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ORIGINAL PAPER

Overview of the current activities related to deep geothermal energy utilisation in the Republic of Croatia

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Abstract

The Pannonian Basin, partly located in Croatia, is well known for its higher-than-average geothermal gradient with good potential for geothermal energy exploitation. Most of the currently known geothermal potential locations in the Croatian part of the Pannonian Basin (CPB) were discovered during the oil and gas exploration and exploitation from the mid-twentieth century onward. Unfortunately, recent geothermal energy utilisation in Croatia, which began in the late 1980s, developed very slowly and sporadically, even though the utilisation of it has been known since the Roman times. Most of the discovered geothermal sources are used for balneology in numerous thermal spas. In the last decade, low-temperature geothermal resources have also been used in agriculture, namely in greenhouses. However, with the change of legal framework in 2018, the market showed an increase in the number of issued geothermal exploration blocks. With Croatia's first geothermal ORC power plant Velika 1, commissioned in 2019, the interest in developing geothermal projects is seen in 13 exploration and six production licenses issued in the last three years, focusing on deep geothermal potential. The planned use of these granted licenses varies from electricity production to agricultural use. Aside from classic geothermal brine production, there is also a good potential of geothermal brine exploitation from bottom aquifers in depleted oil and gas fields. Many hydrocarbon reservoirs in Croatia consist of oil and gas in the upper part of the reservoir and aquifer in the bottom part. During initial depletion-drive exploitation, pressure in the reservoir declines, causing brine from the aquifer to slowly invade the oil zone. While the reservoir is in its final stages of production, some waterflooded peripheral wells could be turned into geothermal ones, even if oil is still produced or after the field is abandoned. So far, several locations with relatively high temperatures of the bottom aquifer have been identified as a good potential for deep geothermal energy exploration and exploitation. This work gives an overview of the current state of geothermal energy utilisation in Croatia and future prospects.

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Graphical abstract

PANNONIAN AREA OF CROATIA AS GEOTHERMAL REGION

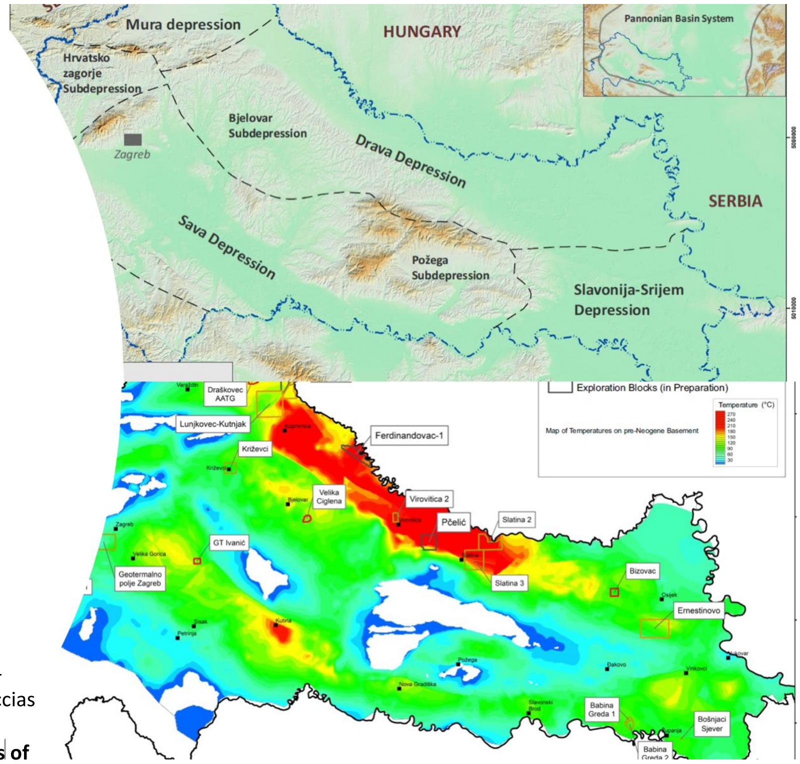
- Region with high potential for the production of geothermal water for energy purpose (electrical and heat energy) according to data **from deep exploration wells in the Croatian part of Pannonian basin**

- **Geothermal potential has been proven in cca 200 wells**

- **Above-average high geothermal gradient** (mean geothermal gradient of Pannonian area of Croatia) is **60 % higher than the European average**

LARGE CAPACITY GEOTHERMAL POTENTIALS:

- **Carbonate-clastic complex of Mesozoic age** (pre-Neogene basement): dolomites, limestones, breccias & conglomerates
- **Dolomite breccias and Lithotamnium limestones of Neogene**
    - Occurrence as massive reservoirs with significant productivity – (capacity of several thousand m^3/d)
    - Petrophysical characteristics: intergranular porosity, double porosity (fractured carbonates), good permeability



Map of Temperature of pre-Neogene Basement

Introduction

As part of a global effort to fight climate change, the promotion of geothermal energy utilisation has been recognised in all EU strategic documents related to the national Member States' plans to reduce greenhouse gases emissions. Energy transition shift from hydrocarbon exploration and exploitation projects towards geothermal brine production is also gaining momentum in the Republic of Croatia. Since the country has long history of domestic oil and gas production, more than 4,000 deep wells have been drilled, mainly in the Pannonian basin. Deep geothermal reservoirs can often be found in a form of bottom-type aquifers, which are an integral part of oil–water reservoir systems. Such aquifers play an important role as a strong energy drive to produce oil from permeable rock. On the other hand, during hydrocarbon exploration drilling, numerous geothermal reservoirs were discovered without the presence of hydrocarbons in different geological environment (Fig. 1). These locations are now frontrunners of geothermal energy research, as well as part of public concessions, a process which is handled by the Croatian Hydrocarbons Agency. The first activities began in the early twentieth century, and along with oil and gas, exploration of geothermal waters started. Testing of wells revealed the presence of a hot aquifer, but for a long time there was no further development of geothermal potential. The beginnings of the use of geothermal water for commercial purposes started in the late 1980s in the Bizovac field, and it is considered to be the longest use of geothermal water for space heating and balneological purposes in the contemporary times. Unfortunately, the application of geothermal water for energy utilisation in Croatia has developed slowly and sporadically while the development of geothermal water for balneological purposes is highly

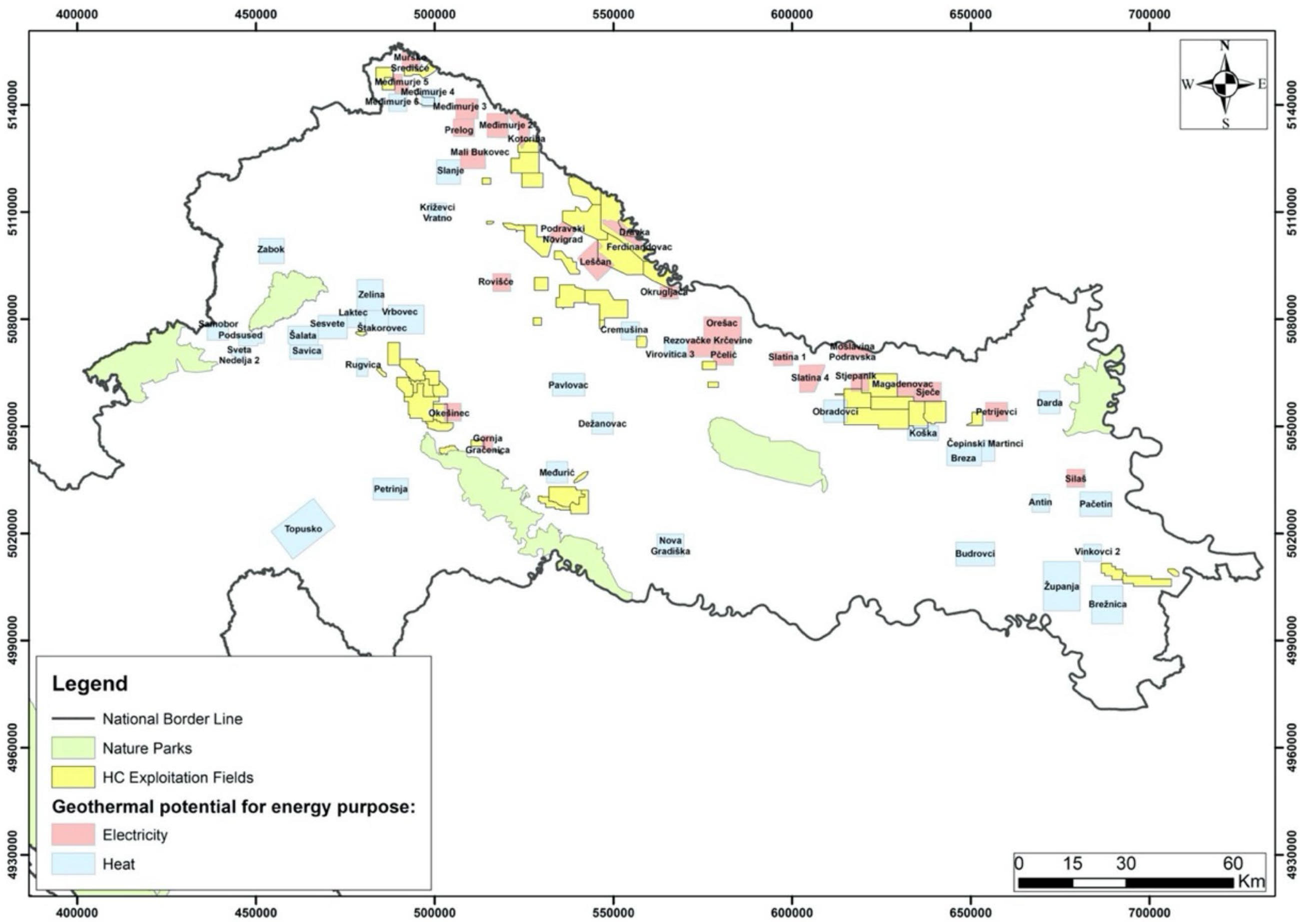


Fig. 1 Existing hydrocarbons exploitation fields and located geothermal potential reservoirs during hydrocarbons exploration era

developed through natural springs and tourist purposes (Lund and Toth 2020). Geothermal water for balneological purposes exists in Croatia at almost 21 sites with installed thermal energy of 24.0 MW_t (Živković et al. 2019), and most of the sites, 16, are located in Hrvatsko Zagorje (Borović and Marković 2015). The geochemical analysis of those sites showed that the associated geothermal reservoirs are in dolomite (Marković et al. 2015). A more intensive period of exploration of geothermal waters began in 2018 when the legislative framework in Croatia changed with the new Act on the Exploration and Production of Hydrocarbons (Official Gazette 52/18; Official Gazette 52/19; Official Gazette 30/21). The Croatian legal framework offers two options when tendering geothermal water for a given area. The tender can be launched by an investor's initiative for a specific area, or the Ministry responsible for energy initiates the tender in the areas where a certain geothermal potential has been assessed. The Croatian legal framework divides activities related to geothermal waters into exploration and exploitation phases. Exploration and exploitation permits are granted in a single procedure, i.e. if the investor fulfils his obligations from the exploration phase, he is automatically granted an exploitation permit. The exploration phase lasts a maximum of 5 years and can be extended for another year. The time frame for the exploration phase is a biddable item, so that the investor can bid for a shorter exploration phase. After commercial discovery, the investor proves its reserves through a reserve study and enters the exploitation phase based on the proven reserves. The exploitation phase lasts 25 years and can be extended if the investor proves that there are reserves that can be exploited commercially (Fig. 2).

Geological setting and geothermal potential

The Mohorovičić discontinuity in the Pannonian Basin varies from 30.0 km to 20.0 km, while its depth in the Dinarides is up to 40 km (Šumanovac et al. 2009), thus creating two very different geothermal regions in Croatia with different geothermal gradients. The Dinarides area

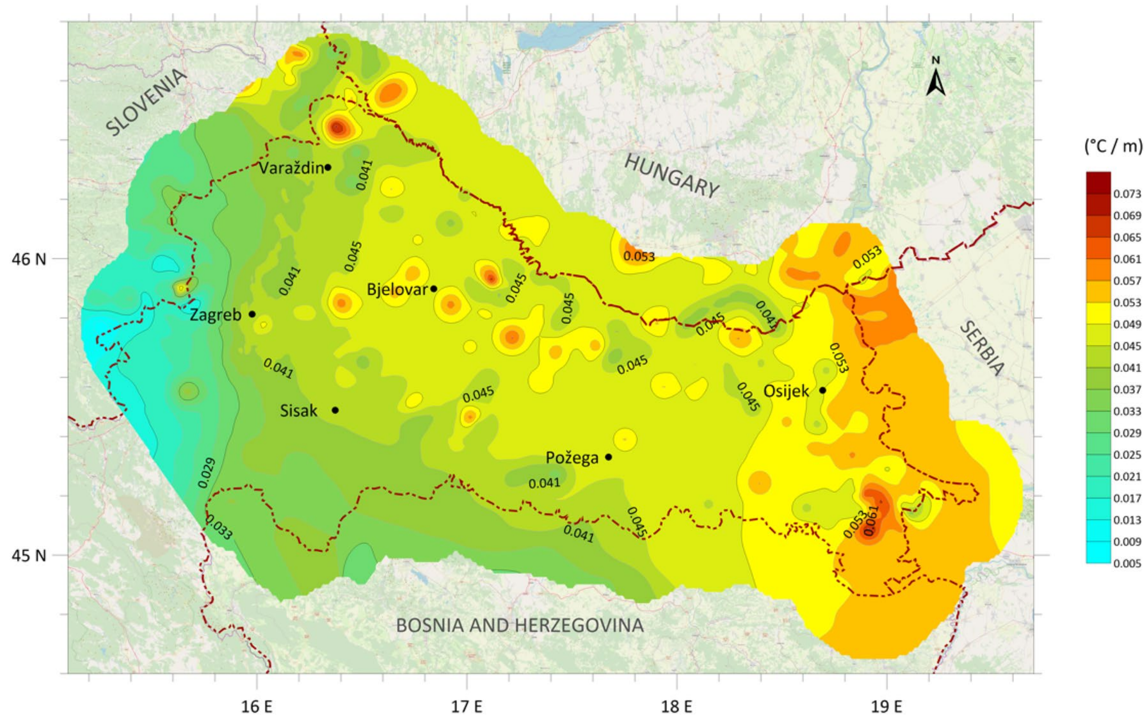


Fig. 2 Novel geothermal gradient map of the panonnian basin (Macenić et al. 2020)

has an average geothermal gradient of 0.018 °C/m with a heat flux of 29.0 mW/m^2 and thus has no significant geothermal potential, while the Pannonian Basin has an average geothermal gradient of 0.049 °C/m and a heat flux of 76.0mW/m^2 and thus has an above average geothermal potential in Europe (Jelić et al. 1995). The Pannonian Basin is characterised by low seismicity and high heat flux (Lenkey et al. 2002). A high heat flux, followed by high temperatures, has developed in the Pannonian Basin (Horváth et al. 2015). Recently, Macenić et al. (2020) presented a novel geothermal map of Croatia, based on gathered data from 154 deep exploration wells (Fig. 2).

Pannonian Basin (PB), as the largest Miocene–Quaternary basin, has been developed within the Alpine–Carpathian–Dinaridic orogenic system (Prelogović et al., 1998). According to Cvetković et al. (2019), the tectonic evolution of the PB started by the Cretaceous–Paleogene collision of Adria Microplate and European foreland. In the Early to Late Miocene, European plate roll-back subduction induced lithospheric extension and back-arc-type extension in the PB. The Neogene sedimentation process occurred within three 2nd-order megacycles, while majority of hydrocarbon source and reservoir rocks were formed during the 1st and 2nd megacycle (Saftić et al. 2003). The main source rocks are marly limestones and limy marls, while hydrocarbons are found in the Neogene basement, Miocence coarse grained clatics and Upper Miocene sandstone (Lučić et al. 2001). The extensional tectonics and the thinning of the crust and lithosphere within the Pannonian Basin are the cause of the high geothermal gradients and the very pronounced heat flux.

The Croatian part of the Pannonian Basin (CPB) is divided into four main depressions (Fig. 3): Mura, Sava, Drava and Slavonia Srijem (Velić et al. 2012). The Mura depression is located in the northernmost part of Croatia and extends from the border with Slovenia and Hungary in the north to a series of Žumberak, Medvednica and Kalnik mountains in the south. The Sava depression extends along the southwestern edge of the Pannonian Basin. The Drava depression covers most of the CPB and extends over the territory of the Drava River and is bounded by the state border with Hungary in the north and reaches the border with the Republic of Serbia in the east. The southern part of the Drava depression borders the mountains from Medvednica to Krndija. Slavonija–Srijem depression is located east of the town of Slavonski Brod and extends to the Serbian and Bosnian–Hercegovina borders and is the smallest of all depressions in the CPB (Malvić and Velić 2011).

The geothermal potential in the CPB is related to the pre-Neogene basement and Lower Neogene deposits (Fig. 4). The pre-Neogene basement is the most important correlation unconformity in the CPB and is visible in almost all well and

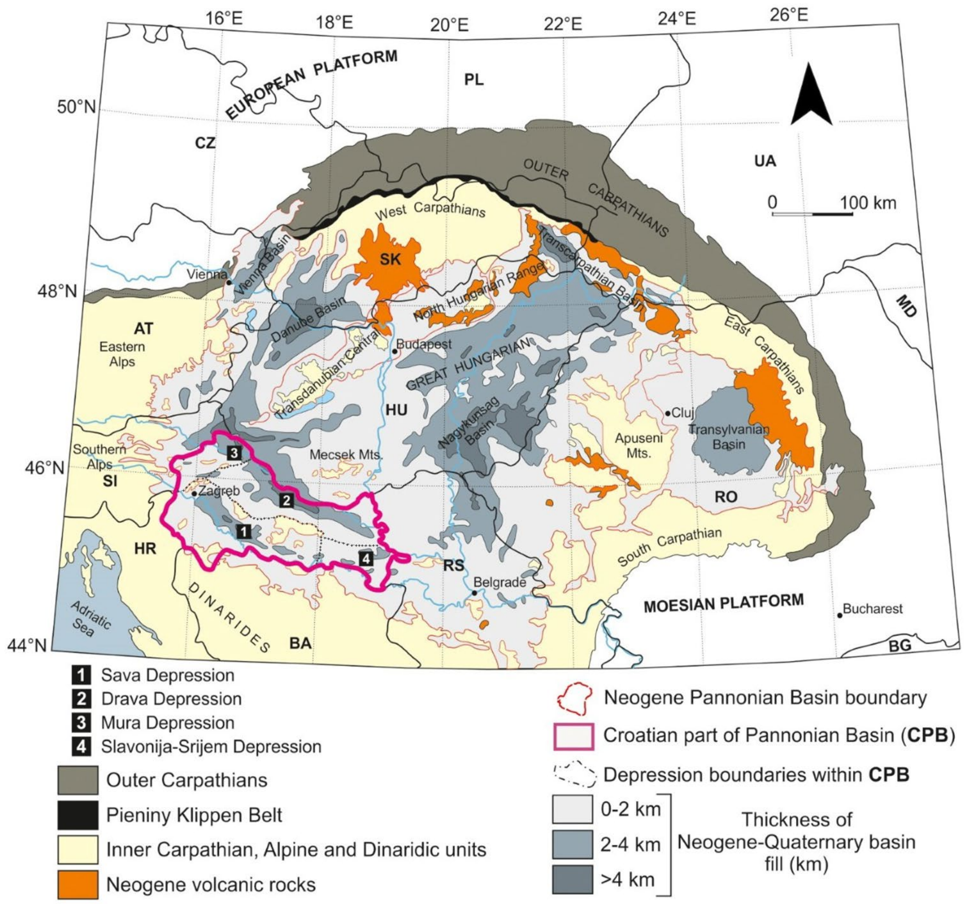


Fig. 3 Schematics of four main depressions in the Croatian part of the Pannonian Basin System (Velić et al. 2012)

seismic data (Saftić et al. 2003) and is characterised by high temperatures in almost the entire surface of the spreading (Cvetković et al. 2019). According to Royden et al. (1983), the evolution of the Pannonian Basin is subdivided into a syn-rift (Early to Mid-Miocene) and post-rift (Late Miocene to Quaternary) phase. The main geothermal plays in CPB are developed in pre-rift and syn-rift phase and considered as plays with high geothermal potential according to the present exploration activities in Croatia. There is a post-rift geothermal clastic play which is usually not a primary target of the geothermal exploration due to the lower geothermal gradient and flow.

Geothermal play developed in the pre-rift phase considers Paleozoic and Mesozoic age deposits and rocks (Sebe et al. 2020). According to the common lithostratigraphic classification, there are two lithological types of the pre-Neogene basement—predominantly Paleozoic magmatic and metamorphic rocks and Mesozoic carbonate deposits (Fig. 5). The Paleozoic, in locally accepted nomenclature "Crystalline Basement Rock", generally consists of granites, gabbro intrusions and fissured and altered metamorphised rocks intrusions. The petrophysical interpretation is based on well data which provide good characterisation of weathering zone, almost always located in the uppermost part of the rock, with secondary porosity. The weathering zone can extend from a few metres to several tens of metres from the top of the bedrock and mainly was formed during the Paleogene. (Malvić et al. 2020). The pre-Neogene deposits consist of carbonate deposits of Mesozoic age, mainly Triassic dolomites, while in the western part of the Pannonian Basin one can also find Jurassic limestones and dolomites as well as Upper Cretaceous Scaglia limestones. Pre-Neogene basement is the log marker "Pt (PN)" in most of the internal studies of CPB (Malvić and Cvetković 2013). The Mesozoic deposits are best preserved in greater thickness in the western part of the CPB. They consist of calcareous dolomite-breccia conglomerates, marly limestones or marbled limestones. It can be concluded that towards the eastern and southern parts of the CPB, they are entirely absent or isolated in the form of blocks or "lobes", which may affect the isolation of aquifers. Cracked massive carbonate deposits have been shown to be good aquifers. Geothermal play developed in syn-rift phase refers to the deposits from the Lower to Middle Miocene. They are defined by log markers from Pt (PN) to Rs7. They are mostly represented by large clastic

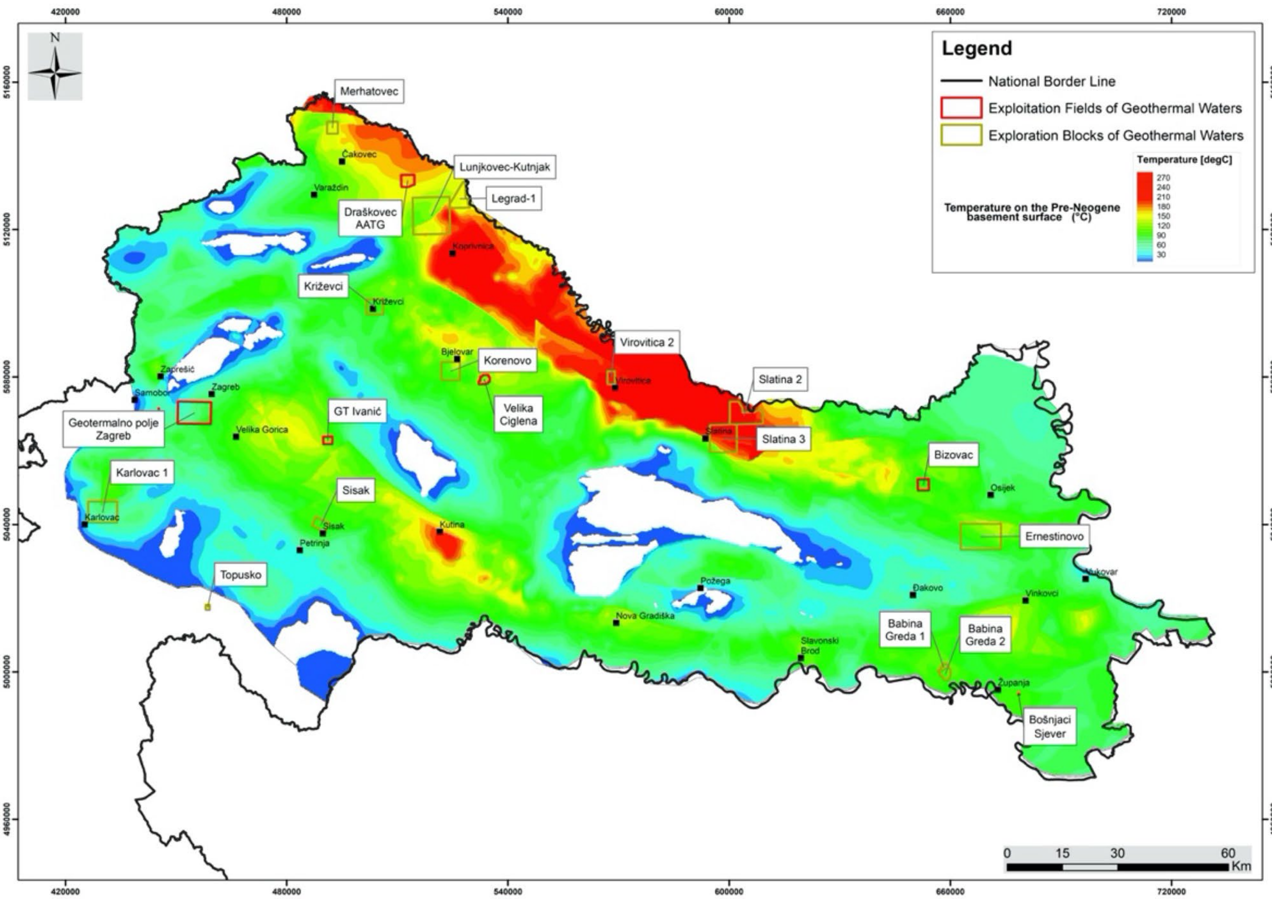


Fig. 4 Temperature of the pre-Neogene basement surface in the pannonian basin (Cvetković et al. 2019)

deposits in the lower parts of the formations, breccias and breccia conglomerates, which may be polymictic or carbonate. In the upper parts of the formations, there can be present sandstones of the lithoarenite or arkose arenite type, siltites, marly and sandy limestones of the biocalcarenite and biocalcrudite type (lithothamnium limestones) and marls (Malvić and Velić 2011).

Croatian geothermal exploration blocks

In 2018, new legal framework was adopted—Croatia's energy resources have been consolidated in one place, which is the basis for creating a positive investment climate in a country that rationally manages its resources. In this regard, special emphasis was placed on the great potential of geothermal and the exploitation of geothermal water for energy purposes. The procedure for assessing the hydrocarbon or geothermal potential and determining the tender conditions is carried out by the Croatian Hydrocarbon Agency, established by the Government of the Republic of Croatia. Currently, potential investors can use the newly formed Geothermal Virtual Data Room which covers geotechnical data of the Pannonian Basin. Access to reports of 191 potential geothermal wells, seismic data (Fig. 6) and GIS data are available for the screening process.

As of 2021, 13 exploration licenses and 6 production licenses for geothermal waters are active in Croatia based on the activities of the last three years (Fig. 7). All licenses are focused on the exploitation of deep geothermal energy. Shallow geothermal energy represents a potential (Macenić et al. 2018) that is underutilised in the zero-emissions energy transition. The Drava depression is the most prolific region of the CPB for geothermal energy development. The geothermal gradient in the Drava depression varies from 0.045 to 0.065 °C/m (Macenić et al. 2020). Due to the good geothermal properties of the Drava depression, most licenses are located within the Drava depression and with possibilities of high increase in geothermal potential from deep gas fields within Drava depression after hydrocarbon lifetime expiration (Kurevija and Vulin 2011). The planned use varies from electricity use to agricultural use by the local community.

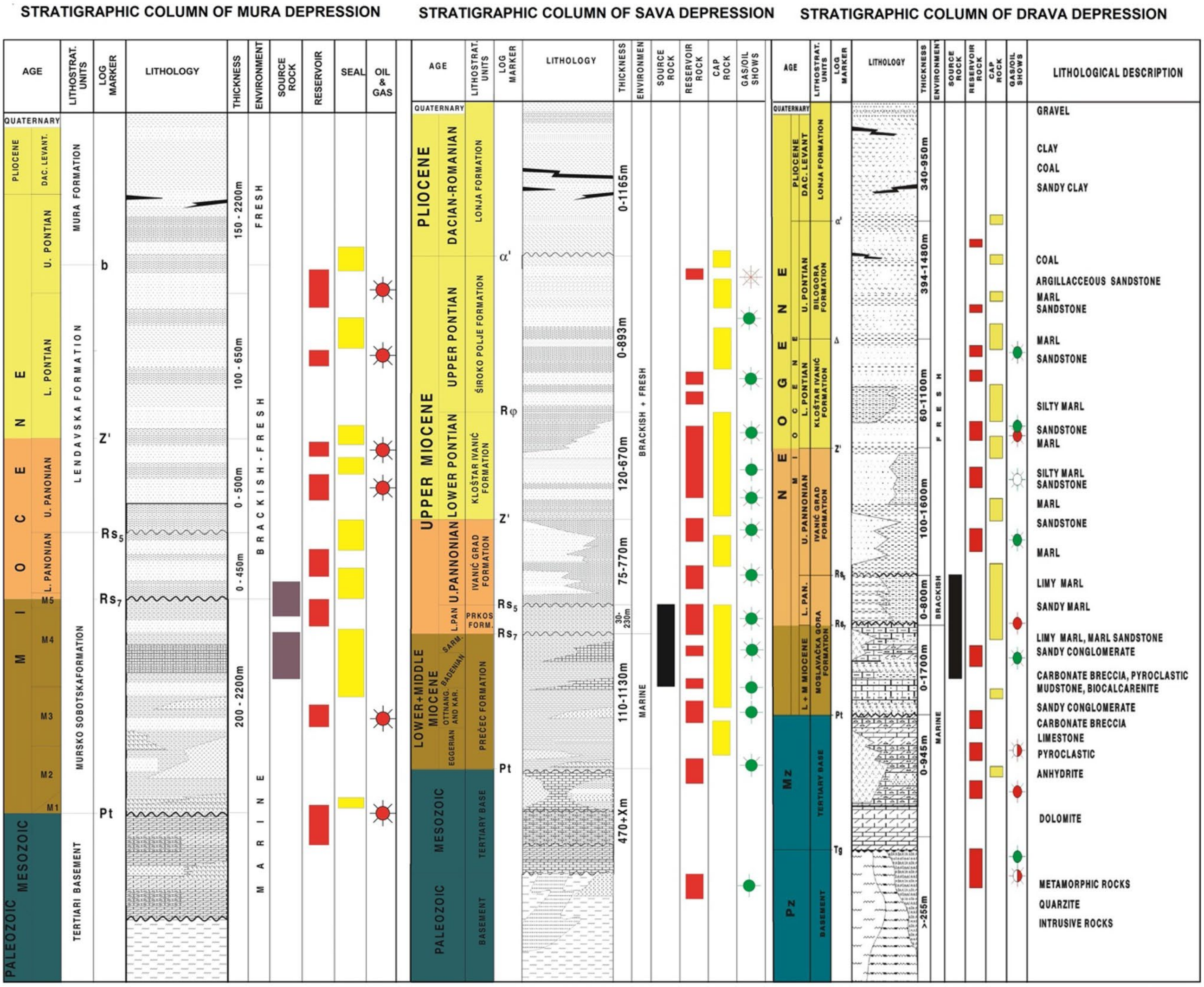


Fig. 5 General geological column of the Mura, Drava and Sava depressions (Durn and Krpan 2016)

In mid-2020, a tender round was announced in the Republic of Croatia for four exploration areas—Legrad-1, Merhatovec, Lunjkovec–Kutnjak and Ernestinovo. Licenses have been issued for all four areas, and exploration activities are planned for the next five years that will lead to the use of geothermal water for energy purposes.

Korenovo exploration block

At the end of 2020, a bid round was carried out for the *Korenovo exploration block* (Fig. 8), which is located in the area of the town of Bjelovar, in the southwest part of the Drava depression. The exploration permit was granted in early 2021 to a company established by the local municipality. It is planned to use the geothermal water for district heating, i.e. for heating of the planned sports and recreation centre and the industrial zone. The geothermal potential of the Korenovo area was discovered in the late 1950s through the construction of the Korenovo-1 (Kor-1) exploration well (Fig. 9). The Korenovo-1 well was also drilled for the purpose of hydrocarbon exploration. The well was not tested as no hydrocarbon phenomena were observed during drilling and geological monitoring of the well. However, during geological monitoring of the well, flooded layers of Neogene sands were found in places. The salinity of the water in these layers is about 8.0 g NaCl/l, while in the permeable interval of lithothamnium limestones the salinity of the water is about 20.0 g NaCl/l. The final depth of the well is 1,457.9 m with a measured temperature of 67.0 °C at the bottom of the well. The average geothermal gradient of the well, based

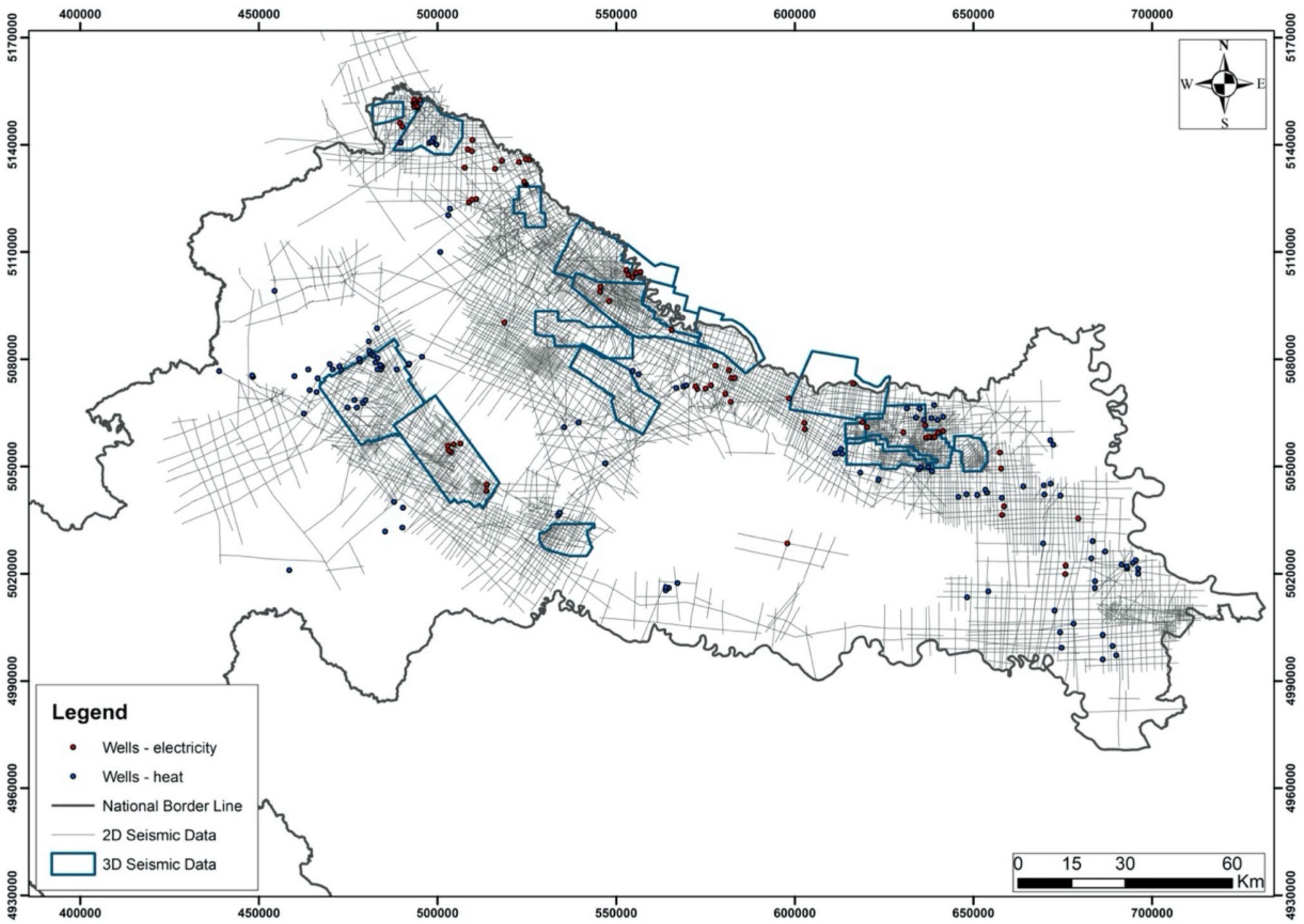


Fig. 6 Existing 2D and 3D seismic data from hydrocarbon exploration available for geothermal reservoirs exploration

on which the exploration area was estimated, is 0.039 °C/m (Croatian Hydrocarbon Agency, 2020a).

Virovitica and Slatina exploration blocks

There are currently 3 exploration blocks in Virovitica-Podravina County—*Virovitica 2, Slatina 2 and Slatina 3*. Exploration permits for Slatina 2 and Slatina 3 exploration blocks were granted in 2018, while Virovitica 2 was granted a permit in February 2020. All three exploration blocks are in the central part of Drava depression. The potential for the Virovitica 2 exploration block was determined based on 6 exploration wells in the vicinity of the exploration block and on 269 km of existing 2D seismic profiles. The temperature of the geothermal reservoir is assumed to be 70.0 °C at a depth of approximately 1,600.0 m. The exploration blocks are licensed to the company formed by the local community and aims to heat business premises in the existing commercial zone and use geothermal water to heat greenhouses (Croatian Hydrocarbon Agency 2019a). Welltesting in the wells of the Slatina 2 exploration block has identified geothermal water reserves with a potential flow rate of 250.0 l/s and a well temperature of 186.0 °C. Future activities in this exploration block will focus on the construction of additional wells, and the possibility of producing electricity, as the reservoir has an extremely high enthalpy. There are two wells on Slatina 3, and the measured temperature at a depth of 4,500.0 m was 191.0 °C. By analysing the data from wells in both exploration areas, we can conclude that the geothermal potential is associated with pre-Neogene pre-rift carbonate deposits (Fig. 10) (Croatian Hydrocarbon Agency 2018).

Križevci exploration block

The *Križevci exploration block* is located in Koprivnica–Križevci County in the Drava depression where exploration activities started in the early 2020. Based on the data from the well, the temperature is estimated to be 74.0 °C at a depth of 1,496.0 m in the limestone, sandstone and breccia complex. During the testing of the well, a

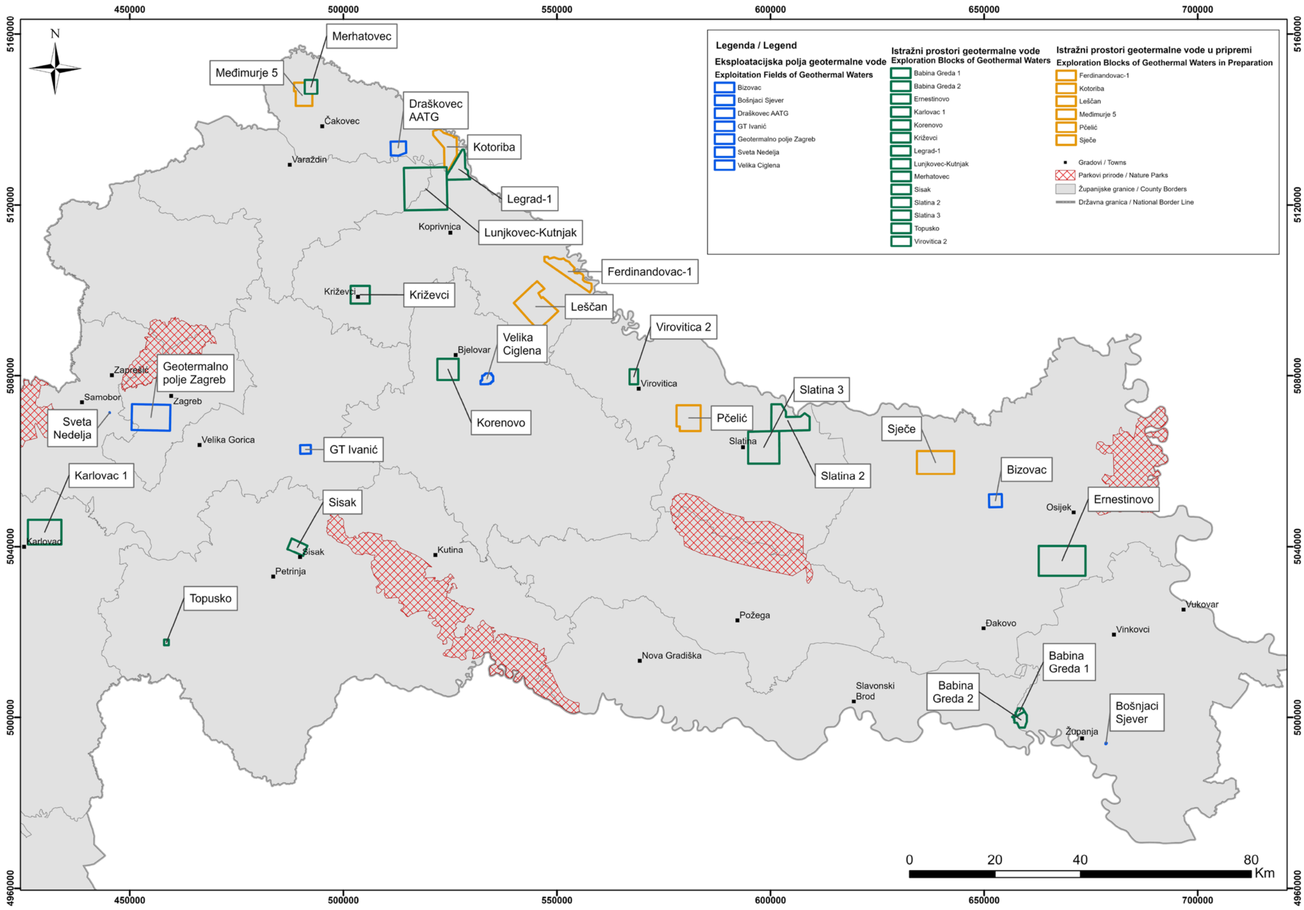


Fig. 7 Exploration blocks and exploitation fields of geothermal water in the Republic of Croatia (Croatian Hydrocarbon Agency 2020a, b, c, d, e)

flow rate of 3.2 l/s was obtained. As the exploration area is located in the town of Križevci, the geothermal water will be used for heating nearby buildings and sports and recreational facilities (Croatian Hydrocarbon Agency 2019b).

Ernestinovo exploration block

The *Ernestinovo exploration block* is located in the south-eastern part of the Drava depression (Fig. 11). The geothermal potential of the Ernestinovo area was also discovered during the construction of deep exploration wells for hydrocarbons–Ernestinovo-2 (Ern-2) and Ernestinovo-3 (Ern-3). Drill Stem Testing (DST) was conducted at both wells, and water was obtained from the reservoir (Table 1). The syn-rift carbonate geothermal play lithologically consists of: conglomerates, breccias, marlitic sandstones, calcitic sandstones, lithothamnium limestones (lithuanians), calcitic marls, clay marls, and their variants (Fig. 12). In the Ern-2 well, a temperature of 165.0 °C was measured at a depth of 3,790.0 m, while in the Ern-3 well, a temperature of 125.5 °C was measured at the bottom of the well at a depth of 3,106.0 m (Croatian Hydrocarbon Agency 2020b).

Merhatovec exploration block

The *Merhatovec exploration block* is located in northwestern Croatia and belongs to the Mura depression (Fig. 13). The geothermal potential was determined by testing of two wells—Merhatovec-1 (Mer-1) and Merhatovec-2 (Mer-2)—and the measured temperature during logging at a depth of 4,195.0 m was 150.0 °C, and at a depth of 3,404.0 m was 140.0 °C. The well testing determined the

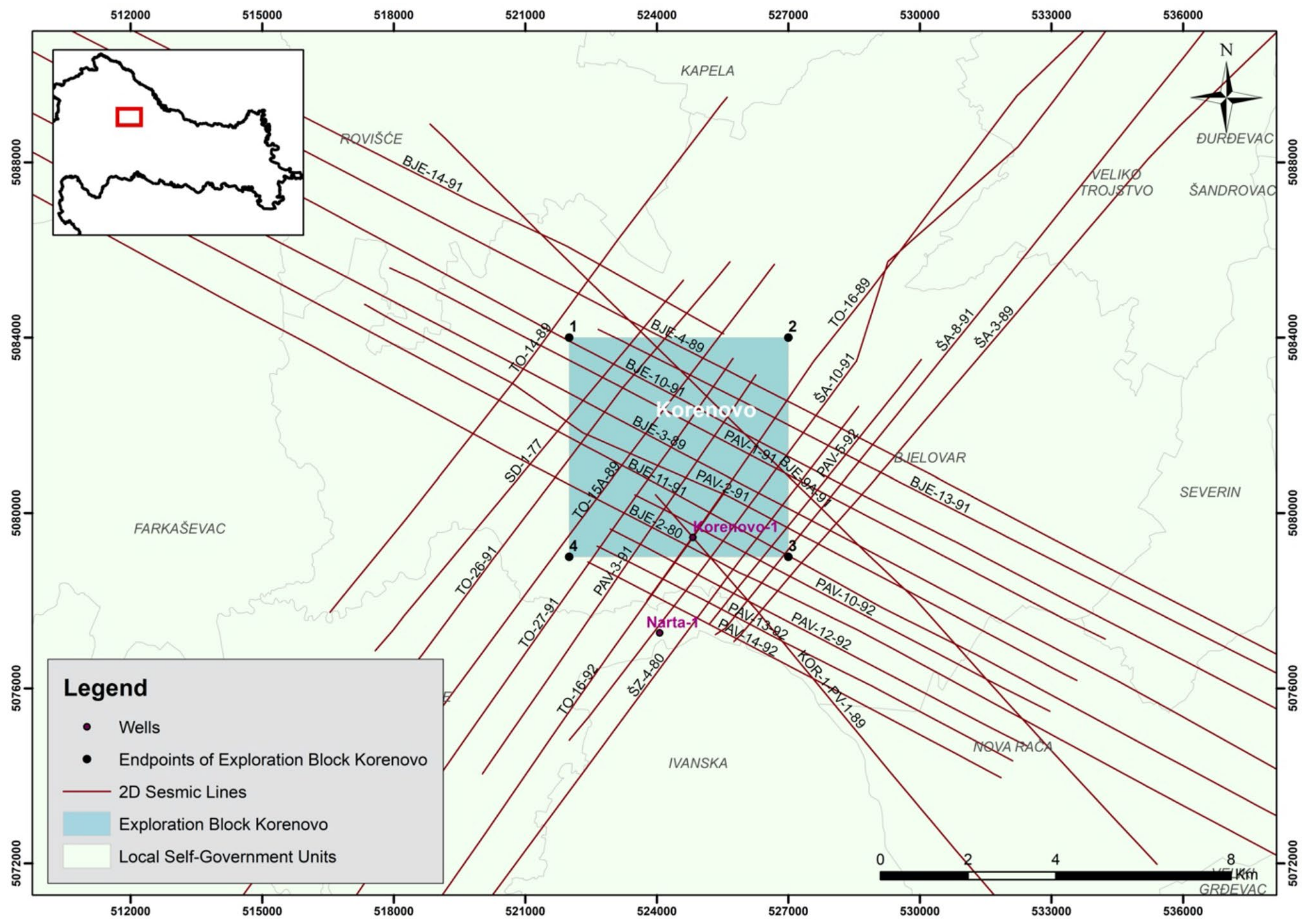


Fig. 8 Exploration block Korenovo (Croatian Hydrocarbon Agency 2020a)

geothermal potential (Table 2) in pre-rift dolomite breccias in the pre-Neogene basement (Fig. 14) (Croatian Hydrocarbon Agency 2020e).

Legrad exploration block

The Legrad-1 exploration block is located at the edge of the northwestern part of the Drava depression and partially overlaps with the Legrad hydrocarbon field (Fig. 15). Legrad geothermal play was determined in pre-Neogene pre-rift carbonates of Mesozoic. The area of the Legrad-1 exploration block is mostly covered by 2D seismic lines, the oldest of which date back to the 1970s, while the most recent ones are from 2016. The area was estimated based on six local wells that revealed the presence of geothermal potential in the complex of dolomite breccias that underlie the Neogene deposits (Fig. 16). The depth of wells ranges from 1,975.0 m to 4,600.0 m, and the temperatures measured at the bottom of the wells range from 105.0 to 212.0 °C, with initial test results seen in Table 3. (Croatian Hydrocarbon Agency 2020c).

Lunjkovec–Kutnjak exploration block

The *Lunjkovec–Kutnjak exploration block* is located in the northwestern part of the Drava depression (Fig. 17). In estimating the geothermal potential of the Lunjkovec–Kutnjak exploration block, data from 9 surrounding wells were considered. Wells were drilled in the 1970s and early 1980s for the purpose of hydrocarbon exploration. The final depths of the wells are 2,203.0 and 2,430.0 m, respectively, with measured temperatures at the bottom of the wells in the range of 128.0 °C to 144.6 °C, and the average geothermal gradient in the area is approximately 0.043 °C/m. The geothermal potential was determined by well testing (Table 4) in the pre-Neogene pre-rift carbonate-clastic complex (Fig. 18) (Croatian Hydrocarbon Agency 2020d). As the Lunjkovec–Kutnjak exploration block is located in an agricultural

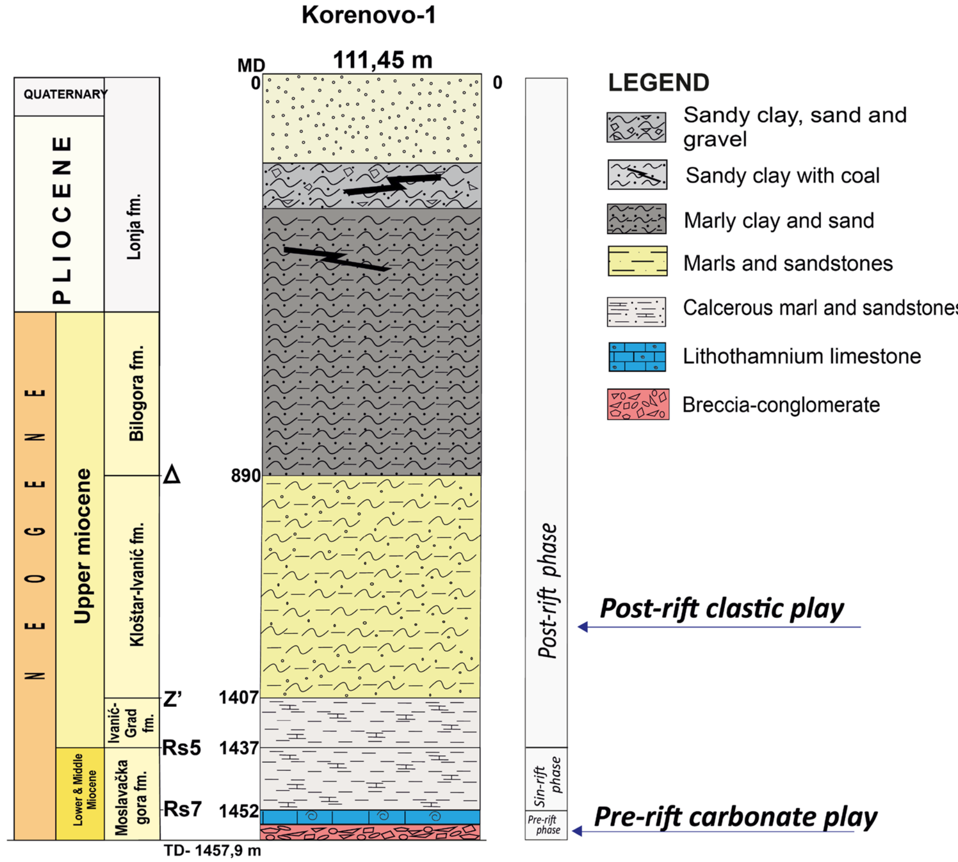


Fig. 9 Schematic lithostratigraphic column of Korenovo-1 well in the Korenovo exploration block (Croatian Hydrocarbon Agency 2020a)

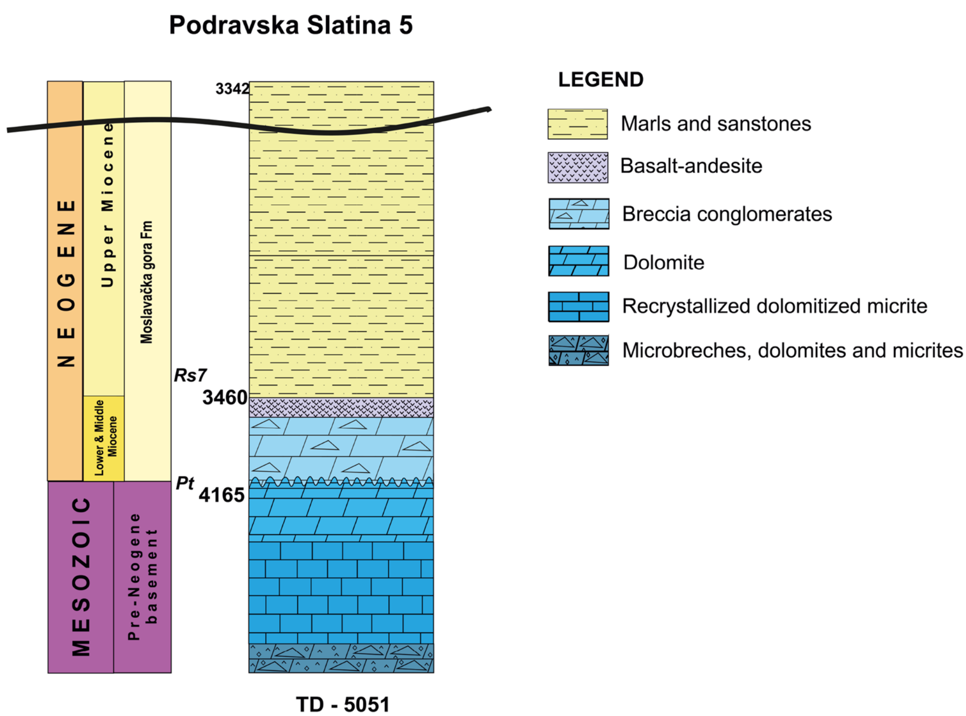


Fig. 10 Schematic lithostratigraphic column of Podravska Slatina-5 well in the Slatina 2 exploration block (Croatian Hydrocarbon Agency, 2018)

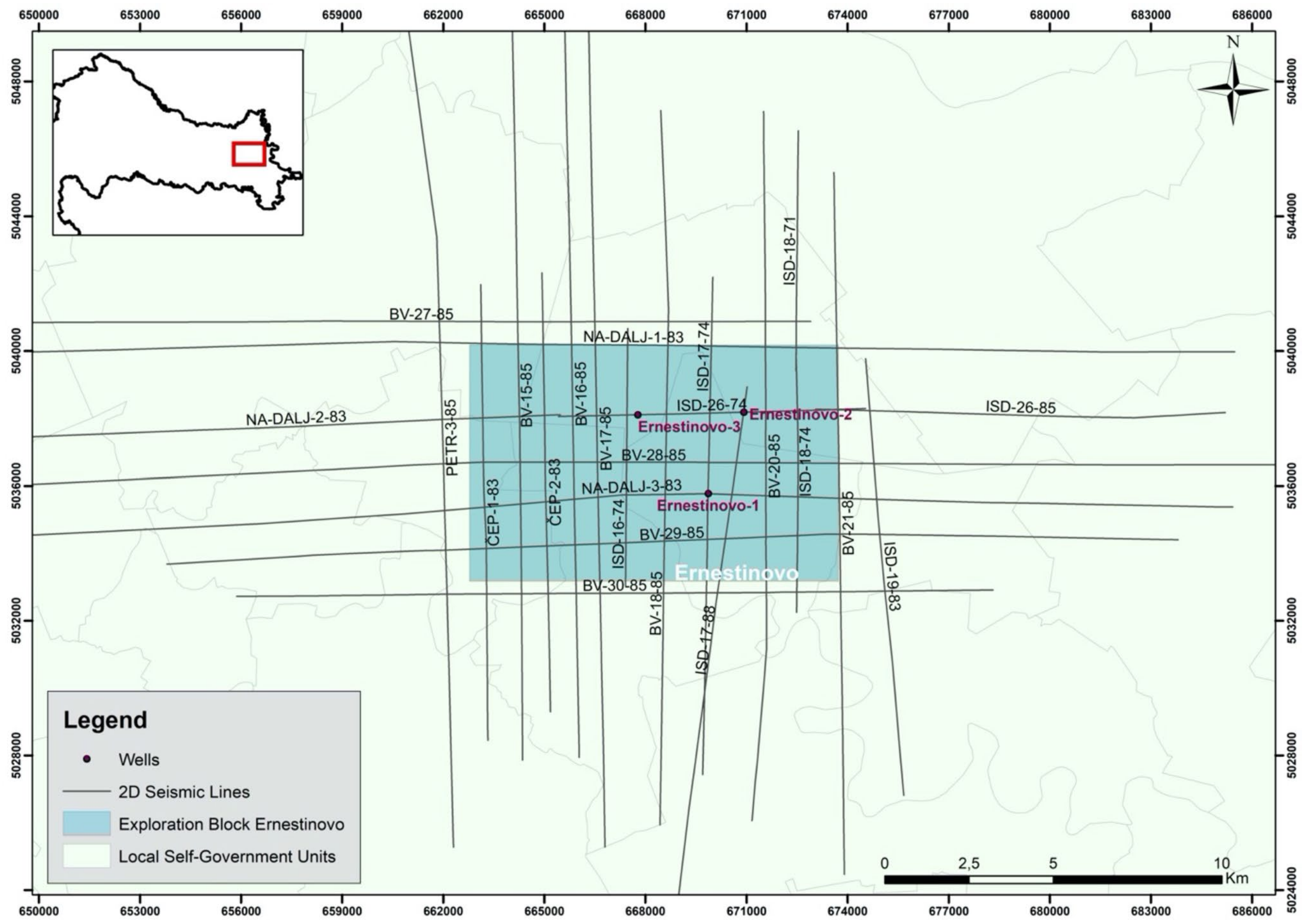


Fig. 11 Exploration block Ernestinovo (Croatian Hydrocarbon Agency 2020b)

area, cogeneration is planned for space heating, electricity generation and greenhouse heating. The estimated electricity generation by the ORC process in the Lunjkovec–Kutnjak exploration area is 2,259.0 kW gross at a flow rate of 34.3 kg/s (Guzović et al. 2012).

Babina Greda exploration blocks

The *Babina Greda 1 and Babina Greda 2 exploration blocks* are located in the easternmost part of the Republic of Croatia, in the Slavonia-Srijem depression. The entire area has been the subject of exploratory drilling as part of hydrocarbon exploration (Fig. 19). In the Babina Greda 1 exploration block, there are three wells, based on which the area was assessed as having geothermal potential. The drilling data and measurements in wells divide the reservoir into the upper part with a temperature of 122.5 °C at a depth of 2,270.0 m, to the deeper part of the reservoir, where temperatures of 161.0 °C were recorded at a depth of 3,802.0 m. No drilling data are available for Babina Greda 2, but based on seismic data the same reservoir development as in the neighbouring exploration block and the same temperature gradients are expected. Permits for these exploration blocks were granted in 2019.

Table 1 Test results of Ernestinovo-2 and Ernestinovo-3 wells

	Ernestinovo-2	Ernestinovo-3
Well depth (m)	3,790.0	3,106.0
Bottomhole temperature (°C)	165.0	125.5
Tested interval (m)	2,932.0–2,888.0	2,603.0–2,584.0
Temperature (°C)	120.0	132.2
Initial tested flow (m^3/day)	15.0	184.8

Karlovac exploration block

The *Karlovac 1 exploration block* is located in the southwestern part of the Karlovac Valley in the immediate vicinity of the town of Karlovac. As there are no wells in the exploration area, correlation was made with wells in the vicinity, Ka-2 and Ka-3. The data from the wells, located

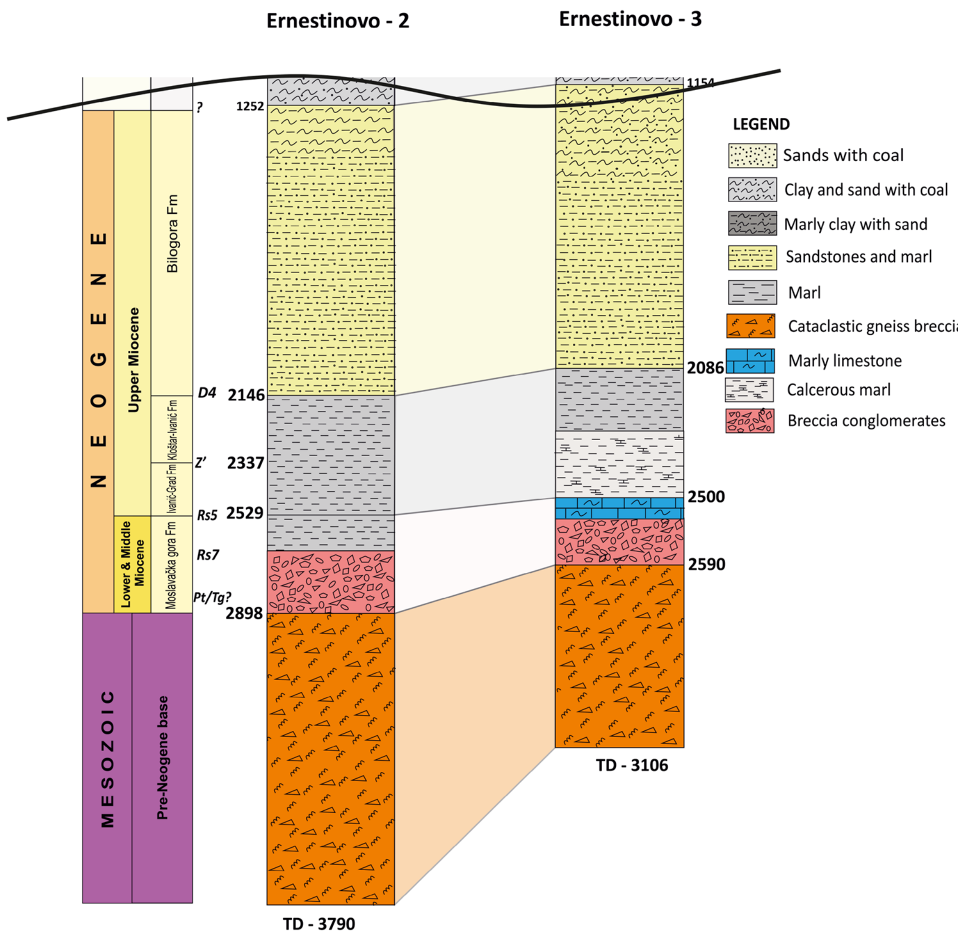


Fig. 12 Schematic lithostratigraphic column of Ernestinovo-2, Ernestinovo-3 wells in the Ernestinovo exploration block (Croatian Hydrocarbon Agency 2020b)

near the northeast corner of the exploration block, showed the existence of a bottom aquifer with a temperature of 139.0 °C, measured at a depth of 4,145.0 m. Since the area is close to the city of Karlovac, which has a developed district heating network, the geothermal water would be used for household heating.

Summary of Croatian geothermal exploration blocks

Table 5 presents summarised data for geothermal exploration fields described in detail in previous subchapters. Favourable geothermal gradients are determined, with lowest value at 0.031 °C/m at the Karlovac site. Further assessment of the locations is needed, especially in the terms of determining flow possibilities, after which energy potential can be calculated.

Evaluation of energy potential in licensed exploration blocks

Almost all exploration blocks of geothermal water for energy purposes in the Republic of Croatia are in the exploration phase, where the exact qualitative and quantitative parameters have not yet been determined. Once these parameters are available, the exact energy potential of each area, and therefore its purpose with a degree of certanity, could be defined. Based on the available data on the exploration blocks themselves or on data available in the vicinity of the exploration area that proved to be correlative for the analysis, an assessment of the energy potential needs to be made. Moreover, the final decision will depend on the investor and his business plan. For this reason, the assessment of thermal and electrical power in each of the study areas needs to be tackled. As mentioned earlier, the temperature data measured in the reservoir were used as input temperature for determining geothermal potential. The internal investigation of the geothermal potential for each field was relied upon a numerous drill stem tests or production well testing data. All of these exploration fields have a high probability of achieving a flow rate between 10.0 and 100.0 l/s, with an initial setup of one exploitation well and one injection well. This was carried out with petroleum production software and simulation of production according to obtained petrophysical data from well testing in the past. In this way, the unit value of each exploration area was determined, and we

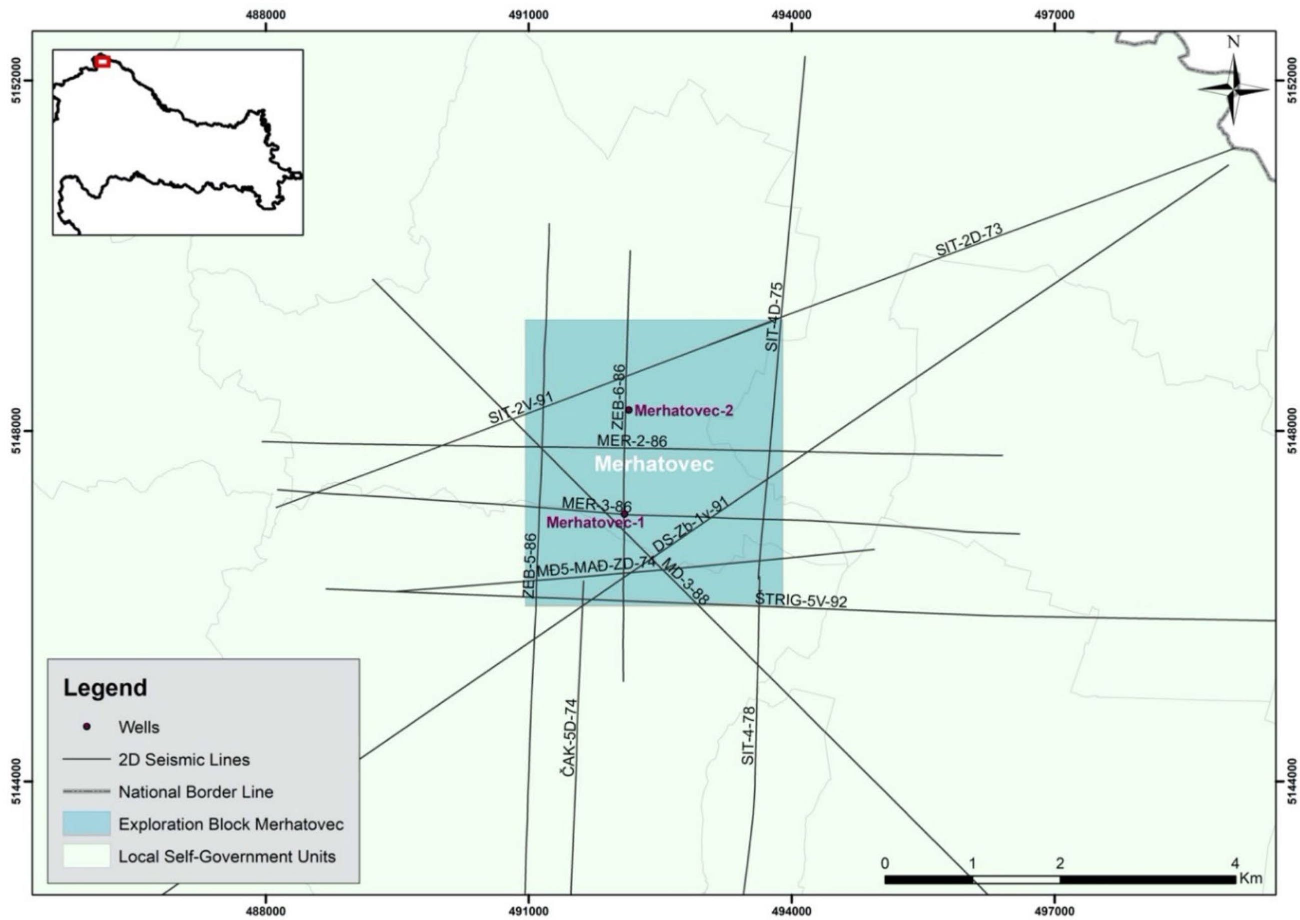


Fig. 13 Exploration block Merhatovec (Croatian Hydrocarbon Agency 2020e)

can assume that the energy availability increases linearly with the number of new development wells. Since, as mentioned above, not all parameters were available at the time of exploitation of the geothermal water, so the temperature of the geothermal water in the reservoir was used as the inlet temperature to the heat exchanger for the first government approximation of potential. According to the Ordinance on Reserves (Official Gazette 95/2018), the classification and categorisation of geothermal waters in the Republic of Croatia are defined. Thus, in case the exit temperature from the reservoir after the heat exchanger is not known, i.e. geothermal waters are not yet categorised into reserves but into contingent resources and the reference water temperature after heat utilisation is set at 30.0 °C and standard pressure values ($p = 1.0$ bar). To estimate the thermal output of the geothermal potential in the exploration blocks as the temperature of the water at the outlet of the heat exchanger for all cases, a temperature of 30.0 °C should be taken. In estimation of the possible electrical power production, 9 exploration blocks were considered because the measured reservoir temperature was higher than 130.0 °C. The temperatures were assumed to be favourable input temperatures in the conversion of geothermal energy into electricity via the binary Organic Rankin System (ORC) (DiPippo 2004).

Table 2 Test results of Merhatovec-1 and Merhatovec-2 wells

	Merhatovec-1	Merhatovec-2
Well depth (m)	4195.0	3404.0
Bottomhole temperature (°C)	150.0	140.0
Tested interval (m)	2405.0–2415.0	2386.85–2399.0
Temperature (°C)	126.7	140.8
Initial tested flow(m^3/day)	937.0	20.0

Geothermal exploitation fields

Ivanić geothermal field

Ivanić geothermal field is a part of the bigger Ivanić oil and gas field. The Ivanić oil and gas exploitation field is located

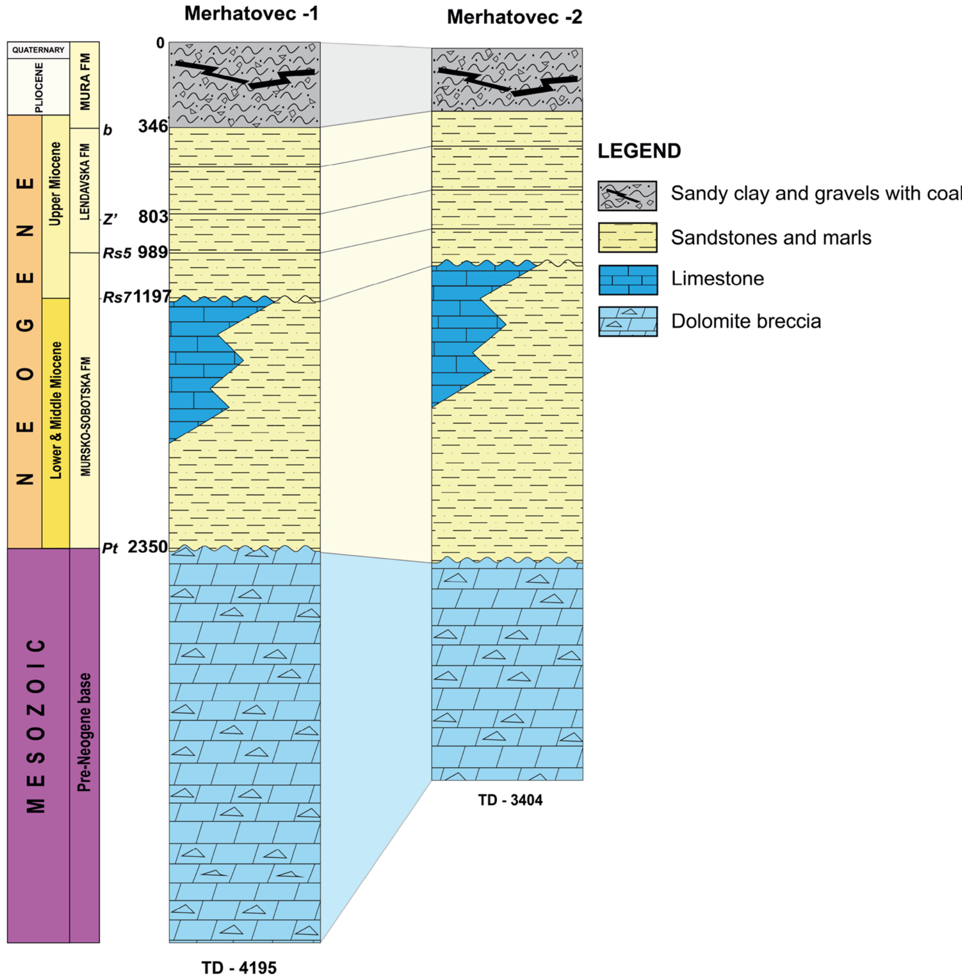


Fig. 14 Schematic lithostratigraphic column of wells Merhatovec-1 (mer-1) and Merhatovec-2 (mer-2) in the exploration block Merhatovec (Croatian Hydrocarbon Agency 2020e)

in the northwestern part of the Sava depression and is one of the oldest oil fields in Croatia. The first exploration work in this area began in 1940 with a regional gravimetric survey and continued in 1954 with seismic surveys. The oil field was discovered in 1959 and hydrocarbon exploitation has been active ever since. In 1962, the presence of reservoir "I" and "K" with water saturation was determined (Fig. 20). The geothermal reservoirs "I" and "K" consist of quartz-mica sandstones with intermediate layers of clay and marl that lie at a depth of 1,200.0–1,300.0 m, varying in thickness between 30.0 and 70.0 m, and belong to Neogene deposit. Reservoirs "I" and "K" are considered unique geothermal reservoir. Based on logging measurements, the porosity of the reservoir is 20.4%, while the interpretation of the hydrodynamic testing showed the permeability of the reservoir to be 94.2 mD. The geothermal gradient of the reservoir is 0.050 °C/m (the average annual temperature of the area is 11.6 °C) (INA-Industrija nafte d.d., 2005). The geothermal waters are produced by production well, Iva-1 T well, while the Iva-2 well is converted to geothermal metering well, with the possibility of conversion to production or injection well, after depletion of the oil reservoir. The exploitation of the Ivanić geothermal filed started in 1988 and at that time production from the well Iva-1 T was eruptive. After the eruption ceased, a deep centrifugal pump with the possibility of pumping up to 492.0 m^3/day was installed in the well. Due to the low demand of the heat users, smaller volumes were produced and the temperature at the wellhead varied between 30.0 and 58.0 °C. The field was produced from a single well and due to low water flows, produced water was injected through the gathering system to the oil reservoir to maintain oil reservoir pressure. The geothermal production potential of the geothermal reservoir "I + K" was estimated based on the production from well Iva-1 T and is 3.0 l/s with the installation of a deep centrifugal pump and with wellhead temperature of 58.0 °C. According to the well flow and the assumed temperature, the installed capacity at ΔT of 28.0 °C is 0.35 MW_t. As the water from this reservoir has

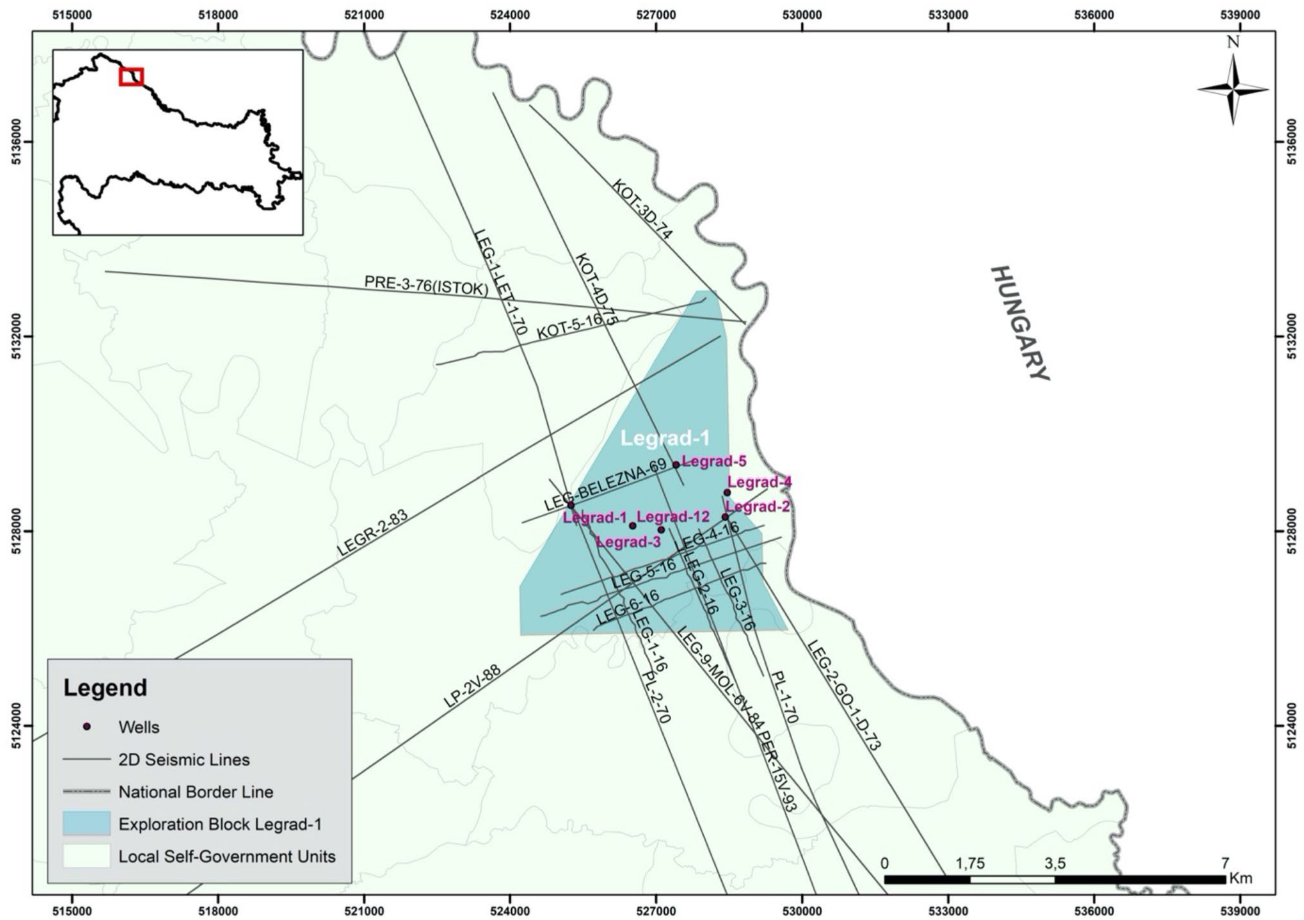


Fig. 15 Exploration block Legrad-1 (Croatian Hyrdocarbon Agency 2020c)

medicinal properties, it was used for balneological purposes in a nearby hospital (INA-Industrija nafte d.d., 2016).

Bizovac geothermal field

The Bizovac geothermal field is located in the eastern part of the CPB and belongs to the Drava depression. The geothermal field was discovered during hydrocarbons exploration activities that began in 1953 with gravimetric measurements and continued in 1954 with seismic surveys. The Bizovac oil field was discovered in 1967 by the Bizovac-1 exploration well. In the same year, two more wells were drilled, and geothermal water reserves were discovered by the Bizovac-2 well (Fig. 21). New wells were drilled, and larger quantities of geothermal water were discovered with the Bizovac-4 well at a depth of 1,761.0 m (INA-industrija nafte 1993a). The geothermal potential is located in two separate reservoirs–the Terme reservoir and the A3 and A4 reservoir. The Terme reservoir is located on the upper part of the basement and is characterised by coarse- and fine-grained breccias, breccia conglomerates and coarse-grained sandstones and is not connected to the oil reservoir. The initial pressure of the Terme reservoir is 208.6 bar, the initial temperature is 111.7 °C at a depth of 1,820.9 m, and the geothermal gradient is 0.055 °C/m. Reservoirs A3 and A4 are located above the oil reservoir and are formed in medium-grained sandstones with a large surface distribution. They are separated from the oil reservoir by up to 100.0 m thick marls and sealed sandstones. Between reservoirs A3 and A4, there is an insulating rock about 15.0 to 25.0 m thick, but the reservoirs are considered to be a unique reservoir of geothermal water with temperature of 103.5 °C at a depth of 1,623.4 m. The geothermal gradient is 0.057 °C/m, and the initial pressure is 159.2 bar. The assumed permeability for the Terme reservoir is 18.6×10^{-3} μm^2, while a permeability of 191.0×10^{-3} μm^2 was assumed for the "A3 + A4" reservoir when analysing the results of hydrodynamic measurements. Three wells are active in the Bizovac geothermal field, namely Bizovac-2 for injection and Bizovac-4 for exploitation in the Terme reservoir, and Slavonka-1 for exploitation of the A3 and A4

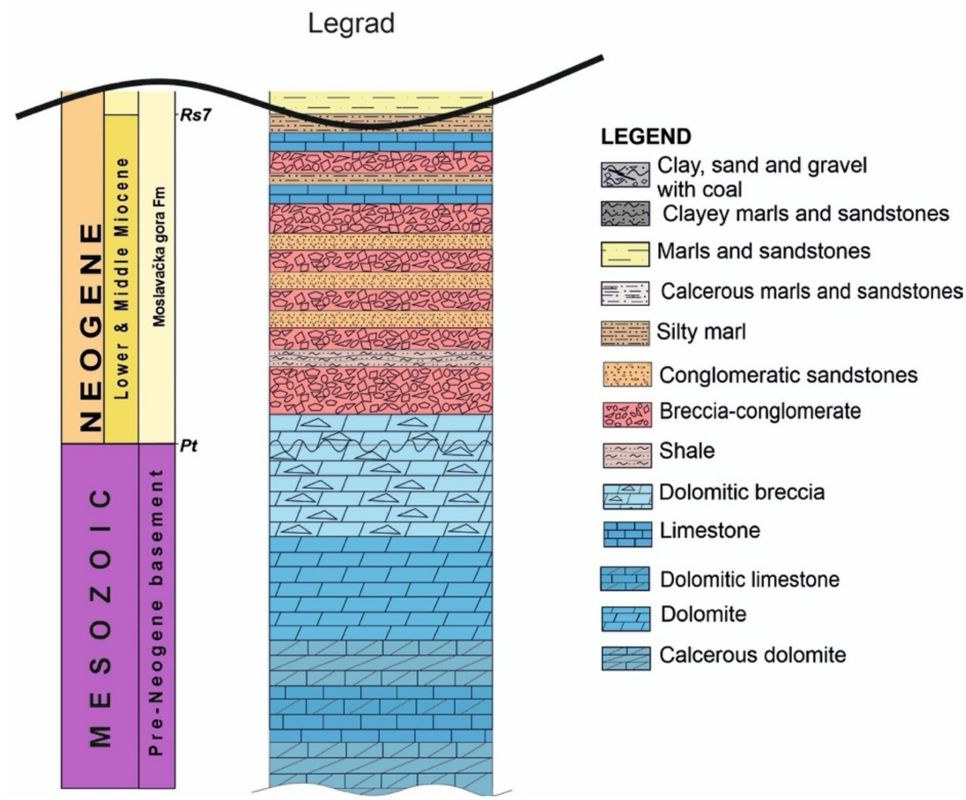


Fig. 16 Schematic general lithostratigraphic column of the Legrad area (Croatian Hydrocarbon Agency 2020c)

reservoirs (Table 6). The proven reserves (1P) of the Bizovac geothermal field are 4.63 l/s and 0.76 MW_t, while the probable (2P) are 7.8 l/s and a thermal output of 1,279.0 MW_t (INA-Industrija nafte d.d 2021). The geothermal water is used for balneological purposes and partly for heating the recreation centre.

Draškovec AATG geothermal field

The Draškovec AATG field is located in northern Croatia in the Mura depression on the border with the Drava depression (Fig. 22). The field was discovered during oil and gas exploration in the 1970s by the Draškovec-1 exploration well, which was drilled in 1977. The bottom temperature (2,710.0 m) of 113.0 °C was measured at the well, and two tests (DST) were performed to obtain water. Near the field, there are several wells drilled in sandstones, lithothamnium limestones or their equivalents and all have confirmed saturation with water and dissolved gas. The same sequence of occurrences was also confirmed in the Draškovec geothermal field. In 2016, a new well, Draškovec-2, was drilled, which confirmed geothermal potential in two reservoirs–shallow sandstone and a deeper limestone reservoir both belonging to Neogene deposits. The measured temperature of the sandstone reservoir at a depth of 2,102.0 m is 105.0 °C with an initial reservoir pressure of 211.0 bar and a geothermal gradient of 0.045 °C/m, while the measured temperature of the limestone reservoir at a depth of 2,274.5 m is 110.0 °C, the initial reservoir pressure is 229.4 bar and the geothermal gradient is 0.044 °C/m. Significant amounts of dissolved gas were encountered during well testing, ranging from 2.62 m^3/m^3 in the sandstone reservoir to 2.89 m^3/m^3 in the limestone reservoir. An increased amount of carbon dioxide was also detected in the composition of the gas. Due to the peculiarity of the reservoir and the large amount of dissolved gas and the presence of CO_2 in the gas, the development of the field and the use of geothermal energy are planned in the innovative sense. The project intends to separate the natural gas from the brine, use it in gas turbine for electric power while the CO_2 is collected at the exhaust and injected into the reservoir. The geothermal brine would be used in cogeneration cycle–electricity

Table 3 Test results of exploration block Legrad-1

	Legrad area
Tested interval (m)	3,515.0–3,531.0
Temperature (°C)	190.0
Initial tested flow (m^3/day)	432.0

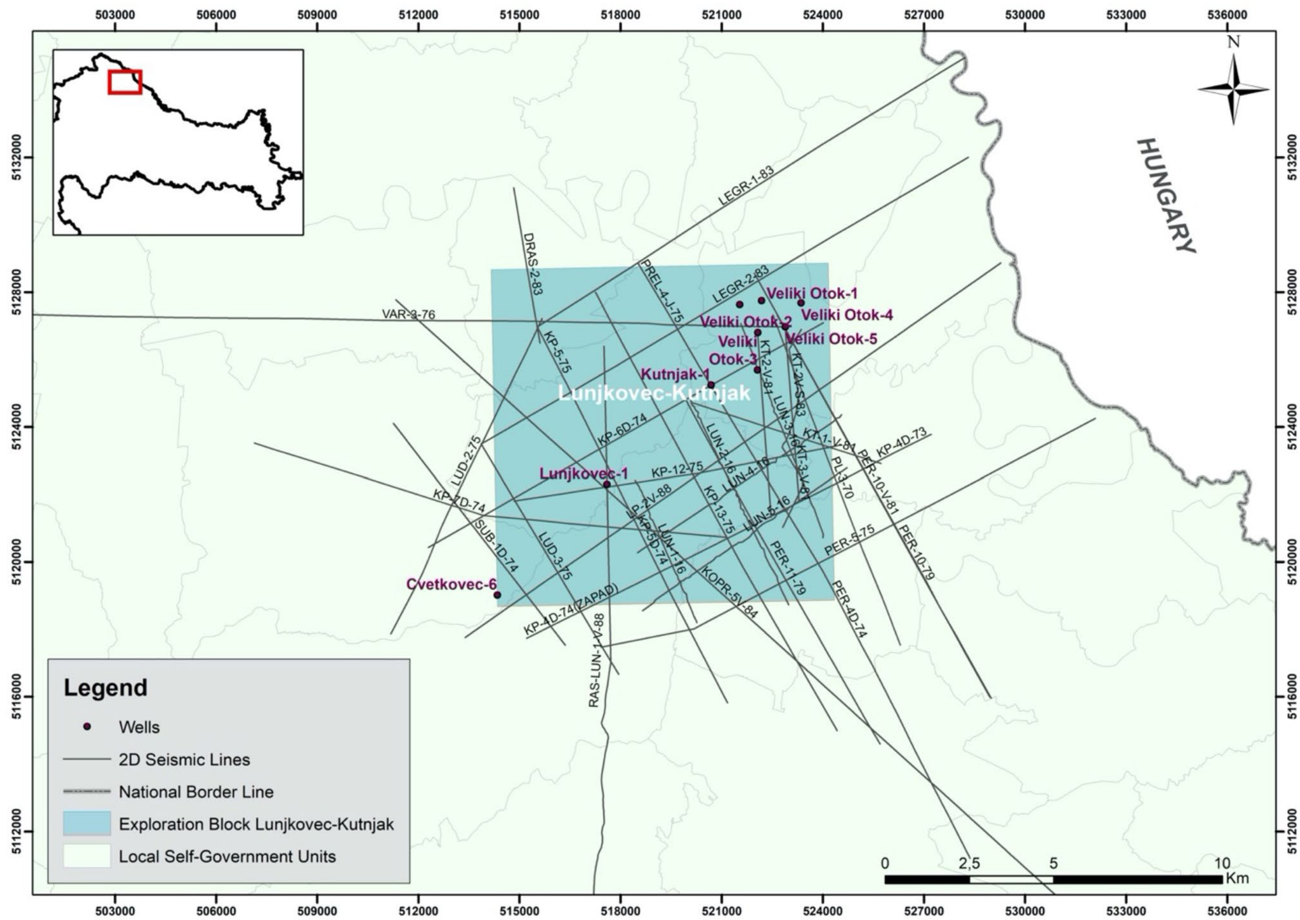


Fig. 17 Exploration block Lunjkovec–Kutnjak (Croatian Hydrocarbon Agency 2020d)

Table 4 Test results of Lunjkovec-1 and Kutnjak-1 wells

	Lunjkovec-1	Kutnjak-1
Well depth (m)	2203.0	2430.0
Bottomhole temperature (°C)	128.0	144.6
Tested interval (m)	1729.0–1755.0	2166.0–2430.0
Temperature (°C)	120.0	95.0
Initial tested flow (m^3/day)	322.9	685.0

generation in a ORC power plant and space heating after the brine leaves the binary system. The project for the development of the AATG Draškovec geothermal field envisages the construction of four pairs of injection and production wells, which will generate electricity and heat the sports and recreation centre with surplus thermal energy (AAT Geothermae Ltd 2017). The 2016 reserves study shows the probable reserves (2P) of 52.1 l/s and thermal capacity of 13.0 MW_t (AATG Geothermae Ltd 2016).

Sveta Nedelja geothermal field

The Sveta Nedelja exploitation field (Fig. 23) completed its exploration activities and began the exploitation of the geothermal brine. The exploitation license was obtained in 2021. The reserves of 25 l/s were determined (Eko Plodovi, Ltd., 2018). Geothermal water is used for agricultural purposes, e.g. for hydroponic tomato cultivation. There is one exploitation well in the block, which measured temperatures of 61.4 °C at a depth of 777.0 m. By extrapolating the data, it is assumed that the temperature at 1,056.0 m is 71.5 °C, with a wellhead temperature of 65.0 °C at a flow rate of 25.0 l/s. The geothermal gradient is then at 0.056 °C/m.

Bošnjaci-North geothermal field

The Bošnjaci-North geothermal field is in the very east of Croatia in the Slavonia-Srijem depression (Fig. 24). The field was discovered during the drilling of the exploration well Bošnjaci-1 in 2011. The geothermal reservoir is a lithofacies of water-saturated sandstone at a depth of

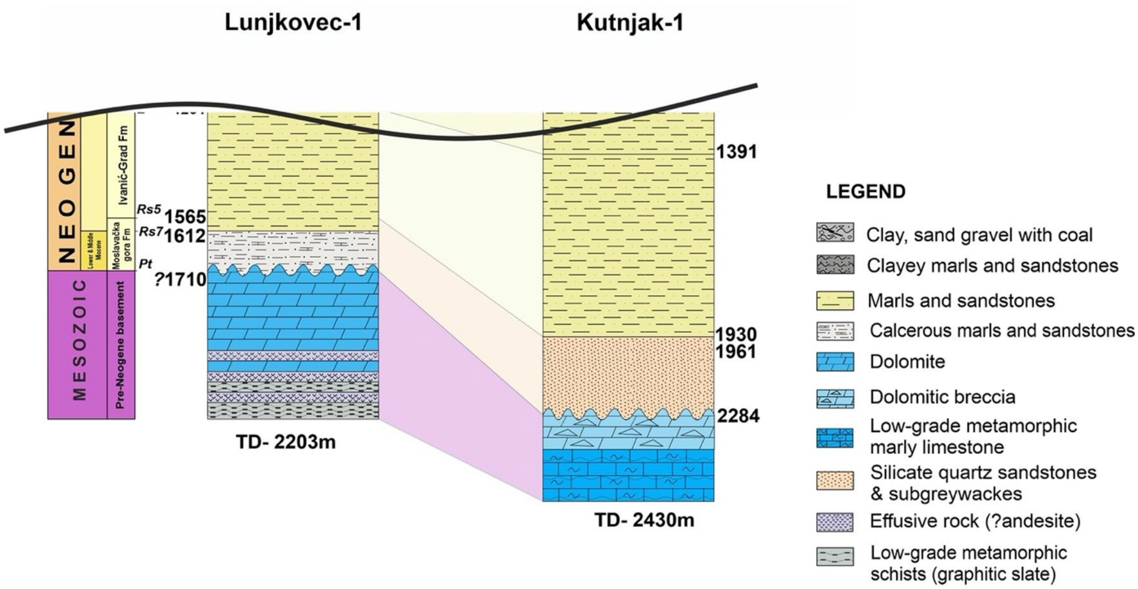


Fig. 18 Schematic lithostratigraphic column of wells Lunjkovec-1 and Kutnjak-1 (Croatian Hydrocarbon Agency 2020a, b, c, d, e)

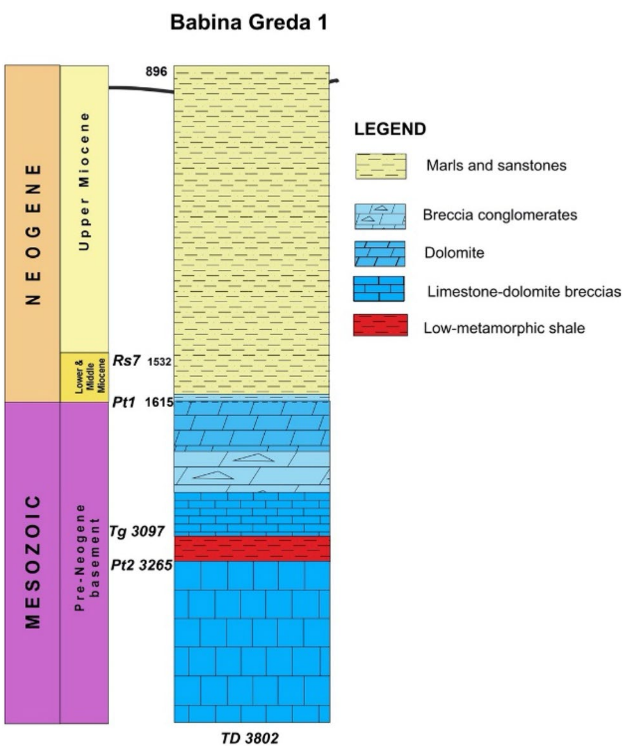


Fig. 19 Schematic general lithostratigraphic column of the Babina Greda area (Croatian Hydrocarbon Agency 2019c)

782.0 m to 1,035.0 m. The temperature of the reservoir is 73.3 °C at a depth of 1,020.0 m, and the geothermal gradient is 0.060 °C/m. The porosity of the reservoir is 22.0%,

Table 5 Summarised data of geothermal exploration fields in Croatia

Exploration field	Number of analysed wells	Average geothermal gradient (°C/m)	Flow (l/s)
Korenovo	1.0	0.039	–
Virovitica 2	–	0.036	–
Slatina 2	–	–	250.0
Slatina 3	2.0	0.040	–
Križevci	1.0	0.042	3.2
Ernestinovo	2.0	0.039	0.2–2.1
Merhatovec	2.0	0,036	0.2–10.8
Legrad	7.0	0.050	5.0
Lunjkovec–Kutnjak	8.0	0.043	34.3
Babina Greda	3.0	0.044	–
Karlovac	2.0	0.031	–

and the permeability was determined by interpretation of hydrodynamic measurements and is 233.0×10^{-3} μm^2. In the wider area, previous exploration activities have identified geothermal water resources in the deeper carbonate rocks of the pre-Neogene age with secondary pore space, but in the Bošnjaci-North exploitation field a satisfactory and economically achievable target for exploration is a sand reservoir belonging to Neogene sediments. In fact, the well was made for the purpose of heating the greenhouse for hydroponic tomato cultivation, and the temperatures of 65.0 °C at the wellhead and the possible supply of 20.0 l/s were sufficient for the planned use. The geothermal water is used through

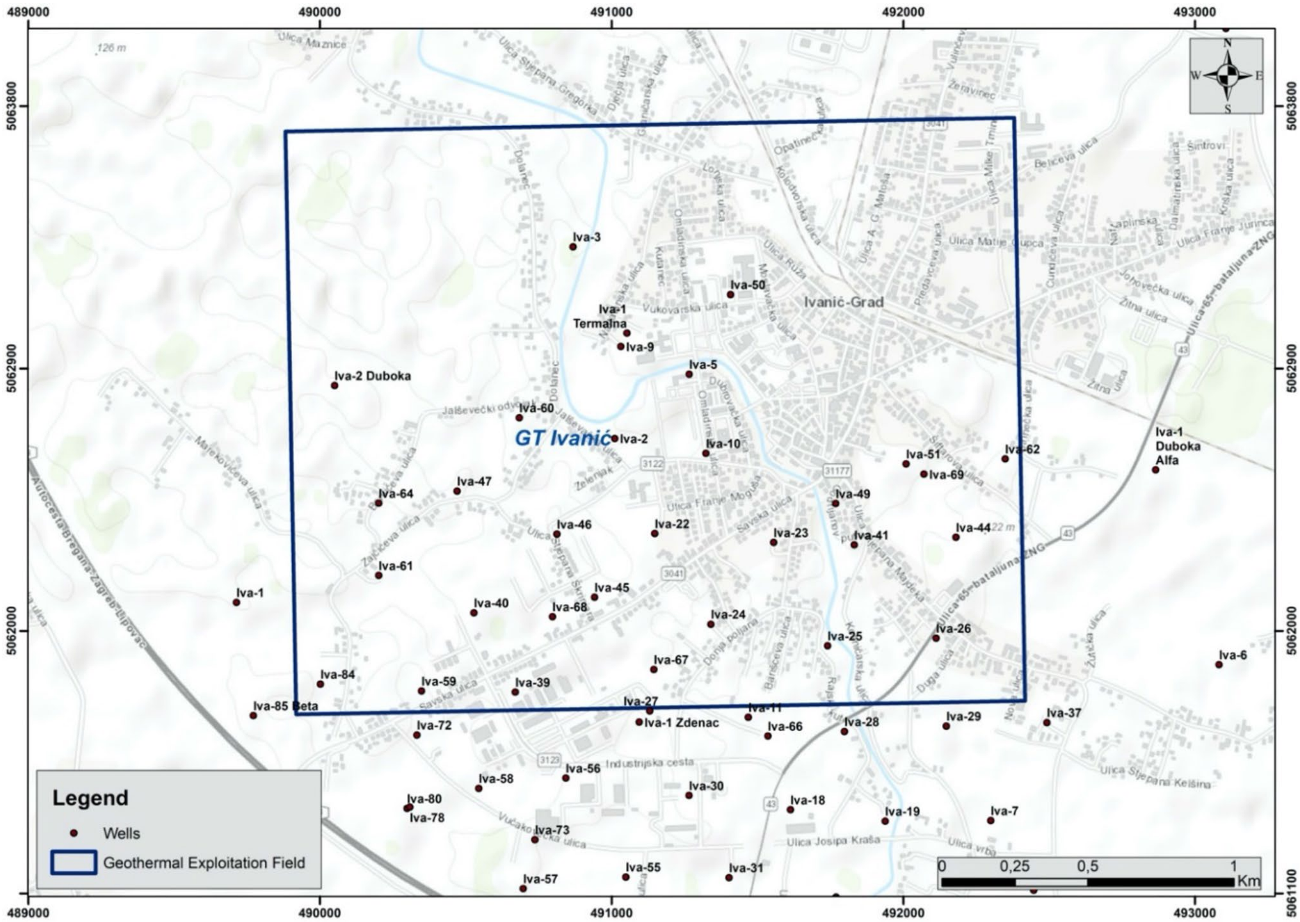


Fig. 20 Geothermal exploitation field Ivanić

a single well, while the return water is discharged into the drainage canal, which is possible due to the water quality. The proved (1P) geothermal water reserves are 10.0 l/s, and the installed thermal capacity is 1.4 MW_t (Ruris 2018).

Zagreb geothermal field

The first well drilled in the area of the Zagreb geothermal field was Stupnik-1 in 1964. The well was drilled for oil exploration but proved negative and was therefore abandoned. New hydrodynamic tests on the well, which followed in 1977, revealed water saturation at a depth of 733.0 to 815.0 m with a temperature of 57.0 °C. The entire geothermal field is located in the area of the city of Zagreb and belongs to the wider area of the Sava depression (Fig. 25). After testing the first well, further exploration activities and interpretation of seismic data began, and on this basis the second geothermal well–Mladost-1 was drilled in 1980. The well was producing eruptive and delivered 3.4 l/s with wellhead temperature of 70.0 °C. In the following years, further wells were drilled, of which there are currently 15. The Zagreb geothermal field was formed in the pre-rift pre-Neogene basement, which consists mostly of dolomites with good storage properties, the thickness of which is up to 200.0 m. Their thickness increases towards the west of the reservoir while in the north and northeast direction they significantly protrude or sink. The basement, which was drilled with the Stupnik-1, KBNZ-2, KBNZ-3 and KBNZ-3B wells, forms the bottom of a geothermal reservoir and consists of impermeable rocks, gneisses, shales and clay slates. The reservoir is characterised by high flow capacity, especially in the central part of the field around the Mladost-3 and KBNZ-1B wells, as well as declared heterogeneity in vertical and areal terms. Porosity of the reservoir is from 6.13 to 14.5% (INA-Industrija nafte 1993b). The initial reservoir pressure

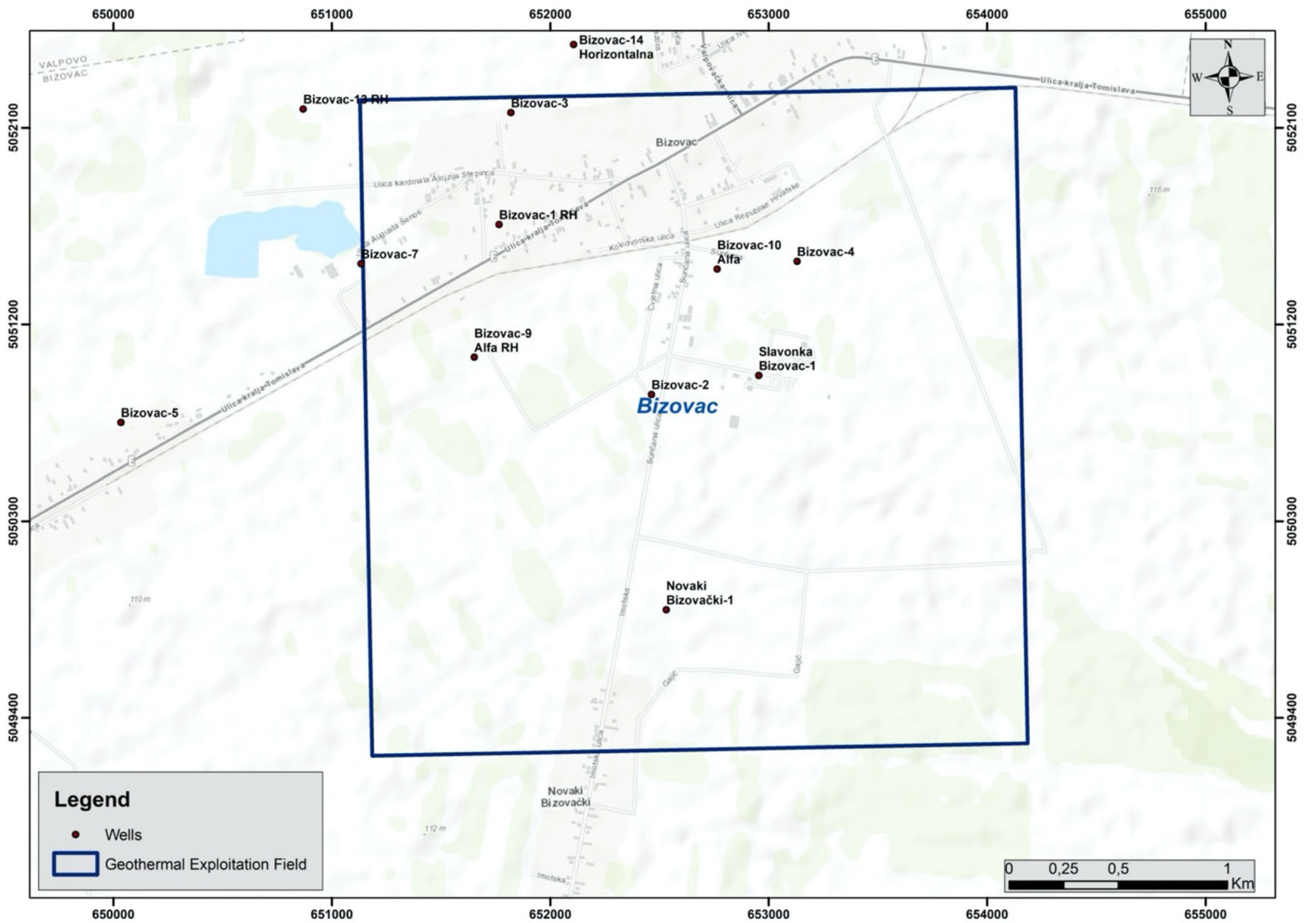


Fig. 21 Geothermal field Bizovac

Table 6 Well status—Bizovac geothermal field

	Well	Depth (m)	Status
1	Bizovac-2	1,862.0	Injection
2	Bizovac-4	1,866.0	Production
3	Slavonka-1	1,668.0	Production

is 104.0 bar at a reference reservoir depth of 979.0 m, and the initial reservoir temperature was 75.0 °C, derived from measurements at the Mladost-1 well. Since most of the production in the geothermal field is performed from wells from the warmest part of the reservoir, a temperature of 80.0 °C was adopted as the initial temperature for the calculation of the reserves. Later measurements confirmed a temperature of more than 80.0 °C at the KBNZ-1B and Mladost-1, and the presumed reason for this is probably the large vertical permeability around these wells and the significantly faster heat transfer. Table 7 shows wells with corresponding depth and recorded bottom temperatures within the geothermal field Zagreb, as well as their status. The geothermal gradient of the Zagreb field is between 0.050 and 0.053 °C/m, at the marginal wells and in the central part of the field between 0.057 and 0.078 °C/m. Proven reserves (1P) of the Zagreb geothermal field amount to 6.2 l/s and installed thermal capacity of 1.3 MW_t, while probable reserves (2P) at a flow rate of 77.1 l/s amount to 15.7 MW_t of installed thermal capacity (GPC Instrumentation process Ltd., 2018). Exploitation in the Zagreb geothermal field is carried out through technological systems on three locations—the Mladost site, the Blato site (KBNZ) and the Lučko site (Cazin and Jurilj 2019). The technological system of the Mladost site consists of an injection well (Mla-2) and a production well (Mla-3) and

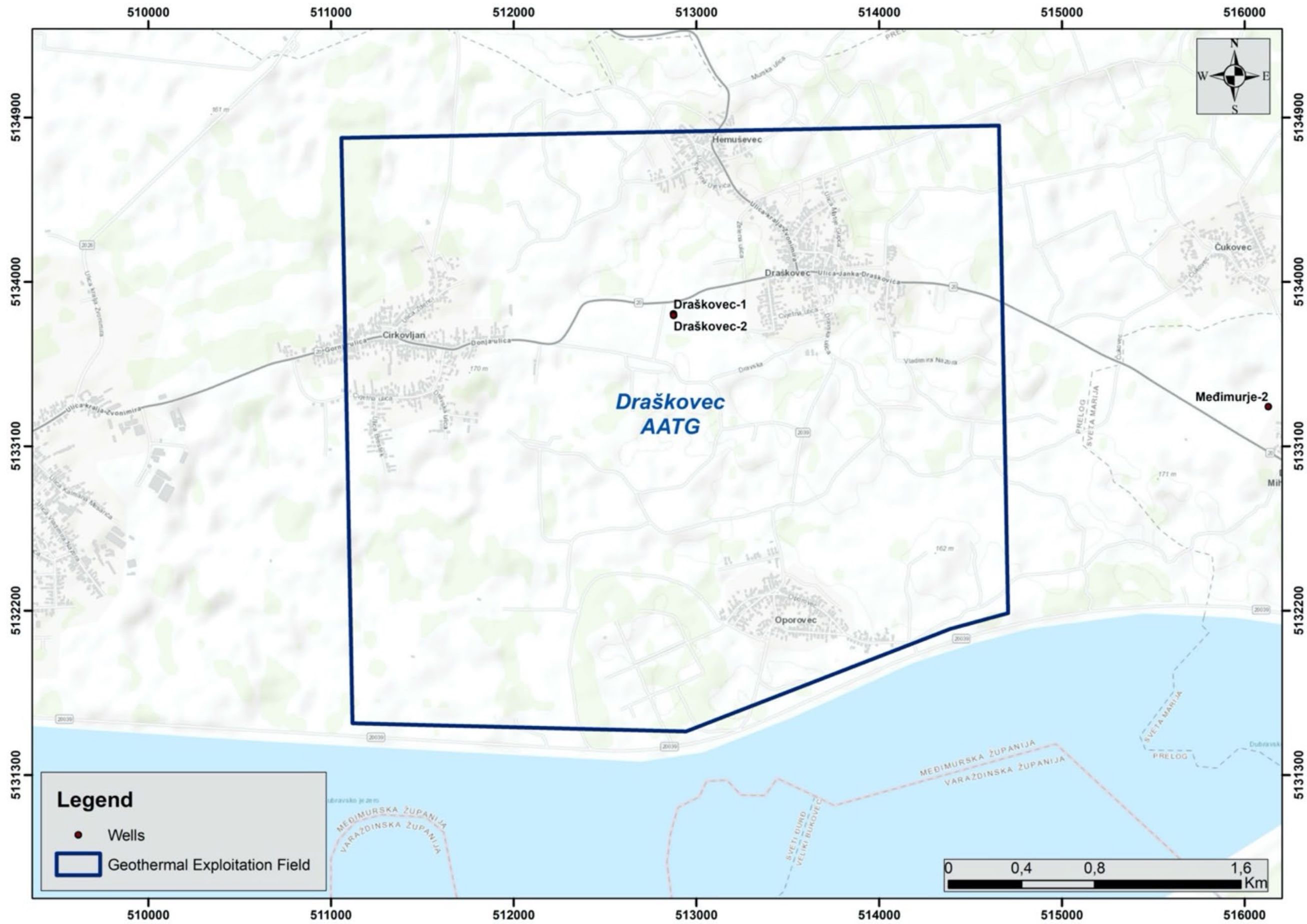


Fig. 22 Geothermal field Draškovec AATG

is used to heat the swimming pool and the premises of the Sports and Recreation Centre "Stjepan Radić" and the Faculty of Kinesiology (Energetika net 2020). The system has the ability to expand the capacity, taking into account the maximum flow rate of the well Mla-3 of 50.0 l/s and the injection capacity of the well Mla-2 of 50.0 l/s at an injection pressure of 10.0 bar. The system can be connected to another injection well Mla-1, whose injection capacity is 8.3 l/s at an injection pressure of 12.0 bar. The Blato technological system is not in operation and is intended for use in the planned sports and recreation zone. Four wells can be included in the system: KBNZ-1A and KBNZ-1B as production wells with flow rates of 5.0 and 65.0 l/s, respectively, KBNZ-3α and KBNZ-2A as injection wells with a maximum injection rate of 50.0 l/s (injection pressure 15.0 bar) and 35.0 l/s (injection pressure 25.0 bar), respectively (GPC Instrumentation process Ltd., 2018). The well Lučanka-1, at the Lučko site, is used for space heating of a private industrial facility. Since there is no injection well, the brine flows into a retention pond where it is cooled and afterward released into the local stream via channel.

Velika Ciglena geothermal field

The Velika Ciglena geothermal field with the first Croatian geothermal power plant is located in the Drava depression, near the town of Bjelovar (Fig. 26). In the 1970s and 1980s,

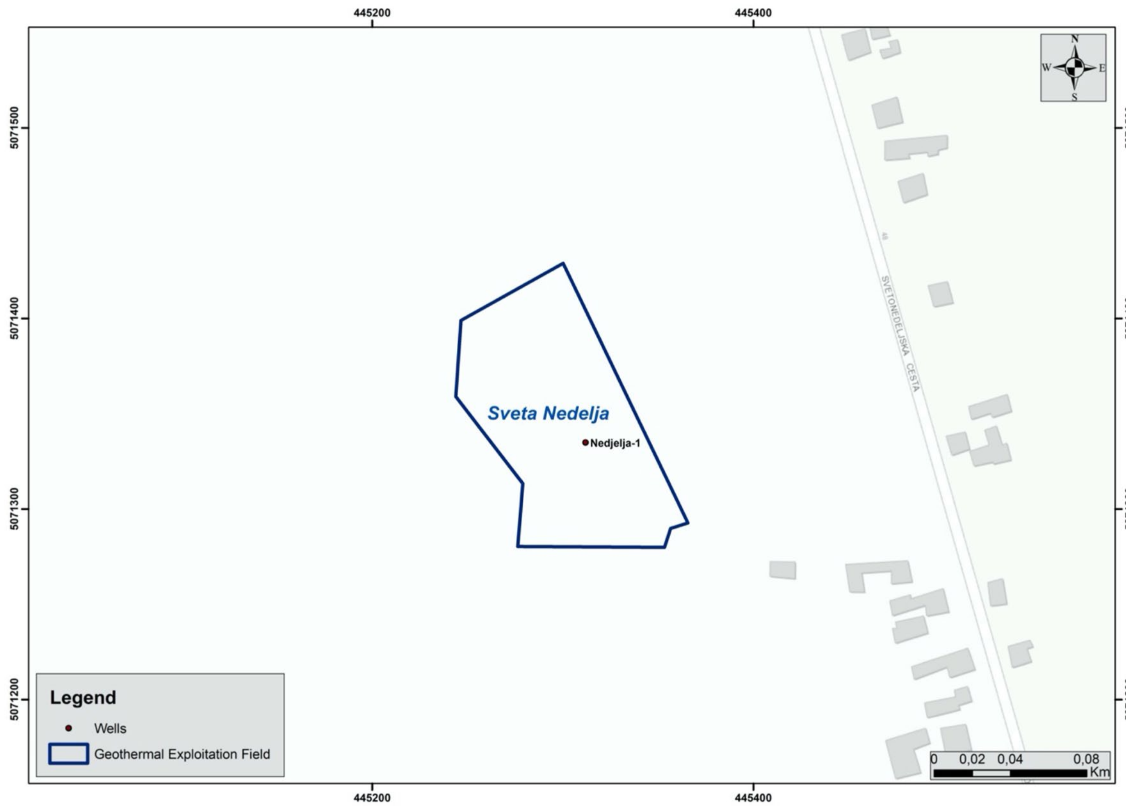


Fig. 23 Geothermal field Sveta Nedelja

the Drava depression was the subject of intensive work for oil and gas exploration. Data from gravimetric, magnetometric and seismic surveys as well as drilling data were collected. The first well in this field was the Velika Ciglena -1 well (VC -1). The Velika Ciglena -1 well was commissioned in 1990 and had the task of drilling pre-Neogene reservoirs and determining the existence of hydrocarbons. During the construction of the well, 5 DST tests were carried out. During the construction of the interval 2,545.0 to 2,607.0 m, dolomite breccias were drilled and total losses occurred during the drilling (2,585.0 m), while the tests (DST-4) showed poor permeability of the layer. When the influx of water occurred, a new DST test was carried out, which again did not give satisfactory results and it was concluded that the well had drilled the Tertiary basement. Losses during the construction of the well continued almost from a depth of 2,607.0 m to the bottom of the well at 4,790.0 m, and fragments of dolomite breccia belonging to the pre-Neogene basement were found throughout the interval. The highest temperature recorded on the thermometer was 170.0 °C. As the measuring instruments were not suitable for measuring such high temperatures, even higher temperatures were assumed. Subsequent well tests confirmed a temperature of 177.6 °C at a depth of 3,593.0 m. Analysis of the measurements showed a low reservoir permeability of 7.73×10^{-3} μm^2 do 13.03×10^{-3} μm^2 (INA-Industrija nafte d.d., 2007). After the drilling was completed and the results collected, it was decided to drill a new directional well to be used as a geothermal well. In the same year, another well was drilled–Velika Ciglena-1A, a deviated well, the wellhead of which is 10.0 m away from the Velika Ciglena-1 well. The final depth of the well is 2,956.0 m (Hv = 2,787.44 m).

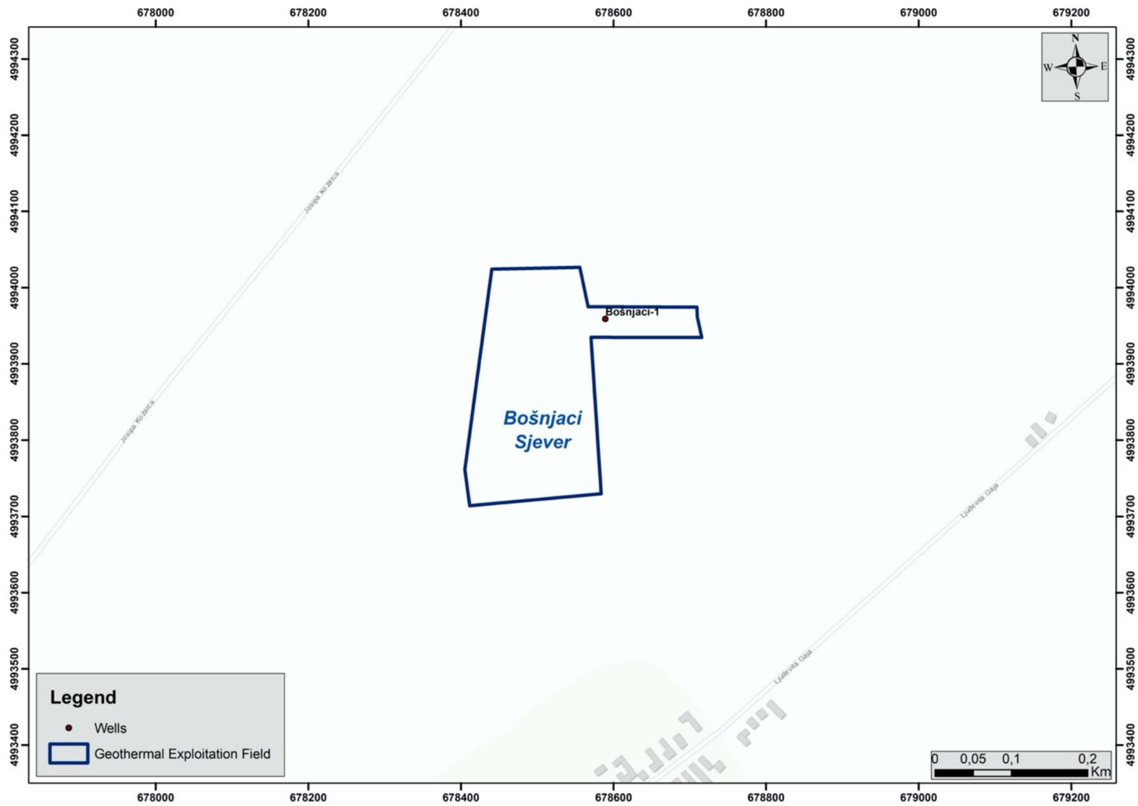


Fig. 24 Geothermal field Bošnjaci-North

During the construction of the well, there were also total mud losses from 2,609.0 m to the final depth of the well of 2,956.0 m. The interval is part of the Tertiary reservoir and consists of dolomite breccias. Subsequent well tests of the reservoir and interference tests between wells Velika Ciglena-1 and -1A a permeability of about 400.0×10^{-3} μm^2. At the Velika Ciglena -1A well, the highest measured flow was 92.77 l/s, while at Velika Ciglena-1 a flow of 99.39 l/s was measured. Two more wells were drilled in the Velika Ciglena field–Patkovec-1 and Velika Ciglena-2, which confirmed the geothermal reservoir and were later completed as injection wells in the field. During further development of the field, additional tests were conducted, which confirmed a flow rate of 227.0 l/s and a well temperature of 166.0 °C, as well as a thermal output of 81.0 MW_t. Due to its reservoir parameters, the Velika Ciglena geothermal field was an ideal candidate for power generation (Rašković et al. 2013; Guzović et al. 2014). Based on the reservoir parameters, the wells VC -1 and VC -1a are used as production wells, while the wells PT -1 and VC -2 are injection wells. The gross installed power capacity of the Velika-1 geothermal power plant is 16.5 MW_e, but due to infrastructure constraints the nominal working capacity is 10.0 MW_e net (Geoen Ltd., 2017). The Velika-1 geothermal power plant was commissioned in March 2019 and produces electricity with an average availability of 85.92% (Croatian Energy Market Operator 2021).

Summary of Croatian geothermal exploitation fields

Table 8 presents summarised data for geothermal exploitation field which are currently under consessions. The geothermal gradient in exploitation sites varies from 0.046 up to 0.060 °C/m. Current power capacity in Croatia is at

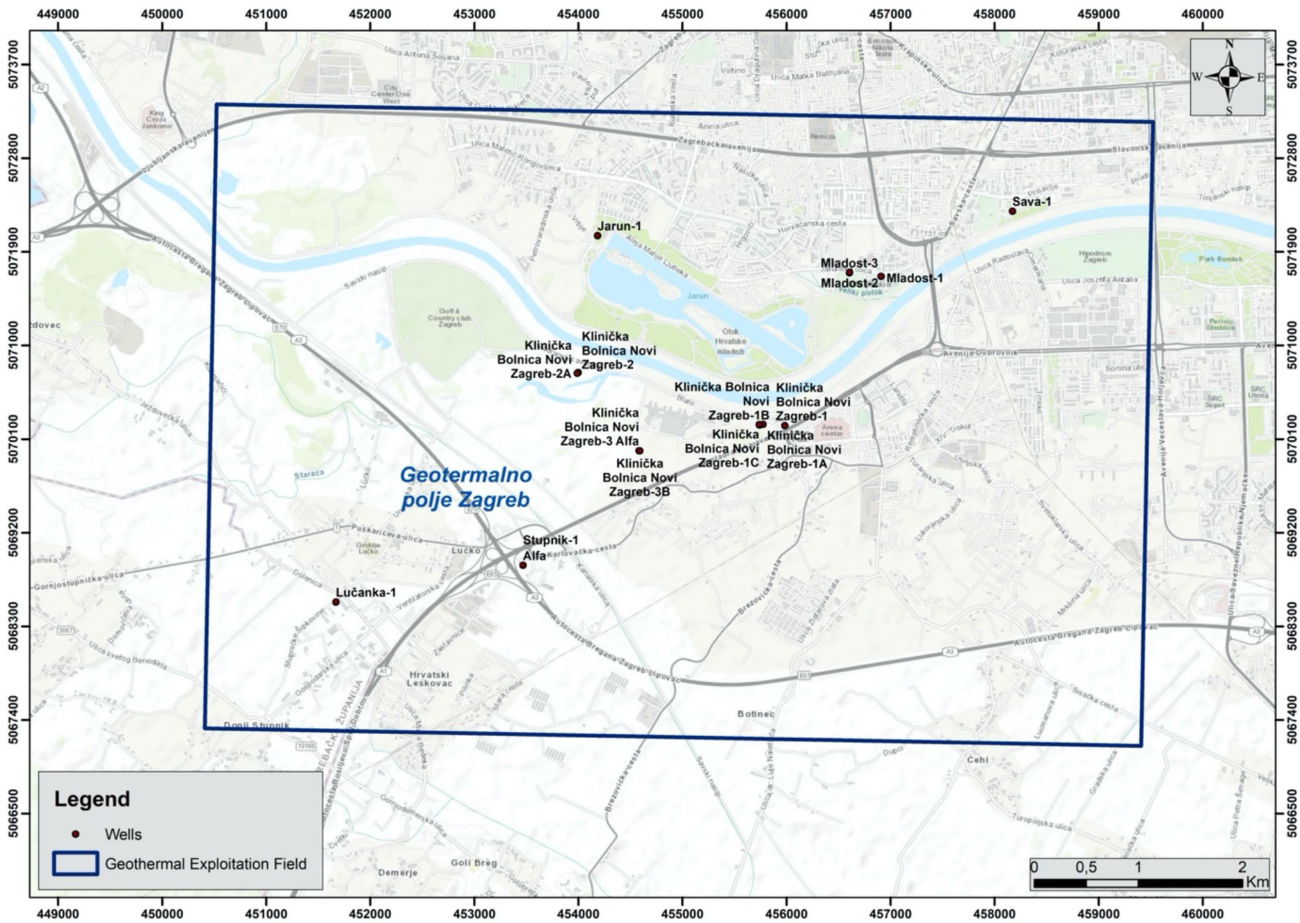


Fig. 25 Geothermal field Zagreb

16.5 MW_e, but more is expected with the development of Draškovec exploitation field as well as exploration sites like Slatina, Lunjkovec–Kutnjak, etc.

Conclusion

Current state of the art of geothermal reservoirs exploration and exploitation was presented for the Republic of Croatia. Described prominent geothermal sites are only a small fragment of the entire geothermal potential of the Pannonian Basin. Summarised data for geothermal exploration and exploitation fields are shown in Tables 5 and 8, respectively. Until now, as part of a broader screening process conducted by the lead author and Croatian Hydrocarbon Agency, drilling data, geophysical exploration data and well testing data from more than 150 well sites were initially collected and categorised or are in the process of research. Alongside sites that initially only contained geothermal brine, there is a long history of hydrocarbon exploration and exploitation in the Croatian part of the Pannonian Basin. Therefore, there are high numbers of bottom-type aquifers available for further research on matured oil and gas fields. Bottom-type aquifers usually have good potential to be used as geothermal energy resource once hydrocarbon production is terminated. Such locations have very detailed geological data available, originating from geological exploration works, as well as

Table 7 Well status—geothermal field Zagreb (Ministarstvo gospodarstva i održivog razvoja, 2014)

	Well	Well depth (m)	Bottom temperature (°C)	Intervals (m)	Status (in 2014)
1	Mladost-1	1,057.0	59.0	911.0–1047.0	Monitoring
2	Mladost-2	911.7 (Hv = 829.9)	63.0	881.0–912.0	Injection
3	Mladost-3	1,362.2 (Hv = 990.8)	83.1	1,169.0–1,362.0	Production
4	KBNZ-1A	1,133.8	80.0	961.2–1,114.5	Injection
5	KBNZ-1B	1,374.0	80.0	1,217.0–1,374.0	Production
6	KBNZ-2	1,508.7	52.9	1,177.2–1,406.0	Monitoring
7	KBNZ-2A	1,267.0 (Hv = 1,190.2)	56.0	1,028.0–1,198.0	Injection
8	KBNZ-3	1,076.50	–	–	Abandoned
9	KBNZ-3a	981.0 (Hv = 825.1)	57.0	900.0–981.0	Injection
10	KBNZ-3B	1.378,7 (Hv = 1,000.2)	34.0	1,245.0–1,374.0	Monitoring
11	Lučanka-1	950.0	53.0	751.0–887.1	Production
12	Jarun-1	1,365.0	45.0	–	Monitoring
13	Sava-1	1,594.3	60.0	990.0–1,203.0	Monitoring
14	Stupnik-1	832.7 (Hv = 826.7)	46.0	–	Abandoned
15	Stupnik-1A	826.7	–	730.0–830.0	Monitoring

Table 8 Summarised data of geothermal exploitation fields in Croatia

Exploitation field	Average gradient (°C/m)	Flow (1P) (l/s)	Flow (2P) (l/s)	Thermal output (1P) (MW_t)	Thermal output (2P) (MW_t)	Power capacity (MW_e)
Ivanić	0.050	3.0	–	0.35	–	–
Bizovac	0.055	4.6	7.8	0.76	1,279.0	–
Draškovec	0.044	–	52.1	–	13.0	–
Sveta Nedjelja	0.056	25.0	–	–	–	–
Bošnjaci-North	0.060	10.0	–	1.4	–	–
Zagreb	0.050	6.2	77.1	1.3	15.7	–
Velika Ciglena	0.046	227.0	–	81.0	–	16.5

data obtained from production, injection, monitoring or exploration wells constructed during the oil and gas field exploitation period. Depending on the temperature from such bottom aquifers, geothermal brine could be used for direct heating purposes, or in some cases even for power generation. The advantage of using bottom aquifer brine is seen not only in good geological determination but also in already present well assets, which could be converted and used for geothermal brine production. Re-using of wells, where possible, also has economical benefits, since such a project would have lower investment costs. Bottom aquifer exploitation can have higher certainty of project completion due to lower geological uncertainty and good know-how derived from hydrocarbon exploration and exploitation works, already present at the location. So, this untapped geothermal potential from the oil and gas industry is the next phase for Croatian geothermal exploration. With this tremendous move forward in developing a geothermal data room available for future investors to analyse, an increase in geothermal energy share in the final energy consumption in the Republic of Croatia would be secured, as part of the green energy transition.

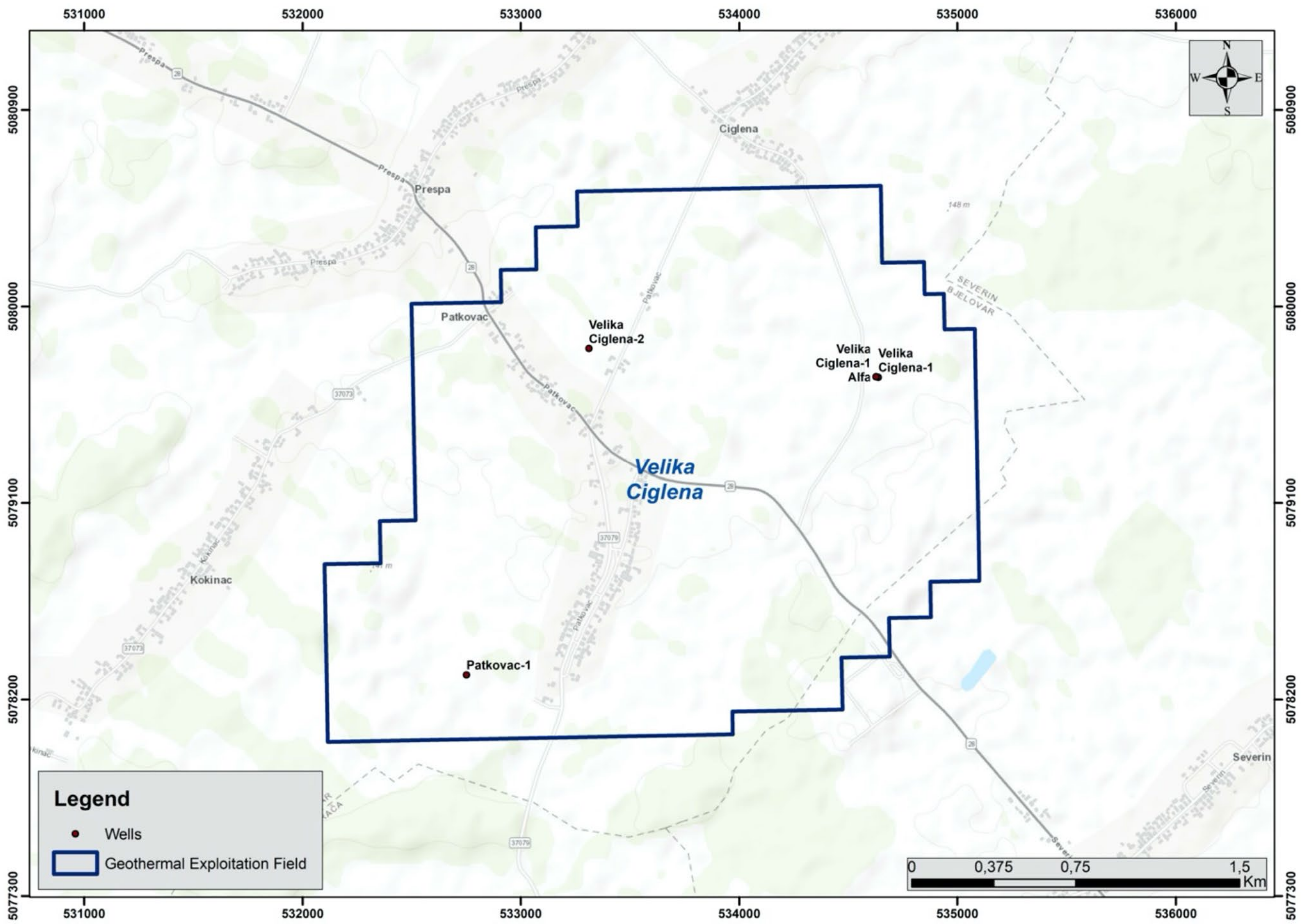


Fig. 26 Velika Ciglena geothermal field

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