection, and the location of the wells in the national capital with numerous potential users, only one doublet system is in operation.

Stratigraphic logs of the wells, borehole logging data and 30 seismic sections were collected, and works are proceeding on their digitalization and arrangement into a database including chemical analyses of the waters, porosity and permeability measurements and bottom hole temperatures. These data will allow obtaining a comprehensive picture of the geological, hydro-geochemical and thermal settings of the reservoir. Seismic and borehole data will be used to perform a 3D geological reconstruction of the subsurface and highlighting the principal fault systems. Contemporary approach to the research of the geothermal resource based on existing data will serve to demonstrate the resource potential to the decision-makers and decrease the risks for future development.

1. INTRODUCTION

Croatia is situated at the junction of major European tectonic units: the Alps, the Dinarides and the Pannonian Basin System (PBS) (Fig. 1a). When considering the area from the perspective of geothermal resources utilization, it can be divided into two distinctive regions (Fig. 1b). Geologically, the north-eastern part of the country represents the south-western margin of the PBS, while the south-eastern part of the country is situated in the Dinarides. Favorable geothermal characteristics of the PBS are well known and demonstrated (e. g. Dővényi and Horváth 1988; Horváth et al. 2015), and its Croatian part shares these traits. Lithosphere thinning in the back-arc extensional area leads to high heat transfer from the mantle and anomalously high surface heat flow as a consequence. On the other hand, the Dinaridic area is characterized by a combination of thick lithosphere and kilometers thick carbonate platform deposits, which are also karstified - enabling deep meteoric water percolation, leading to an almost negligible surface heat flow. That is why, for all practical purposes, geothermal research (excluding heat pump applications) is concentrated to the Pannonian part of the country.

There are dozens of natural thermal springs in the Pannonian part of Croatia, and they were known and utilized since prehistoric times and antiquity (Schejbal, 2003). However, many more geothermal aquifers were discovered in the period from 1950s to 1990s, owing to extensive exploratory surveys and drilling conducted by hydrocarbon industry (in those times, the former Yugoslav publicly owned petroleum company INA-Naftaplin) - one of those being the Zagreb geothermal aquifer. Unfortunately, many boreholes which could have been prospective for geothermal water abstraction were technically abandoned because they yielded negative results in the sense of hydrocarbon content. However, detailed logs of those surveys have remained, which make a large pool of existing information relevant for geothermal prospection - in theory. In reality, on the other hand, the previously public petroleum company was partially privatized and no access was given to the researchers to this fundus of documentation, notwithstanding the fact that the data was obtained in full using public funding. The Ministry of Economy of the Republic of Croatia has long negotiated with INA about these data, and the they were finally released into the physical custody of the Croatian Geological Survey. The ministry remained the owner of the data, while the access to data is regulated by the Croatian Hydrocarbon Agency (AZU) on a case-by-case basis.

For the purpose of activities in the scope of Horizon 2020 funded projects, HotLime and GeoTwinn, the area of Zagreb geothermal field (ZGF) was selected. This geothermal field, discovered during prospection for hydrocarbons in the 1960s, has an area of about 54 km^2 and is situated in the City of Zagreb, the national capital. Considering the number of potential users (790,000 inhabitants according to the last population census in 2011, and around 100,000 consumers in the district heating system [DZS 2019]) it represents an example of an available resource which could be put into good use. The permission to use the borehole and seismic data for research purposes in the scope of the above-mentioned projects was obtained from the AZU.

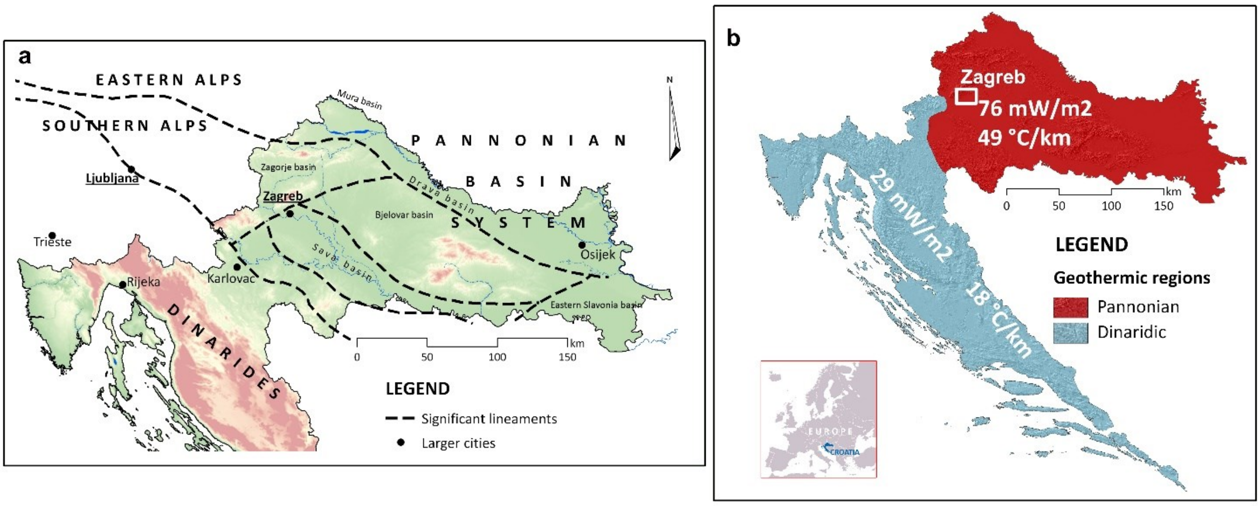

Figure 1: (a) Position of Croatia in relation to major European tectonic units (according to Lučić et al. 2001; Tari and Pamić 1998; Velić et al. 2012); (b) Heat flow density and geothermal gradient in different Croatian regions, modified from Borović et al. 2016.

2. ZAGREB GEOTHERMAL FIELD CHARACTERISTICS

The ZGF is a very suitable locality to test the methodologies and workflows to be established in the scope of the mentioned projects.

As part of the hydrocarbon research in the 1960s, a geothermal aquifer with favorable properties was discovered. Unlike many other localities in the Croatian part of the PBS, this aquifer was not abandoned. Rather, the opportunity of using the resource was recognized and it was further developed as a geothermal field. Research and drilling continued until 1988. Although the boreholes in the external part of the field are also utilized (e.g. Lučanka and Nedelja boreholes), the main development is represented by two so called *technological systems*: Mladost and KBNZ (in the central part of the field, with the highest measured temperatures and geothermal gradients). Fig. 2 shows the schematic cross-section of the ZGF area.

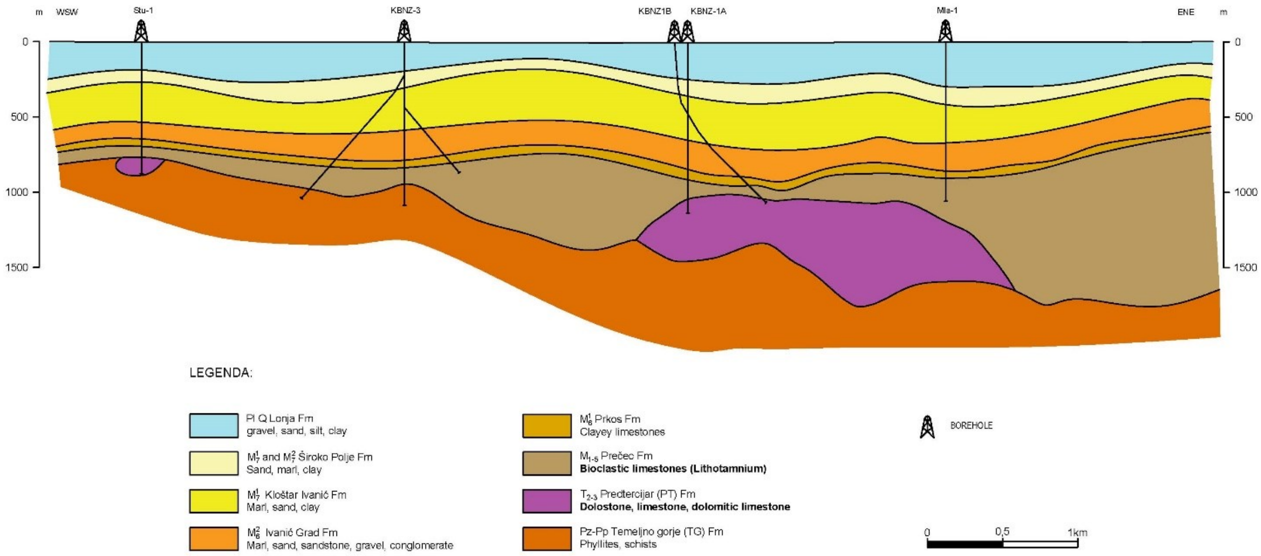

Figure 2: Schematic geological cross-section, redrawn according to Zelić et al (1995)

The main geothermal aquifers, as identified in the existing boreholes are M_{1-5} Prečec Formation bioclastic (*Lithotamnium*) limestones and T_{2-3} Podloga tercijara (PT) Formation dolostones, limestones, and dolomitic limestones. They vary significantly in thickness in this small area: M_{1-5} from 35 m to greater than 1016 m and T_{2-3} from 5 m to 357 m. *Lithothamnium* limestones are characterized by primary and secondary porosity which results in good overall permeability. The Triassic carbonates have low matrix porosity so good permeability is attributed only to secondary porosity. Recorded water temperatures in the boreholes ranged from a minimum of 34 °C up to a maximum of 78 °C at the Mladost technological system and 82 °C in the KBNZ system.

In the majority of the boreholes, the formation yielding water is the Miocene bioclastic limestone. However, for practical purposes the two formations are considered as a single hydro-stratigraphic unit.

3. STATUS OF THE DATA

In the area of ZGF, 27 boreholes were drilled, 34 seismic reflection profiles were measured, and 589 points of gravimetric measurements (i.e. 11 points/ km^2) and 389 magnetometric measurements (i.e. 7 points/ km^2) were taken (Zelić et al. 1995). In communication with the AZU, borehole and seismic data were obtained, while the gravimetric and magnetometric data seemed to be missing. Inquiries were also made toward the INA plc., but they claimed they are unaware of these data.

Firstly it must be stated that no database exists, containing organized information from decades of hydrocarbon exploration and exploitation in Croatia. Also, creating one was impossible until a few years ago because the archive data were unavailable to the research community, as explained in Section 1. Even now, as was the case for HotLime and GeoTwinn projects data requests, the whole procedure had to be undertaken to get the data, after which the data is obtained in a very raw form of scanned paper reports.

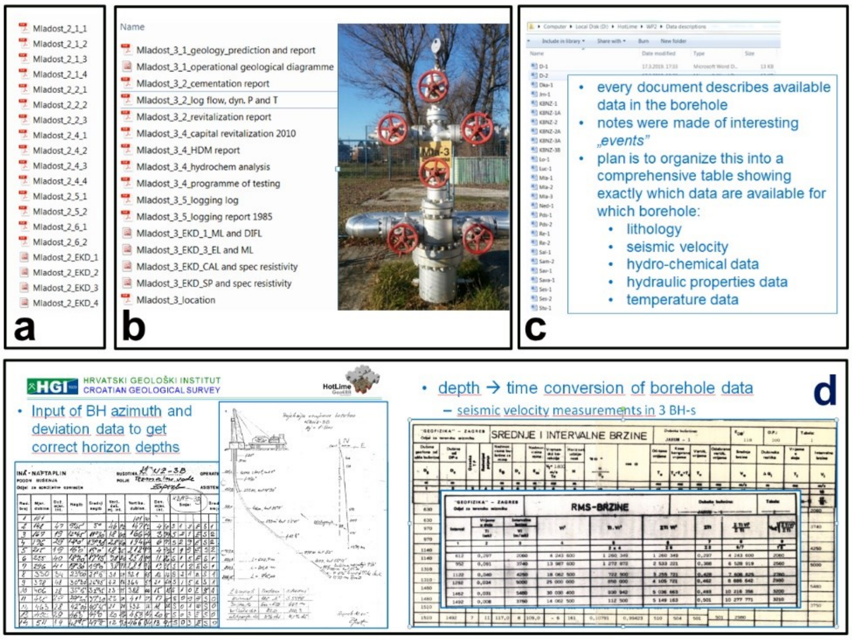

Figure 3: (a) Original data and file names; (b) renamed files; (c) created data descriptions; (d) examples of the scanned PDF documents.

The documents needed to be inspected one by one (Fig. 3a) to determine their actual content, then renamed for future use (Fig. 3b), and data descriptions were done for data relevant for current investigations. It is clear that it would have been wiser to start creating the full data base, but due to human resource shortages at the HGI-CGS, there is no possibility to extract all the useful data at this point. Fig. 3d shows some of the data which have been delivered to us, as an example.

4. PRELIMINARY RESULTS

Owing to the fact that the data was obtained in a disorganized form as described above, the works have been progressing slower than planned. However, the initial premise of the projects was indeed that the partners will be starting from different levels of data availability and organization, as well as with different availability of human resources skilled in geothermal research. The goal is to bring all the partners to the higher level of expertise, taking into account the difference in starting points inside the project consortium. That is why three levels of outputs were foreseen in the scope of the HotLime project: minimum, ideal and optional achievements. Due to a low starting point in the Zagreb pilot area, the HGI-CGS has opted for minimum achievement which will include: 3D geological model, stationary temperature model, hydrochemical facies overview, resource estimation and classification and involvement of local stakeholders.

4.1. Resource Estimation and Classification

Probabilistic estimates (P10, P50 and P90) of possible power output were calculated for two technological systems of the ZGF mentioned in section 2: Mladost and KBNZ, based on the ZGF main mining design data (Zelić et al. 1995). The DoubletCalc 1.4.3 software (TNO 2014) was used, which is conceived for permitting purposes in The Netherlands.

Mladost is a doublet system in successful and continuous operation since 1987. Mladost is also a name of the sports park where the doublet is situated, and the thermal energy is used for space and water heating. Due to its longevity, it is known that it operates on average 335 days annually, so this number was used for the calculation of energy output. The calculation was done for a 50-year period.

The KBNZ system is situated ca. 1 km to the south from Mladost. Three boreholes were drilled in the area, all of them including side-tracks. The system was planned for heating of the University hospital which was being constructed at the time. However, with changing circumstances, the hospital was never completed, and the geothermal boreholes are in place, but not utilized. Possible power output was also calculated, and the annual energy output was predicted based on the same operational regime as the neighboring Mladost system. Predicted power output for both systems is graphically summarized in Fig. 4.

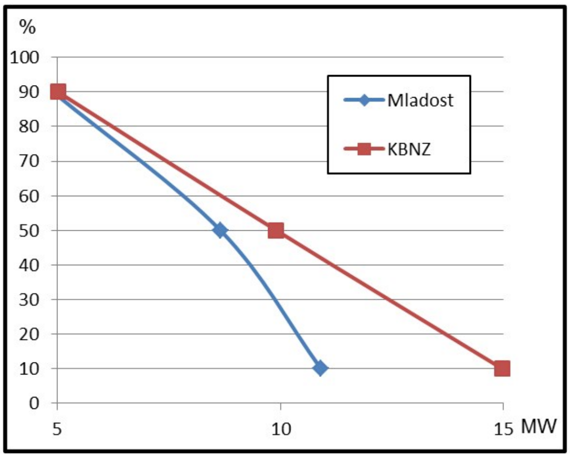

Figure 4: Probability plot for Mladost and KBNZ systems power outputs

Since the UNFC-2009 classification is project-based, it was necessary to ensure the comparable level of quantification. That means that the classification of any regional example would result in **E.3; F3; G4** classification of the resource, based on notional 'standard' projects, as exemplified for the sub-basins of the PBS in the scope of DARLINGe project (Nador 2018).

Technological systems already in place in the ZGF: Mladost (in operation) and KBNZ (idle) were classified. Looking at the whole theoretical 'Zagreb Basin' (sub-basin of the PBS), the DARLINGe project classified the resource as mentioned above. The Mladost system classifies as **7 PJ** E1.1; F1.1; G1 + **5 PJ** E1.1; F1.1; G2 + **3 PJ** E1.1; F1.1; G3 – thereby absolutely contrasting the sub-basin scale classification. This system is in successful continuous operation since 1987, so it is clearly feasible and socio-economically accepted. On the other hand, the neighboring system KBNZ of the same geothermal field must be classified as **7 PJ** E3; F1.3; G1 +**7 PJ** E3; F1.3; G2 + **7 PJ** E3; F1.3; G3 because – although all the wells are in place since 1987, they have been tested, concession was granted etc. – the system never became operational. KBNZ case is a typical example of legislative, administrative and political barriers to project implementation, leading to E3 classification of a project which could have been in operation for decades.

The Mladost system has been operational for 32 years, so its thermal output can be compared to the theoretical output (and planned by the main mining design). According to the most recent published data (Getliher and Cazin 2014), the actual annual utilization is 0.32 MW in capacity and 9.3 TJ of thermal energy, which is an insignificant proportion (6.5 %) of the possible thermal output, i.e. the exploitation should be organized in a much more efficient fashion. The KBNZ system is not in operation, so none of the available energy is put into useful function. Considering that the field is situated in the national capital with a number of possible heat users, it can be considered as an example of a resource abandoned for decades due to socio-economic circumstances.

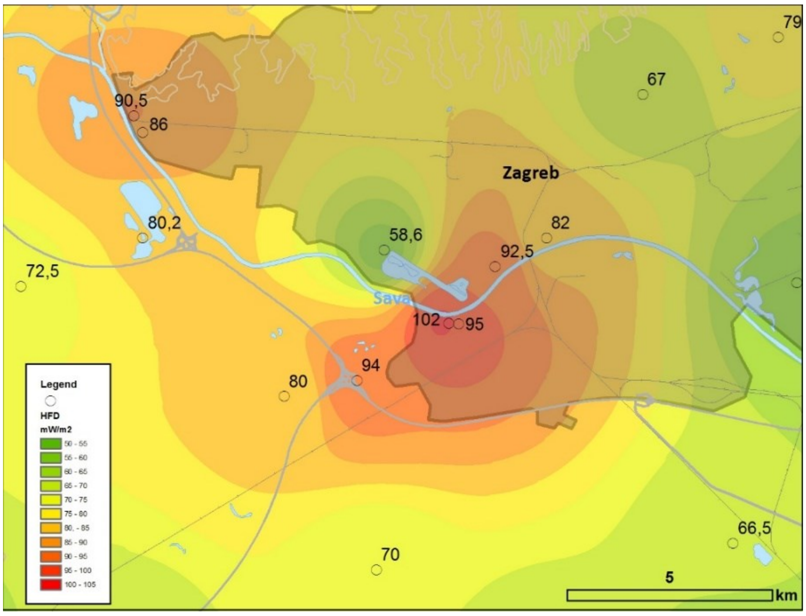

Figure 5: Interpolation of the heat flow density (HFD) in the ZGF. Outline of the City of Zagreb area is represented by the grey polygon.

4.2. Surface Heat Flow Estimates

Surface heat flow estimates were conducted based on geothermal gradients and thermal conductivities summarized in Kovačić (2002). Various deterministic interpolations were tested and the one with the lowest RMS error was considered an optimal one (in this case, it was the "Spline" interpolation in the ArcGIS tool by ESRI). The result of the interpolation with the lowest RMS error is shown in Fig. 5. The highest HFDs are present at the unutilized area of KBNZ (up to 102 mW/m^2), while at the Mladost area it reaches a maximum of 92.5 mW/m^2.

4.3. Hydrochemical Facies Determination

Laboratory analyses of water samples from ZGF boreholes were done between the years of 1984 and 1992. These data were also found in the borehole documentation. Principal anion and cation composition is shown numerically and graphically in Fig. 6. It is shown in Fig. 6a that the total mineralization is not high (around 2 mg/l). The only exception is the water from KBNZ-3A borehole, which has much lower mineralization (0.6 mg/l) - not even considered mineral water (the limit is set at 1 g/l in Croatia, Marković et al. 2015). From Fig. 2 it is seen that KBNZ-3A punctured the geothermal aquifer at shallower depth, so that could be the cause of lower TDS - a hypothesis to be tested via future data analyses. Also, the majority of hydrothermal systems in the Republic of Croatia are fed by fractured carbonate (predominantly dolostone) aquifers (Borović et al. 2015), and they do not exhibit mineralization of 1 g/l, i.e., they are more similar to cold and potable groundwaters from carbonate aquifers (Borović, 2015; Marković et al., 2015; Šimunić, 2008; Šimunić and Hećimović, 1999).

a

	Mla-1	Mla-2	Mla-3	KBNZ-1A	KBNZ-1B	KBNZ-3A
Ca^{2+}	65	56	20	43	46	36
Mg^{2+}	12	9	8	28	16	11
Na^{+}	576	550	495	516	525	125
K^{+}	23	30	27	28	25	15
HCO_3^{-}	991	926	732	973	814	247
Cl^{-}	252	255	234	248	294	50
SO_4^{2-}	322	290	296	239	284	158
TDS	2248	2122	1822	2083	2013	645

b

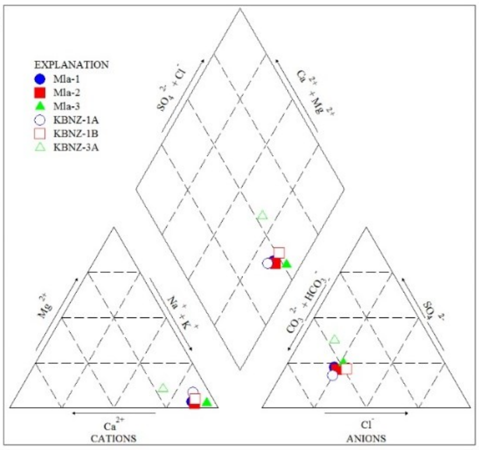

Figure 6: Major ion composition (a) and Piper diagram (b) of the waters from ZGF boreholes in Mladost and KBNZ technological systems

UPCOMING ACTIVITIES AND CONCLUSIONS

5.1. Upcoming activities

It can be seen in Fig. 2 that no fault structures were defined, although the cross-section is from the main mining design of the ZGF (Zelić et al. 1995), and declaratively it is based on both borehole data and interpretation of seismic cross-sections. However, initial analyses of seismic cross-sections clearly indicate the presence of fault structures. This is the part of the conceptual model which obviously needs to be revised, and the work in the scope of HotLime project is proceeding in that direction. Cross section coordinates were defined and organized into the project (Fig. 7). An upcoming task is to make a combined interpretation of seismic reflection and borehole data (converted to time domain), and then perform a conversion of the interpreted cross-sections back to the depth domain. Also, it is important to input borehole inclination azimuths and make corrections of thermal log data, in order to get a more realistic representation of temperatures at true vertical depths.

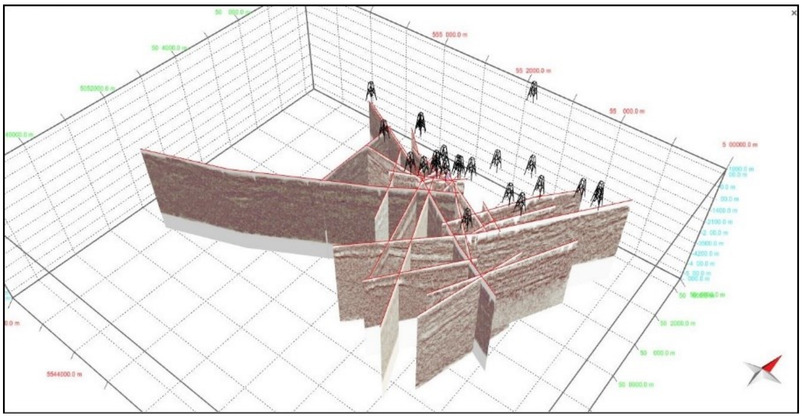

Figure 7: Project of seismic and borehole data in the MOVE software by Midland Valley

Seismic and borehole data will be used to perform a 3D geological reconstruction of the subsurface and to highlight the principal fault systems. The 3D geological model will be used to numerically reconstruct the subsurface thermal regime. Coupled fluid flow and heat transport numerical simulations will be performed using data on the hydrodynamic and thermal properties of the formations. First, the simulations will be run at steady state to assess the contribution of conductive processes to the thermal regime. Further transient simulations will be performed to evaluate the impact of the (most likely convective) processes occurring in the fractured carbonate reservoir and contributing to the local temperature increase. The obtained results of temperature model will be compared and calibrated with available bottom hole temperatures and thermal logs.

5.2. Conclusions

The HotLime project aims at overcoming the deficiencies due to data paucity in the research of hydrothermal carbonate reservoirs through transnational exchange of knowledge and experience. So far, the approach was proven successful in terms of methodologies used to resolve geological issues, conceptual models and the identification of generic controls, although final outcomes have not yet been prepared. The GeoTwinn project also aims at increasing the scientific capacities at the Croatian Geological Survey, which should result in new approaches to existing data. Project results accomplished until now have been presented in this paper, and it is already visible how the vintage data can be put to good use by utilizing contemporary methodologies and tools. It also became clear that the disorganized data gathering, no data base organized according to current standards, and the lack of human resources dealing with the topic of geothermal energy hinder stronger project development, even in the most prospective areas, like the national capital with existing boreholes. Projects are in progress and the results accomplished by April 2020 will be compiled and discussed at the WGC2020.

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REFERENCES

Borović, S.: Integrated hydrogeological-hydrogeochemical model of Daruvar geothermal aquifer, University of Zagreb -Faculty of Mining, Geology and Petroleum Engineering, (2015), Zagreb, 148 p.

Borović, S., Marković, I.: Utilization and tourism valorization of geothermal waters in Croatia. Renewable and Sustainable Energy Reviews, **44**, (2015), 52-63.

Borović, S., Marković, T., Larva, O., Brkić, Ž., Mraz, V., Mineral and thermal waters in the Croatian part of the Pannonian basin. In: Papić, P. (Ed.): Mineral and Thermal Waters of Southeastern Europe. Springer, Cham, (2016), 31-45.

Croatian Bureau of Statistics (DZS), Results of the 2011 population census, https://www.dzs.hr/ [2019-07-30]

Dővényi, P., Horváth, F.: Review of Temperature, Thermal Conductivity and Heat Flow Data for the Pannonian Basin. In: Royden, L. H., Horváth, F. (Eds.): The Pannonian Basin – a Study in Basin Evolution. American Association of Petroleum Geologists, Tulsa, Oklahoma, (1988), 195-233.

Getliher, A., Cazin, V: Geothermal waters of the Republic of Croatia – unutilized wealth. In: Barkovic, D. and Golub, M. (Eds.): Geothermal resource assessment of the Drava Basin. University of Osijek – Faculty of economy, Osijek, (2014), 59-73. (in Croatian)

Horváth, F., Musitz, B., Balázs, A., Végh, A., Uhrin, A., Nádor, A., Koroknai, B., Pap, N., Tóth, T., Wórum, G.: Evolution of the Pannonian basin and its geothermal resources. Geothermics, **53**, (2015), 328-352.

Kovačić, M.: Causes of a positive geothermal anomaly in the Zagreb area. PhD thesis. University of Zagreb - Faculty of Mining, Geology and Petroleum Engineering, (2002), 102 p.

Lučić, D., Saftić, B., Krizmanić, K., Prelogović, E., Britvić, V., Mesić, I., Tadej, J.: The Neogene evolution and hydrocarbon potential of the Pannonian Basin in Croatia. Marine and Petroleum Geology, **18**, (2001), 133-147.

Marković, T., Borović, S., Larva, O.: Geochemical characteristics of thermal waters of Hrvatsko zagorje. Geologia Croatica, **58(1)**, (2015), 67-77.

Nador, A.: Training on UNFC-2009 geothermal specifications, and case studies in the Central and SE-European region – DARLINGe project examples. Presentation, 25 April 2018, UNECE Geneva, (2018). https://www.unece.org/fileadmin/DAM/energy/se/pp/unfc_egrm/egrc9_apr2018/25.04/p.5_DARLING_Nador.pdf [2019-07-26]

Schejbal, B.: New considerations about Aquae Balissae and the Iassi people. Opvuscula archaeologica, **27**, (2003), 393-416.

Šimunić, A: Influence of geological structure to the emergence of thermal and mineral waters. In: Šimunić, A. (Ed.): Geothermal and mineral waters of the Republic of Croatia. Croatian Geological Survey, Zagreb, (2008), 5-36. (in Croatian)

Šimunić, A., Hećimović, I.: Geological aspects of thermal and mineral water occurrences of northwestern Croatia. Nafta, **50(3)**, (1999), 95-102.

Tari, V., Pamić, J.: Geodynamic evolution of the northern Dinarides and the southern part of the Pannonian Basin. Tectonophysics, **297**, (1998), 269-281.

TNO: DoubletCalc, a program for calculating the indicative power of a geothermal doublet, v. 1.4.3, (2014). https://www.nlog.nl/en/tools [2019-07-22]

UNFC (UNFC Geothermal Working Group): Specifications for the application of the United Nations Framework Classifi-cation for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to Geothermal Energy Resources, (2016). http://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/UNFC_GEOTH/UNFC.Geothermal.Specs.pdf [2019-04-28]

Velić, J., Malvić, T., Cvetković, M., Vrbanac, B.: Reservoir geology, hydrocarbon reserves and production in the Croatian part of the Pannonian Basin System. Geologia Croatica, **65(1)**, (2012), 91-101.

Zelić, M., Čubrić, S., Kulenović, I., Kušek, M., Marčan, B. et al.: Main mining design of the Zagreb Geothermal Field. INA plc., Zagreb, (1995), 268 p. (in Croatian)