RGNZ/MGPB

Insight into rock thermal conductivities in the North Croatian Basin through in situ measurements

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 552.1; 550.8
DOI: 10.17794/rgn.2024.4.1

Original scientific paper

Iva Kolenković Močilac[1]; Marko Cvetković[2]; David Rukavina[3]; Josipa Kapuralić[4]; Ana Brcković[5]; Bruno Saftić[6]; Ivan Cindrić[7]; Josipa Babić[8]

[1] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, https://orcid.org/0000-0002-0125-2627*
[2] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, https://orcid.org/0000-0002-4555-6083*
[3] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, https://orcid.org/0000-0001-7541-4353*
[4] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, https://orcid.org/0000-0002-2613-2859*
[5] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, https://orcid.org/0009-0004-1915-3266*
[6] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, https://orcid.org/0000-0001-9919-2134*
[7] *Taus Plc, Savska cesta 84, 10 000 Zagreb, Croatia*
[8] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, https://orcid.org/0000-0001-9919-2134*

Abstract

The thermal conductivity of rocks represents one of the significant variables when investigating geothermal potential of an area on a local scale as well as regionally when performing basin analysis with the aim of estimating hydrocarbon potential. While steady-state methods of measuring thermal conductivity are presumed to yield more reliable results, transient methods allow for in situ measurements, thereby considerably simplifying and reducing measurement costs. This study was performed with the goal to expand the understanding of thermal conductivity of rocks typical for the North Croatian Basin (NCB) infill, as well as the underlying basement rocks. The measured values reveal distinct ranges across various lithologies. The thermal conductivity values measured in crystalline rocks are quite consistent, showing narrow ranges of values for each lithotype: for granite the measured values are between 2.317 and 2.486 $W\ m^{-1}\ K^{-1}$, the value range for gneiss is between 3.332 and 3.565 $W\ m^{-1}\ K^{-1}$ and the thermal conductivity of amphibolite is in the range between 1.549 and 1.623 $W\ m^{-1}\ K^{-1}$. In contrast, the thermal conductivity values of sedimentary rocks vary within broader ranges – the values in sandstones range between 1.778 and 2.433 $W\ m^{-1}\ K^{-1}$, for marlstones the registered range is between 0.917 and 2.323 $W\ m^{-1}\ K^{-1}$, the values measured in shales range between 0.894 and 2.304 $W\ m^{-1}\ K^{-1}$ and biocalcarenites show values of thermal conductivity between 0.990 and 2.023 $W\ m^{-1}\ K^{-1}$. The greater variability in values measured for sedimentary rocks is attributed to the variability in porosity and fluid saturation, as well as the greater variability of mineral composition. Further research is needed to determine which factor has the greatest influence on the variability of thermal conductivity values, i.e. to establish to which extent each of the factors contributes to the measured values.

Keywords:
thermal conductivity of rock; single-needle method; North Croatian Basin; sedimentary rocks

1. Introduction

Many countries, including Croatia, are dependent on imported energy sources (**IEA, 2021**) and the consequent risk of shortages in supply leads towards the diversification of energy sources and investments in the development of renewable sources, as well as energy storage (**Tuschl et al., 2022**). In this sense, geoenergy research is of the utmost importance to ensure viable knowledge regarding subsurface geological settings, including present structures, and the characterization of rocks and fluids. Understanding the geological processes is a key element for the identification and characterization of potential resources, being it geothermal energy reservoirs or potential energy storage objects. Another key factor in geoenergy exploration is the knowledge of the distribution of the temperature in the subsurface which mostly relies on well data (**Alnes et al., 2011**; **Dong et al., 2020**). It should be noted that by "geoener-

---

Corresponding author: Marko Cvetković
e-mail address: marko.cvetkovic@rgn.unizg.hr

Table 1: Thermal conductivities for rocks of various lithological composition

Lithology	**Measured values of thermal conductivity (W m^{-1} K^{-1})**	**Reference**
granite	1.5-3.62	after **Côté and Konrad (2005); Cho et al. (2009)**
andesite	0.64-2.87	after **Yaşar et al. (2008); Mielke et al. (2017)**
amphibolite	1.35-3.9	after **Dalla Santa et al. (2020)**
gneiss	0.84-4.86	after **Dalla Santa et al. (2020)**
migmatite	1.8-2.4	after **Ramakrishnan et al. (2013)**
schist	1.5-4.88	after **Andújar Márquez et al. (2016); Gangyan (2005)**
phyllite	1.5-3.33	after **Dalla Santa et al. (2020)**
limestone	1.1-5.16	after **Lienhard and Lienhard (2020); Gangyan (2005); Chicco et al. (2019)**
dolomite	0.61-5.73	after **Tang et al. (2019)**; **Dalla Santa et al. (2020)**
marl and marlstone	0.5-3.66	after **Iosif Stylianou et al. (2016); Dalla Santa et al. (2020); Chicco et al. (2019)**
shale	1.05-6.06	after **Blackwell and Steele (1989); Labus and Labus (2018)**
siltstone	1.1-5.94	after **Andújar Márquez et al. (2016); Xiaoqing et al. (2018)**
sandstone	0.6-5.24	after **Duchkov et al. (2014); Gangyan (2005); Tang et al. (2019)**
calcarenite	0.673-1.989	after **Genova and Kilian (2017); Rahmouni et al. (2023)**
conglomerate	1.5-5.1	after **Dalla Santa et al. (2020)**

gy research," a broader range of energy-related activities and resources associated with the subsurface are considered. This includes not only fossil fuels and deep geothermal energy resources, but also the utilization of subsurface reservoirs for carbon dioxide geological storage, as well as the potential for subsurface energy storage. Assessment of the thermal conductivity of rocks also plays a significant role in the planning of the utilization of shallow geothermal energy sources (**Chicco et al., 2023**).

The North Croatian Basin (NCB) has potential for the exploitation of geothermal resources. It is characterized by an increased geothermal gradient corresponding to a regional geothermal anomaly present in the Pannonian Basin, which is a result of crust thinning and the consequent position of hot melted rocks of the mantle closer to the surface (**Dövényi and Horváth, 1988**; **Hurtig et al., 1992**; **Lenkey et al., 2002**). In the Bjelovar Subbasin, the first Croatian geothermal power plant Velika Ciglena started operating in 2018, exploiting hydrothermal fluid from the geothermal reservoir situated in fractured Triassic carbonates approximately 2500 m deep, having a temperature of 170°C (**Čubrić, 2012**). Within the investigated area, geothermal energy is so far exploited in the Bizovačke toplice spa, where the hydrothermal fluid of temperatures higher than 95°C comes from an approximately 1800 m deep geothermal reservoir consisting of fractured basement gneiss and polymictic breccias of unconfirmed, probably Miocene age (**Hećimović, 2008**).

Given the obvious potential for geothermal energy use, there are ongoing attempts to access the geothermal potential of the subsurface in Croatia. However, most of them were delimited to the mapping of the geothermal gradient (**Cvetković et al., 2019**; **Jelić et al., 1995**; **Macenić et al., 2020**) or the mapping of the temperature at a certain depth (**Jelić et al., 1995**), or focused only on one type of geothermal reservoir (e.g. overpressured reservoirs **Mesić et al., 1996**).

When assessing heat flow and modelling heat distribution in the subsurface, one of the most important parameters to evaluate is the thermal conductivity of rocks, because it largely controls heat conduction through the subsurface (**Rudnick et al., 1998**; **Song et al., 2023**). The thermal conductivities of rocks of different lithological composition are important for basin modelling (**Chekhonin et al., 2020**; **Makhous and Galushkin, 2004**), but also for the numerical modelling of geothermal reservoirs (**Pandey et al., 2018**; **Raymond, 2018**).

Different rocks conduct heat differently because the thermal conductivity depends on their density, mineral composition, porosity, permeability, pore-filling fluids, pressure and temperature (**Somerton, 1992; Popov et al, 2003; Eppelbaum et al., 2014**). Additionally, in clastic sediments, thermal conductivity can be affected by grain size (**Midttomme and Roaldset, 1998**) and sorting (**Deepagoda et al., 2018**; **Sun, 2017**). **Table 1** shows a compilation of thermal conductivity values sourced from literature that is reported for lithotypes corresponding to the sedimentary infill and basement rocks in NCB. It is obvious that the values vary within the wide range (see **Table 1**), which makes the use of data from the literature unsatisfactory, as it is difficult to estimate which data would most closely describe the properties of the rocks in the research area.

There is a lack of data regarding the thermal conductivities of rocks in the Croatian part of the Pannonian Basin system. Research conducted by **Kovačić (2007)** was geographically limited to the wider Zagreb area but gave significant insight into the thermal properties of Miocene, Pliocene and Quaternary sediments. The measurements were conducted mostly on samples from deep wells, but also on samples from the outcrops.

Kovačić (2007) conducted the measurements of thermal conductivity using the steady-state method and his research offers valuable insight into thermal conductivities of Miocene fine to coarse grained clastic sediments, as well as Triassic carbonates (dolomites) and clastic sediments derived from those carbonates. This data offers a basis for the characterization of the regional model. However, further investigation was needed to provide values for all other relevant lithologies. The authors' aim was to repeat the measurement on the outcrops and compare the measurements with those of **Kovačić (2007)**, but unfortunately the locations of the outcrops where the "surface samples" were collected were not presented in the mentioned paper.

Another study of thermal conductivities of soil and rocks was conducted by **Soldo et al. (2016)**. They used the distributed thermal response (DTR) test along the borehole heat exchangers to assess the thermal properties of soils and shallow rocks in 8 locations in Croatia, 3 of which are situated in the NCB. While informative and having an obvious impact for the planning of the installation of ground-coupled heat pumps, the study by **Soldo et al. (2016)** didn't provide data that would enable the linking of the reported averaged values of thermal conductivity with the lithological composition of the tested intervals. Namely, the values of thermal conductivity were expressed as average values for 6-meter intervals, without indicating the lithological composition of the intervals.

Research performed by **Borović et al. (2018)** was mainly focused on thermal conductivities of loose soil and rocks in the shallow subsurface. The measurements were conducted using the single needle method on samples coming from shallow boreholes from five locations in the Croatian part of the Pannonian Basin (Čakovec, Požega, Osijek and two locations in the Zagreb area). In four of those boreholes the thermal response test (TRT) was conducted, providing the average thermal conductivity (K) across the whole well column. Most of the measurements with the single probe device were performed on loose sediment and are thus of limited interest. Altogether 15 samples of rocks were also measured, including greenschist with a registered value of 1.91 W/mK, marlstone with a measured value of 0.98 W/mK and sandstone with a measured value of 1.55 W/mK. Unfortunately, except for lithology, no other information about the rock samples were given.

The aim of this study is to present thermal conductivity data obtained from measurements conducted directly on the outcrops, as a supplement to the previously mentioned studies (**Kovačić, 2007**; **Borović et al., 2018**). For this purpose, measurements were conducted on magmatic and metamorphic rocks that lithologically correspond to Basement rocks, as well as the sedimentary rocks corresponding to sedimentary basin infill. This is the first step in creating a database of thermal properties of characteristic lithotypes for future geoenergy projects in the area of the NCB.

2. Geological setting of the research area

In the study area, shown in **Figure 1**, covering the rims of Slavonian Mountains - Papuk, Psunj and Krndija, as well as Mt. Moslavačka gora, three different units can be distinguished. The first one represents the crystalline basement (below "Tg" unconformity in **Figure 2**) mainly consisting of Palaeozoic magmatic rocks that are partially metamorphosed - granites, granitoids, gneisses, and amphibolites, to a lesser extent the basement is represented by metamorphosed sediments, like schists and phyllites (**Pamić and Lanphere, 1991**). The second unit is represented by Mesozoic carbonates (**Pamić and Lanphere, 1991**), named Base Neogene (underneath "BNg" unconformity in **Figure 2**) and the third unit comprises the sediments, igneous rocks and pyroclastics of Neogene and Quaternary age that represent the basin infill (**Malvić and Cvetković, 2013**; **Pavelić and Kovačić, 2018**; **Saftić et al., 2003**).

The study area underwent continental rifting from the Ottnangian to the Badenian, which resulted in the formation of the various rift structures, such as half-grabens (**Lučić et al., 2001**; **Pavelić, 2001**; **Pavelić and Kovačić, 2018**; **Rukavina et al., 2023**; **Saftić et al., 2003**). Sedimentation during Ottnangian and Karpatian is mostly represented by coarse-grained clastics deposited in alluvial to lacustrine environments, with occasional pyroclastics resulting from syn-sedimentary volcanism, characteristic for the initial rift phase (**Pavelić, 2001**). Marine transgression in Middle Badenian (**Ćorić et al., 2009**) caused a transition from a lacustrine environment to marine environments (**Pavelić and Kovačić, 2018**), characterized by the mixed clastic and carbonate sedimentation, mostly represented by the distal sedimentation of thick marl layers with sporadic intercalations of coarse-grained clastic sediments, while in proximal areas conglomerates, bioclastic sediments and limestones were deposited (**Ćorić et al., 2009**; **Pavelić et al., 1998**). The Sarmatian period is marked by local inversion on one hand and by isolation of the Paratethys from the open sea on the other. The Pannonian period was characterized by a post-rift thermal subsidence as a result of the gradual cooling of the asthenosphere into the denser lithosphere (**McKenzie, 1978**), as well as the progradation of delatic environments over the Pannonian Lake system (**Pavelić and Kovačić, 2018**; **Saftić et al., 2003**; **Sebe et al., 2020**). The progression of these settings eventually led to the filling of the basin. Neotectonic activity in the Pliocene and Quaternary was characterized by compression and dextral transcurrent displacements, which resulted in the filling of the remnants of Lake Pannon with coarse clastic sediments and clay (**Lučić et al., 2001**; **Pavelić and Kovačić, 2018**; **Saftić et al., 2003**). During the Pleistocene, glacial periods resulted in the deposition of loess and aeolian sands, while interglacial periods were characterized by lacustrine and marsh sedimentation.

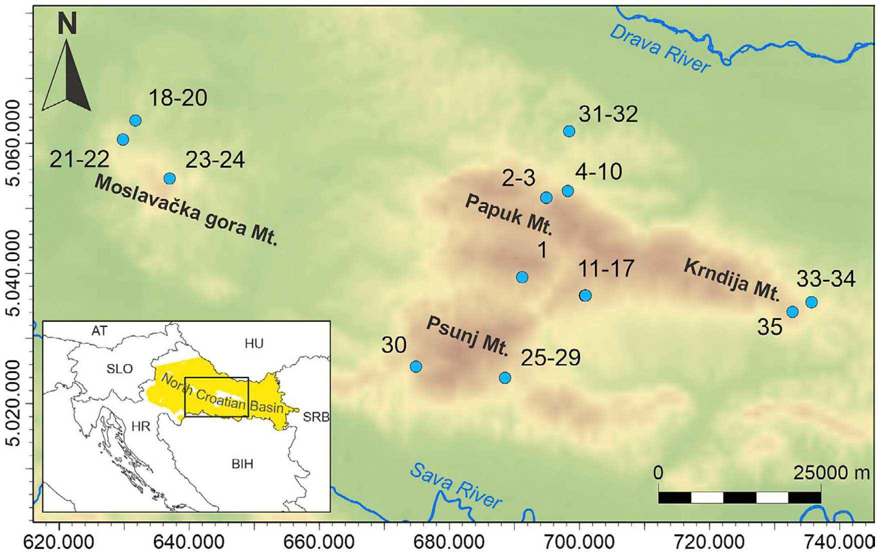

Figure 1: Locations of outcrops where thermal conductivity was measured (numbers assigned to outcrops correspond to the measurement points in **Table 2**)

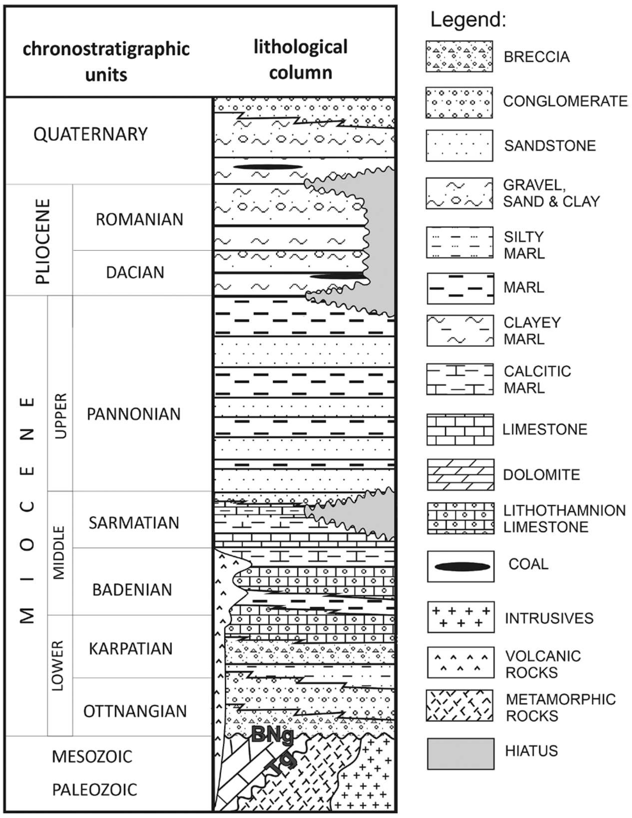

Figure 2: Generalized lithological column of the North Croatian Basin (modified from **Malvić and Cvetković, 2013; Saftić et al., 2003; Vulin et al., 2023**)

3. Methodology

A transient line source method (**Giordano et al., 2019**; **Somerton, 1992**) was used to measure thermal conductivities in situ, using a TEMPOS Thermal Analyzer with an RK-3 sensor used for hard rocks, having a measurement accuracy of +/-10% within the measurement range between 0.1 and 6.0 W/mK (https://metergroup.com/products/tempos/tempos-tech-specs/). The applied method is based on the use of a single needle sensor. The thermal conductivity sensor consists of a 60 mm long stainless steel needle with a heater and a precise thermistor. The thermal conductivity of a material was assessed by inserting the needle probe (3.9 mm diameter) covered with a thin film of thermal paste in the measurement hole drilled in the rock and applying current to raise the temperature of the probe, while measuring the temperature increase with the thermistor. The thermal conductivity can be calculated considering power input and rise of the temperature during the measurement. Prior to the measurement, the temperature of the probe is monitored for a time interval lasting at least 30 seconds to determine the temperature drift. The temperature drift represents changes in the temperature measured every second for 30 consecutive seconds and the measurement of thermal conductivity should not be started if the temperature drift is exceeding the permissible temperature range of 0.003°C between two consecutive measurements. The start temperature and the determined drift are then subtracted from the measurements (**Meter, 2023**). Current is then run through the heater, leading to a temperature rise during the period of 60 seconds and the probe temperature is registered every second. It should be noted that measurement holes in magmatic and metamorphic rocks were drilled using a percussion drill, and for the drilling of measurement holes in sedimentary rocks a rotary drill was used. In both cases, the drill bit diameter was 4 mm to ensure good contact of the probe and the tested rock. An alumina or ceramic polysynthetic thermal paste with thermal conductivity >4 W/mK was used to cover needle sensor and ensure better contact of the needle sensor and the rock.

The values given by the device represent calculated values of the thermal conductivity from measurements, by using a non-linear least-squares inversion technique.

This is a simplified analysis, which gives adequate results, approximating the exponential integral by the most significant term of its series expansion (**ASTM D5334-14, 2022**):

$$\Delta T = (q/4\pi k)\cdot \ln(t) \qquad (1)$$

Where ΔT represents the change in temperature (K), q is the applied heat by the unit length of the probe (W/m), k is the thermal conductivity (W/mK), t is the time from the beginning of heating (s).

Equation 1 can give correct results for a long time of measurement; since the method is based on observing changes in temperature over time, measurements need to be taken at various time intervals throughout the heating process to accurately describe the behaviour of the material. For that reason, **Equation 1** is expected to give correct results for a rather long time of measurement, especially for measurements of low-conductivity materials.

According to **Equation 1**, thermal conductivity is proportional to the inverse of the slope when temperature is plotted versus ln t (**Nix et al., 1967**). After a long time of heating, the temperature hardly changes, so noise in the measurements can strongly affect the measurement. Shorter measurement times lead to problems related to the neglected terms in the exponential integral expansion which are functions of diffusivity, so sample diffusivity affects the calculated conductivity. Another problem lies in a finite dimension of the probe and its heat capacity, as explained by **Wechsler (1992)**, so the thermal needle probe apparatus must be calibrated before its use (**ASTM D5334-14, 2022**).

Calibration was conducted before every round of measurements by comparing the measured value of the thermal conductivity of a standard material (glycerin was provided by the device manufacturer as a verification standard) to its known value of 0.282 W m^{-1} K^{-1}. A calibration factor, C, is automatically calculated as follows (**ASTM D5334-14, 2022**):

$$\text{Calibration} = \lambda\text{material}/\lambda\text{measured} \qquad (2)$$

where: λmaterial represents the known thermal conductivity of the calibration material, and λmeasured the thermal conductivity of that material measured with the single-needle apparatus. All the measurements of the device are automatically multiplied by C before being registered and reported.

There is also a problem of contact resistance between the probe and the medium in which the measurement is conducted (**Fadeeva and Duchkov, 2017**). This problem is minimized by applying the thermal paste having thermal conductivity above 4 W/mK (**ASTM D5334-14, 2022**).

The measuring time of the device is very short, only 60 seconds. This is not due to the simplicity of the measurement, but the developers simulated the measurements and calculation of thermal conductivity using **Equation 1** for a broad span of conductivities, diffusivities, and contact resistances. They concluded that the greatest problem was in the time scale, which was accommodated for by introducing time offset as a correction factor, firstly suggested by (**Underwood and McTaggart, 1960**), thus changing the equation to (**Meter, 2023**):

$$\Delta T = (q/4\pi k)\cdot \ln\,(t+t_o)+C \qquad (3)$$

where t_o is the time offset. After this modification, all of the data fit well with heating times of 60 seconds, meaning that the effects of contact resistance and diffusivity were significantly and sufficiently reduced. The values of k, t_o, and C are determined by least squares. Values of t_o are calculated using an iterative method where t_o is varied until the value minimizing the standard error of the estimate is found. This procedure was tested on samples of known conductivity (that are used as standards) and it was found that one-minute readings on all of these samples, with a time offset of 16 seconds, were more accurate compared to 10 minute readings using **Equation 1**.

The measurements were performed in a way that two consecutive measurements were made in the same measuring hole and if their difference was less than 10%, the average value was calculated and reported as the value of thermal conductivity in this point. For better control, on most of the outcropping lithotypes, two or three measuring holes were drilled in close proximity to one another and the values reported in this work represent the average values of those measurements; they were assigned to the same measurement point. In some cases, the values between two consecutive measurements in the same hole differed by more than 10% and those values were discarded. For a certain number of measurement points, only one value is presented due to problems related to the measurement preparation. Although the measurement itself is very quick, the preparation of the measurement site can be rather challenging since it is necessary to ensure an almost perfect fit of the needle probe in the measurement hole. The preparation involves levelling the rock surface at the outcrop using an angle grinder and drilling a measuring hole perpendicular to the levelled surface to achieve optimal contact between the rock and the probe. During and after the drilling, the hole was repeatedly cleaned using compressed air and before measurement the probe was coated in a thermal paste. After the preparation and before the measurement, a sufficient time was allowed for the rock to cool down from the friction caused by levelling and drilling. Numerous problems occurred, mainly due to an insufficient amount of paste applied or inappropriate probe insertion, resulting in pockets of air that lead to anomalous measurements which were easily spotted and discarded.

4. Results

Values of the thermal conductivity of rocks measured with the field device TEMPOS Meter at localities in the NCB are presented in **Table 2**. Location selection (see

Table 2: Thermal conductivities measured in situ on outcrops on the rims of Moslavačka gora and Slavonian Mountains (locations presented in **Figure 1**)

Measurement point	Outcrop mark	Type of rock	Number of measurements	Average value of K (W m^{-1} K^{-1})*
1	Kot1	phyllite	2	2.125
2	NZ-V1	gneiss	2	3.565
3	NZ-V2	gneiss	1	3.332
4	VocA1	marlstone (medium hard)	2	0.917
5	VocA2	biocalcarenite to biocalcrudite	1	1.686
6	VocA3	marlstone	2	1.028
7	VocA4	biocalcarenite	2	0.990
8	VocA5	marlstone	2	0.996
9	VocB1	laminated marlstone	1	0.936
10	VocB2b	laminated marlstone	2	1.087
11	Polj1	coarse grained lithic sandstone	2	1.778
12	Polj2	coarse grained lithic sandstone	2	1.968
13	Polj3	shale	2	0.894
14	Polj4	shale	2	1.575
15	Polj5	shale	1	2.304
16	Polj6	silty marlstone	1	2.323
17	Polj7	siltstone	2	1.374
18	Plet1	granitoid	3	2.313
19	Plet-core	amphibolite	2	1.591
20	Plet2	granite showing low level of metamorphism	3	2.416
21	Mikl1	granite with tourmalines	2	2.317
22	Mikl2	granite with tourmalines	2	2.486
23	Garic1	amphibolite	2	1.623
24	Garic2	amphibolite	2	1.549
25	SEPs1	weathered calcarenite	2	1.839
26	SEPs2	clayey marlstone	2	1.852
27	SEPs3	poorly sorted lithic sandstone	2	2.433
28	SEPs4	biocalcarenite	3	2.023
29	SEPs5	biocalcarenite to biocalcrudite	3	1.851
30	Okuc1	gneiss altered to clay	2	2.778
31	G-103	peperite	2	1.182
32	G-105	peperite	2	1.488
33	G-106	trachyandesite	3	1.291
34	G-107	trachyandesite	2	1.240
35	G-108	effusive	2	1.381

*Except for measurements in points 3, 5, 9, 15 & 16 where only 1 measurement was carried out and reported

Figure 1) was limited to the availability of outcrops. Miocene sediments were measured in locations around Voćin (points 4-10), as well as in the Poljanska Quarry on the southern slopes of Papuk Mt. (points marked 11-17), where Miocene sediments that are exposed in an open pit are expected to match the sediments in the subsurface of the Drava Basin in terms of their characteristics, given the similarity of local sedimentation conditions. In addition, the values of the thermal conductivity of the rocks forming the basement were measured in the Pleterac Quarry (18-20), the Miklouš Quarry (21 & 22) and in the Garić-grad location (23 & 24), as well as near Koturić Village (point 1 in **Table 2**) and in an abandoned quarry near Voćin (points 2 & 3). Additional measurements on the Miocene clastic sediments were conducted on the outcrops on the SE slopes of Psunj Mt. (25-29). Miocene effusives were also encompassed – trachyandesites on the eastern slopes of Krndija Mt. (points 33 & 34) and unclassified effusive on the southeastern slopes of Krndija Mt. (point 35).

Results summarized for general lithology types and their comparison to literature data is presented in **Figure 3**. It can be observed that in situ measurements in granites gave rather narrow range of values, from 2.317-2.486 W m^{-1} K^{-1} (see points 20-22 in **Table 2** and in **Figure 1**). Granitoid from Pleterac Quarry (point no. 18) has a thermal conductivity of 2.313 W m^{-1} K^{-1}, also within the range of values measured on granites (points 20-22). Values of gneiss are measured only on two outcrops (see points 2 and 3 in **Figure 1**) and the values are simi-

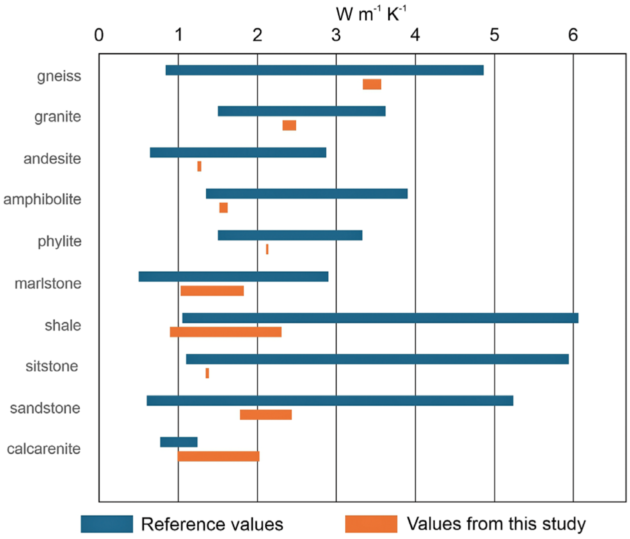

Figure 3: Comparison of thermal conductivity reference values from **Table 1** and the obtained results

lar, 3.332 and 3.565 W m^{-1} K^{-1} (the difference is 6.5%). The values of thermal conductivity measured in amphibolite also vary in a narrow range, from 1.549-1.623 W m^{-1} K^{-1}. Trachyandesites values measured on two outcrops differ by less than 4%, the average values are 1.240 and 1.291 W m^{-1} K^{-1}. Coarse grained sandstones measured in Poljanska Quarry show significantly lower values (1.778 and 1.968 W m^{-1} K^{-1}) compared to poorly sorted lithic sandstone from the outcrop near Podvrško (2.433 W m^{-1} K^{-1}), point no. 27. However, all the measured values are higher than the value reported by **Borović et al. (2018)**, which is 1.55 W m^{-1} K^{-1} and significantly lower than the average value of Lower Miocene sandstone reported by **Kovačić (2007)**, which is 2.899 W m^{-1} K^{-1}. The value of Upper Miocene clayey sandstone reported by **Kovačić (2007)** of 2.058 W m^{-1} K^{-1} fits within the range of values measured within this study. The values of biocalcarenites and transitional lithology between biocalcarenite and biocalcrudite vary in a rather wide range. The lowest value is measured on biocalcarenite from the Voćin location, 0.990 W m^{-1} K^{-1}, while the significantly higher value of 1.686 W m^{-1} K^{-1} is measured on the nearby outcrop. Even higher values are measured on outcrops on the southern slopes of Psunj Mt. (points 25, 28 & 29), where the lowest value is registered for the weathered outcrop (point 25), which could be attributed to increased porosity. The largest number of measurements were made on marlstones, altogether seven measurements, out of which the results from the Voćin location (points 4, 6, 8, 9 & 10) vary in a rather narrow range, from 0.917 to 1.087 W m^{-1} K^{-1} . Significantly higher values of 1.852 and 2.323 W m^{-1} K^{-1} were observed on the southern slopes of Psunj Mt. (point 26) and in the Poljanska Quarry outcrop (point 16), respectfully. A similarly wide range of values was registered for shale, ranging from 0.894 to 2.304 W m^{-1} K^{-1} with all measurements made on the outcrops in the Poljanska Quarry (points 13-15). Thermal conductivity was measured on only one outcrop of siltstone, showing a low value of 1.374 W m^{-1} K^{-1}. The values measured on peperites were 1.182 W m^{-1} K^{-1} (point 31) and 1.488 (point 32), which are similar to the value of 1.381 W m^{-1} K^{-1} measured on unclassified effusive (point 35). It should be noted that peperite is defined after **Le Maître (2002)** as "…a tuff or breccia, formed by the intrusion of magma into wet sediments. Usually consists of glassy fragments of igneous rock and some sedimentary rock".

5. Discussion

There are several concerns arising with the use of properties of analogue outcrop samples to characterize the subsurface rock formations, i.e. several factors should be regarded as a source of difference between the *in situ* measurements conducted at the outcrops and the actual values of thermal conductivity of rocks in the subsurface. The first factor influencing the value of thermal conductivity is porosity (**Brigaud and Vasseur, 1989**; **Jiang et al., 2021**; **Labus and Labus, 2018**) and the reason behind the potential difference lies primarily in differences of intensity of diagenetic processes in sediments, while for crystalline rocks the value of porosity will be mainly influenced by the intensity of weathering and stress driven fracturing. The differences in porosity for medium and coarse-grained sediments are influenced by the intensity of cementation. Namely, **Tadej et al.** (**1996**) and **Kolenković Močilac et al.** (**2022**) suggested that cementation plays a key role in controlling the petrophysical properties of sandstones in the Sava Basin. **Tadej et al. (1996)** based their conclusions on the analyses of hundreds of thin sections as well as laboratory measurements of porosity and permeability, while **Kolenković Močilac et al. (2022)** assigned a significant role on control of petrophysical properties to cementation based on a comparison between granulometric properties and petrophysical properties of Miocene sandstones, which was confirmed by the findings of SEM studies conducted by **Matošević et al., (2021, 2023)**. Considering the similarities in sedimentation environments, it is reasonable to assume that cementation has a similar effect on sandstones in the Drava Basin. This influence is not assumed to have significant importance on fine-grained sediments. On the other hand, the petrophysical properties of the outcrop sediments are influenced by exhumation. The stresses experienced during exhumation can lead to the development of fractures within the sedimentary rocks, potentially significantly affecting their petrophysical properties. However, these influences are too complex to be included in this study and the research suggests that the intensity of the exhumation of the Neogene rocks is not significant. The authors can only conclude that the influences of diagenetic processes may have been the reason for differences in porosity, thus affecting differences in thermal conductivity values of measured outcrop rocks and their subsurface analogues.

Another important factor influencing thermal conductivity is fluid saturation (**Jin et al., 2017**; **Nagaraju and Roy, 2014**; **Popov et al., 2003**). While the rocks at the surface are in the vadose zone and their pores are thus saturated with both water and air, it is assumed that the rock formations in the subsurface are water saturated (pore water having increased salinity). The difference between the thermal conductivity of water and air is significant, thus the rocks saturated with water have significantly higher thermal conductivities when compared to the same lithology saturated with air. **Kovačić (2007)** observed that there was a difference between the thermal conductivity of dry and water saturated rock samples up to 30%, and **Chicco et al. (2019)** who investigated thermal conductivities of Umbria-Marche carbonate succession reported that, on average, the difference between thermal conductivities of water wet and dry samples was 20%. Although, it is expected that this difference is more emphasized for rocks with greater porosity, primarily medium and coarse-grained clastic sediments, **Iosif Stylianou et al. (2016)**, registered a pronounced difference between the thermal conductivity of dry and water saturated values for all tested clastic sediments, including siltstone (the average values being 0.6 and 1.0 W m^{-1} K^{-1} respectively), marl (the average recorded values were 0.7 and 1.0 W m^{-1} K^{-1} respectively), sandstone (the average recorded values were 0.9 and 1.3 W m^{-1} K^{-1} respectively), as well as for calcareous clastic – calcarenite (the average recorded values were 1.1 for dry and 1.5 W m^{-1} K^{-1} for wet samples). **Cho et al. (2009)** observed surprisingly pronounced differences in thermal conductivity (around 10-40%) of water-wet and dry granite samples with rather low porosity (0.6-2.5% effective porosity), supporting the results of the study conducted by **Schärli and Rybach (1984)** who reported that a porosity difference of 0.8% between dry and water-saturated samples resulted in a difference of thermal conductivities amounting to 30%. Another interesting observation of this study was that the thermal conductivity of samples saturated with water varied within a significantly narrower range (2.99 – 3.62 W m^{-1} K^{-1}) with respect to values for dry samples which showed a more substantial difference, ranging from 2.12-3.12 W m^{-1} K^{-1} (**Cho et al., 2009**). On the other hand, based on the results of the study presented here, it can be noticed that thermal conductivities of basement rocks – granites and granitoids, gneisses, amphibolites and trachyandesites vary in a narrow range, which could probably be attributed to very low porosity and a consequentially small effect of fluid saturation on thermal conductivity values. Also, the measurements were conducted in similar conditions, on vertical outcrops which could limit water infiltration. The uniformity of values measured on granite outcrops indicate that this lithology in the study area shows medium value with respect to the values reported in literature. Values reported for gneisses indicate that in the study area, gneisses have values higher than the average value reported in literature, while values measured on amphibolites suggest that this lithology in the study area is characterized with rather low values with respect to values reported in literature. In that sense, these values bear a certain importance even though they are based on a limited number of measurements, since they enable more reliable characterization of geological formations. It can be argued that local measurements conducted on crystalline rocks reflect the influence of specific geological properties, such as variations in mineral composition, porosity, and fluid saturation, which can significantly affect thermal conductivity.

Measurements conducted on sedimentary rocks exhibit larger variability, as seen for bioclastic sediments (points 5, 7, 25, 28, 29), which show marked variability and significantly lower values than 2.726 W m^{-1} K^{-1} reported by **Kovačić (2007)** or for sandstones varying in a more narrow range (1.778-2.433 W m^{-1} K^{-1}), similar to the discrepancy reported by **Kovačić (2007)**. It is reasonable to assume that this variability is associated with an increased porosity range and consequent fluid saturation. In this regard, more detailed research is needed to determine the extent of the influence of mineral composition, porosity variation, and fluid saturation on thermal conductivity. Thus, future studies should be focused on sediments and include the determination of mineral composition, laboratory porosity measurements and thermal conductivity measurements in dry and water-wet state. This should enable a better understanding of factors influencing the measured values. Also, a comparison of values obtained by *in situ* measurements and using laboratory steady-state method would be beneficial.

6. Conclusion

The development of geothermal projects in continental Croatia calls for an estimation of thermal properties of rocks, including their thermal conductivity. This study presents the thermal conductivity measurements of various rock types constituting the North Croatia Basin infill, as well as the crystalline basement rocks.

Based on the in situ measurements performed using the transient line source method, it can be observed that narrow ranges of thermal conductivity are observed in granites, gneisses, amphibolites, and trachyandesites, i.e. in the crystalline basement rocks. Values measured in granite range between 2.317 and 2.486 W m-1 K-1, the value range for gneiss is between 3.332 and 3.565 W m-1 K-1 and values measured in amphibolite lie in the range between 1.549 and 1.623 W m-1 K-1. This could be assigned to the low porosity of these rocks since the measurements were carried out at outcrop sections without any visible fractures, so it is expected that fluid saturation didn't play as significant role as in clastic sediments. The saturation of rocks with water significantly impacts their thermal conductivity compared to air saturation, with variations observed based on porosity and rock type. These findings underscore the complexities involved in characterizing subsurface rock formations using surface outcrop samples, suggesting caution in extrapolating results. Apart from calcarenites, all other clastic sediments showed relatively lower values compared to reference values (see **Figure 3**). Sandstones exhibit a rather wide range of thermal conductivity values, from 1.778 and 2.433 W m-1 K-1, with variability attributed to factors such as sorting, mineral composition, and the greatest effect arguably assigned to porosity, influenced by diagenetic processes and exhumation. Cementation during diagenesis is also suggested to affect sandstone properties, since it affects porosity and permeability of the sandstones in the NCB. Registered thermal conductivities of marlstones vary between 0.917 and 2.323 W m-1 K-1, while values measured in shales range between 0.894 and 2.304 W m-1 K-1, and the greatest variation with respect to reference values from literature are found for biocalcarenites with measured values of thermal conductivity between 0.990 and 2.023 W m-1 K-1. Further considerations include the influences of burial history, other diagenetic processes, and fluid saturation, which collectively contribute to the variability in thermal conductivity measurements. Although local data provides a more reliable basis for understanding the thermal properties of rocks in a given area, further research is needed to determine which factor has the greatest influence on the variability of thermal conductivity values in sediments, i.e. to establish to which extent each of the factors contributes to the measured values. This is by far the most important step to be taken before a more substantiated regional geothermal model can be constructed.

Acknowledgement

This work has been supported in part by the Croatian Science Foundation under the project “GEOlogical characterization of the Eastern part of the Drava Depression subsurface intended for the evaluation of Energy Potentials” (UIP-2019-04-3846).

7. References

Alnes, H., Eiken, O., Nooner, S., Sasagawa, G., Stenvold, T., and Zumberge, M. (2011): Results from Sleipner gravity monitoring: Updated density and temperature distribution of the CO2 plume. *Energy Procedia*, *4*, 5504–5511. https://doi.org/10.1016/j.egypro.2011.02.536

Andújar Márquez, J., Martínez Bohórquez, M., and Gómez Melgar, S. (2016): Ground Thermal Diffusivity Calculation by Direct Soil Temperature Measurement. Application to very Low Enthalpy Geothermal Energy Systems. *Sensors*, *16*(3), 306. https://doi.org/10.3390/s16030306

ASTM D5334-14. (2022): *Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure*. https://www.astm.org/d5334-14.html

Blackwell, D. D., and Steele, J. L. (1989): Thermal Conductivity of Sedimentary Rocks: Measurement and Significance. In *Thermal History of Sedimentary Basins* (pp. 13–36). Springer New York. https://doi.org/10.1007/978-1-4612-3492-0_2

Borović, S., Urumović, K., Terzić, J., and Pavičić, I. (2018): Examining thermal conductivities of shallow subsurface materials for ground source heat pump utilization in the Pannonian part of Croatia. *Rudarsko-Geološko-Naftni Zbornik*, *33*(5), 27–35. https://doi.org/10.17794/rgn.2018.5.3

Brigaud, F., and Vasseur, G. (1989): Mineralogy, porosity and fluid control on thermal conductivity of sedimentary rocks. *Geophysical Journal International*, *98*(3), 525–542. https://doi.org/10.1111/j.1365-246X.1989.tb02287.x

Chekhonin, E., Popov, Y., Peshkov, G., Spasennykh, M., Popov, E., and Romushkevich, R. (2020): On the importance of rock thermal conductivity and heat flow density in basin and petroleum system modelling. *Basin Research*, *32*(5), 1261–1276. https://doi.org/10.1111/bre.12427

Chicco, J. M., Fonte, L., Mandrone, G., Tartaglino, A., and Vacha, D. (2023): Hybrid (Gas and Geothermal) Greenhouse Simulations Aimed at Optimizing Investment and Operative Costs: A Case Study in NW Italy. *Energies*, *16*(9), 3931. https://doi.org/10.3390/en16093931

Chicco, J., Verdova, M., Giuli, G., and Invernizzi, C. (2019): Thermophysical properties and mineralogical composition of the Umbria-Marche carbonate succession (central Italy). In C. Koeberl & D. M. Bice (Eds.), *250 Million Years of Earth History in Central Italy: Celebrating 25 Years of the Geological Observatory of Coldigioco* (pp. 59–67). Geological Society of America. https://doi.org/10.1130/2019.2542(02)

Cho, W. J., Kwon, S., and Choi, J. W. (2009): The thermal conductivity for granite with various water contents. *Engineering Geology*, *107*(3–4), 167–171. https://doi.org/10.1016/j.enggeo.2009.05.012

Ćorić, S., Pavelić, D., Rögl, F., Mandic, O., Vrabac, S., Avanić, R., Jerković, L., and Vranjković, A. (2009): Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys). *Geologia Croatica*, *62*(1), 31–43. https://doi.org/10.4154/gc.2013.05

Côté, J., and Konrad, J.-M. (2005): A generalized thermal conductivity model for soils and construction materials. *Canadian Geotechnical Journal*, *42*(2), 443–458. https://doi.org/10.1139/t04-106

Čubrić, S. (2012): Basic characteristics of hydraulic model for the Velika Ciglena geothermal reservoir. *Nafta*, *42*(2), 173–179.

Cvetković, M., Matoš, B., Rukavina, D., Kolenković Močilac, I., Saftić, B., Baketarić, T., Baketarić, M., Vuić, I., Stopar, A., Jarić, A., and Paškov, T. (2019): Geoenergy potential of the Croatian part of Pannonian Basin: insights from the reconstruction of the pre-Neogene basement unconformity. *Journal of Maps*, *15*(2). https://doi.org/10.1080/17445647.2019.1645052

Dalla Santa, G., Galgaro, A., Sassi, R., Cultrera, M., Scotton, P., Mueller, J., Bertermann, D., Mendrinos, D., Pasquali, R., Perego, R., Pera, S., Di Sipio, E., Cassiani, G., De Carli, M., and Bernardi, A. (2020): An updated ground thermal properties database for GSHP applications. *Geothermics*, *85*, 101758. https://doi.org/10.1016/j.geothermics.2019.101758

Deepagoda, T. K. K. C., Smits, K., Jayarathne, J. R. R. N., Wallen, B. M., and Clough, T. J. (2018): Characterization of Grain-Size Distribution, Thermal Conductivity, and Gas Diffusivity in Variably Saturated Binary Sand Mixtures. *Vadose Zone Journal*, *17*(1), 1–13. https://doi.org/10.2136/vzj2018.01.0026

Dong, Y., Zeng, J., Zhao, X., Wang, Y., Chen, T., Zhang, Y., and Feng, S. (2020): The Temperature Evaluation of the Buried Hill Geothermal Reservoirs in the Jizhong Depression, Bohai Bay Basin, China. *Geofluids*, *2020*, 1–14. https://doi.org/10.1155/2020/4814515

Dövényi, P., and Horváth, F. (1988): A Review of Temperature, Thermal Conductivity, and Heat Flow Data for the Pannonian Basin. In *The Pannonian Basin A Study in Basin Evolution* (pp. 195–233). American Association of Petroleum Geologists. https://doi.org/10.1306/M45474C16

Duchkov, A. D., Sokolova, L. S., Rodyakin, S. V., and Chernysh, P. S. (2014): Thermal conductivity of the sedimentary-cover rocks of the West Siberian Plate in relation to their humidity and porosity. *Russian Geology and Geophysics*, *55*(5–6), 784–792. https://doi.org/10.1016/j.rgg.2014.05.021

Eppelbaum, L., Kutasov, I., and Pilchin, A. (2014): Thermal Properties of Rocks and Density of Fluids. In *Lecture Notes in Earth System Sciences* (pp. 99–149). Springer. https://doi.org/10.1007/978-3-642-34023-9_2

Fadeeva, I. I., and Duchkov, A. A. (2017): Determination of heat transfer properties of media with a single-needle probe. *Journal of Applied and Industrial Mathematics*, *11*(4), 506–513. https://doi.org/10.1134/S199047891704007X

Gangyan, G. (2005): *Physical Properties of Alpine Rocks: A Laboratory Investigation* [PhD Thesis]. University of Geneva.

Genova, E., and Kilian, R. (2017): Thermal and hygrometric properties of traditional calcarenite stones in the area of Palermo. *Energy Procedia*, *122*, 1081–1086. https://doi.org/10.1016/j.egypro.2017.07.431

Giordano, N., Chicco, J., Mandrone, G., Verdoya, M., and Wheeler, W. H. (2019): Comparing transient and steady-state methods for the thermal conductivity characterization of a borehole heat exchanger field in Bergen, Norway. *Environmental Earth Sciences*, *78*(15), 460. https://doi.org/10.1007/s12665-019-8397-7

Hećimović, I. (2008): Bizovac thermal spa (In Croatian). In A. Šimunić (Ed.), *Geothermal and mineral waters of Republic of Croatia* (pp. 39–43). Croatian Geological Institute.

Hurtig, E., Čermak, V., Haenel, R., and Zui, V. (1992): *Geothermal atlas of Europe* (1st ed.). Hermann Haack.

IEA. (2021): *Energy system of Croatia*. Https://Www.Iea.Org/Countries/Croatia.

Iosif Stylianou, I., Tassou, S., Christodoulides, P., Panayides, I., and Florides, G. (2016): Measurement and analysis of thermal properties of rocks for the compilation of geothermal maps of Cyprus. *Renewable Energy*, *88*, 418–429. https://doi.org/10.1016/j.renene.2015.10.058

Jelić, K., Kevrić, I., and Krasić, O. (1995): Temperatura i toplinski tok u tlu Hrvatske [Temperature and heat flow in the soil of Croatia]. In I. Vlahović, I. Velić, & M. Šparica (Eds.), *Proceedings of the First Croatian Geological Congress* (pp. 245–249). Croatian Geological Society.

Jiang, X., Wu, C., Fang, X., and Liu, N. (2021): A New Thermal Conductivity Estimation Model for Sandstone and Mudstone Based on Their Mineral Composition. *Pure and Applied Geophysics*, *178*(10), 3971–3986. https://doi.org/10.1007/s00024-021-02824-w

Jin, H., Wang, Y., Zheng, Q., Liu, H., and Chadwick, E. (2017): Experimental Study and Modelling of the Thermal Conductivity of Sandy Soils of Different Porosities and Water Contents. *Applied Sciences*, *7*(2), 119. https://doi.org/10.3390/app7020119

Kolenković Močilac, I., Cvetković, M., Saftić, B., and Rukavina, D. (2022): Porosity and Permeability Model of a Regionally Extending Unit (Upper Miocene Sandstones of the Western Part of Sava Depression, Croatia) Based on Vintage Well Data. *Energies*, *15*(16), 6066. https://doi.org/10.3390/en15166066

Kovačić, M. (2007): Correlations of Thermal Conductivity Between Stratigraphic Units in the Broader Area of Zagreb (In Croatian). *Rudarsko-Geološko-Naftni Zbornik*, *19*, 27–33.

Labus, M., and Labus, K. (2018): Thermal conductivity and diffusivity of fine-grained sedimentary rocks. *Journal of Thermal Analysis and Calorimetry*, *132*(3), 1669–1676. https://doi.org/10.1007/s10973-018-7090-5

Le Maître, R. W. (2002): *Igneous Rocks: A Classification and Glossary of Terms* (R. W. Le Maitre, A. Streckeisen, B. Zanettin, M. J. Le Bas, B. Bonin, & P. Bateman, Eds.; 2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511535581

Lenkey, L., Dövényi, P., Horváth, F., and Cloetingh, S. A. P. L. (2002): Geothermics of the Pannonian basin and its bearing on the neotectonics. *Stephan Mueller Special Publication Series*, *3*, 29–40. https://doi.org/10.5194/smsps-3-29-2002

Lienhard, I. J. H., and Lienhard, V. J. H. (2020): *A Heat Transfer Textbook* (5th ed.). Phlogiston Press.

Lučić, D., Saftić, B., Krizmanić, K., Prelogović, E., Britvić, V., Mesić, I., and Tadej, J. (2001): The Neogene evolution and hydrocarbon potential of the Pannonian Basin in Croatia. *Marine and Petroleum Geology*, *18*(1), 133–147. https://doi.org/10.1016/S0264-8172(00)00038-6

Macenić, M., Kurevija, T., and Medved, I. (2020): Novel geothermal gradient map of the Croatian part of the Pannonian Basin System based on data interpretation from 154 deep exploration wells. *Renewable and Sustainable Energy Reviews*, *132*, 110069. https://doi.org/10.1016/j.rser.2020.110069

Makhous, M., and Galushkin, Y. I. (2004): *Basin Analysis and Modeling of the Burial, Thermal and Maturation Histories of Sedimentary Basins* (Issue 4). Editions Technips.

Malvić, T., and Cvetković, M. (2013): Lithostratigraphic units in the Drava Depression (Croatian and Hungarian parts) – a correlation. *Nafta*, *63*(1), 27–33.

Matošević, M., Kovačić, M., and Pavelić, D. (2021): Provenance and diagenesis of the Upper Miocene sandstones from the Pannonian Basin System. In O. Bábek & S. Vodrážková (Eds.), *Book of Abstracts of 35th IAS Meeting of Sedimentology*.

Matošević, M., Marković, F., Bigunac, D., Šuica, S., Krizmanić, K., Perković, A., Kovačić, M., and Pavelić, D. (2023): Petrography of the Upper Miocene sandstones from the North Croatian Basin: Understanding the genesis of the largest reservoirs in the southwestern part of the Pannonian Basin System. *Geologica Carpathica*, *74*(2). https://doi.org/10.31577/GeolCarp.2023.06

McKenzie, D. (1978): Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, *40*(1), 25–32. https://doi.org/10.1016/0012-821X(78)90071-7

Mesić, I., Krištofek, B., and Babić, T. (1996): Geothermal Energy Resources in the Republic of Croatia - Overpressured Zone. *Geologia Croatica*, *49*(2), 265–269.

Meter. (2023): *Tempos Manuall*. Tempos Manuall. https://publications.metergroup.com/Manuals/20645%20TEMPOS_Manual_Web.pdf

Midttomme, K., and Roaldset, E. (1998): The effect of grain size on thermal conductivity of quartz sands and silts. *Petroleum Geoscience*, *4*(2), 165–172. https://doi.org/10.1144/petgeo.4.2.165

Mielke, P., Bär, K., and Sass, I. (2017): Determining the relationship of thermal conductivity and compressional wave velocity of common rock types as a basis for reservoir characterization. *Journal of Applied Geophysics*, *140*, 135–144. https://doi.org/10.1016/j.jappgeo.2017.04.002

Nagaraju, P., and Roy, S. (2014): Effect of water saturation on rock thermal conductivity measurements. *Tectonophysics*, *626*, 137–143. https://doi.org/10.1016/j.tecto.2014.04.007

Nix, G. H., Lowery G. W., Vachon, R. I., and Tanger, G. E. (1967): Direct Determination of Themral Diffusivity and Conductivity with a Refined Line-Source Technique. *AIAA Thermophysics Specialist Conference*, 1–7.

Pamić, J., and Lanphere, M. (1991): Hercynian granites and metamorphic rocks from the Mts. Papuk, Psunj, Krndija, and the surrounding basement of the Pannonian Basin in Slavonija (Northern Croatia, Yugoslavia). *Geologija*, *34*(1), 81–253. https://doi.org/10.5474/geologija.1991.004

Pandey, S. N., Vishal, V., and Chaudhuri, A. (2018): Geothermal reservoir modeling in a coupled thermo-hydro-mechanical-chemical approach: A review. *Earth-Science Reviews*, *185*, 1157–1169. https://doi.org/10.1016/j.earscirev.2018.09.004

Pavelić, D. (2001): Tectonostratigraphic model for the North Croatian and North Bosnian sector of the Miocene Pannonian Basin System. *Basin Research*, *13*(3), 359–376. https://doi.org/10.1046/j.0950-091x.2001.00155.x

Pavelić, D., and Kovačić, M. (2018): Sedimentology and stratigraphy of the Neogene rift-type North Croatian Basin (Pannonian Basin System, Croatia): A review. *Marine and Petroleum Geology*, *91*, 455–469. https://doi.org/10.1016/j.marpetgeo.2018.01.026

Pavelić, D., Miknic, M., and Sarkotić Šrlat, M. (1998): Early To Middle Miocene facies succession in lacustrine and marine environments on the southwestern margin of the Pannonian Basin System (Croatia). *Geologica Carpathica*, *December*, 433–443.

Popov, Y., Tertychnyi, V., Romushkevich, R., Korobkov, D., and Pohl, J. (2003): Interrelations Between Thermal Conductivity and Other Physical Properties of Rocks: Experimental Data. *Pure and Applied Geophysics*, *160*(5–6), 1137–1161. https://doi.org/10.1007/PL00012565

Rahmouni, A., Boulanouar, A., El Rhaffari, Y., Hraita, M., Zaroual, A., Géraud, Y., Sebbani, J., Rezzouk, A., and Nabawy, B. S. (2023): Impacts of anisotropy coefficient and porosity on the thermal conductivity and P-wave velocity of calcarenites used as building materials of historical monuments in Morocco. *Journal of Rock Mechanics and Geotechnical Engineering*, *15*(7), 1687–1699. https://doi.org/10.1016/j.jrmge.2023.02.008

Ramakrishnan, D., Bharti, R., Singh, K. D., and Nithya, M. (2013): Thermal inertia mapping and its application in mineral exploration: results from Mamandur polymetal prospect, India. *Geophysical Journal International*, *195*(1), 357–368. https://doi.org/10.1093/gji/ggt237

Raymond, J. (2018): Colloquium 2016: Assessment of subsurface thermal conductivity for geothermal applications. *Canadian Geotechnical Journal*, *55*(9), 1209–1229. https://doi.org/10.1139/cgj-2017-0447

Rudnick, R. L., McDonough, W. F., and O'Connell, R. J. (1998): Thermal structure, thickness and composition of continental lithosphere. *Chemical Geology*, *145*(3–4), 395–411. https://doi.org/10.1016/S0009-2541(97)00151-4

Rukavina, D., Saftić, B., Matoš, B., Kolenković Močilac, I., Premec Fuček, V., and Cvetković, M. (2023): Tectonostratigraphic analysis of the syn-rift infill in the Drava Basin, southwestern Pannonian Basin System. *Marine and Petroleum Geology*, *152*, 106235. https://doi.org/10.1016/j.marpetgeo.2023.106235

Saftić, B., Velić, J., Sztanó, O., Juhász, G., and Ivković, Ž. (2003): Tertiary subsurface facies, source rocks and hydrocarbon reservoirs in the SW part of the Pannonian Basin (Northern Croatia and south-western Hungary). *Geologia Croatica*, *56*, 101–122.

Schärli, U., and Rybach, L. (1984): On the thermal conductivity of low-porosity crystalline rocks. *Tectonophysics*, *103*(1–4), 307–313. https://doi.org/10.1016/0040-1951(84)90092-1

Sebe, K., Kovačić, M., Magyar, I., Krizmanić, K., Špelić, M., Bigunac, D., Sütő-Szentai, M., Kovács, Á., Szuromi-Korecz, A., Bakrač, K., Hajek-Tadesse, V., Troskot-Čorbić, T., and Sztanó, O. (2020): Correlation of upper Miocene–Pliocene Lake Pannon deposits across the Drava Basin, Croatia and Hungary. *Geologia Croatica*, *73*(3), 177–195. https://doi.org/10.4154/gc.2020.12

Soldo, V., Boban, L., and Borović, S. (2016): Vertical distribution of shallow ground thermal properties in different geological settings in Croatia. *Renewable Energy*, *99*, 1202–1212. https://doi.org/10.1016/j.renene.2016.08.022

Somerton, W. H. (1992): *Thermal properties and temperature-related behaviour of rock/fluid systems*. Elsevier.

Song, J., Wang, G., Xing, L., Qian, J., Dai, L., and Di, H. (2023): Influencing factors of rock thermal conductivity and applicability evaluation of its mixing law predictive models. *Geothermics*, *110*, 102680. https://doi.org/10.1016/j.geothermics.2023.102680

Sun, Q. (2017): Analyses of the factors influencing sandstone thermal conductivity. *Acta Geodynamica et Geomaterialia*, 173–180. https://doi.org/10.13168/AGG.2017.0001

Tadej, J., Marić Đureković, Ž., and Slavković, R. (1996): Porosity, Cementation, Diagenesis and Their Influence on the Productive Capability of Sandstone Reservoirs in the Sava Depression (Croatia). *Geologia Croatica*, *49*(2), 311–316.

Tang, B., Zhu, C., Xu, M., Chen, T., and Hu, S. (2019): Thermal conductivity of sedimentary rocks in the Sichuan basin, Southwest China. *Energy Exploration & Exploitation*, *37* (2), 691–720. https://doi.org/10.1177/0144598718804902

Tuschl, M., Kurevija, T., Krpan, M., and Macenić, M. (2022): Overview of the current activities related to deep geothermal energy utilisation in the Republic of Croatia. *Clean Technologies and Environmental Policy*, *24*(10), 3003–3031. https://doi.org/10.1007/s10098-022-02383-1

Underwood, W. M., and McTaggart, R. B. (1960): The thermal conductivity of several plastics, measured by an unsteady state method. *Chemical Engineering Progress Symposium Series*, *56*(30), 262–268.

Vulin, D., Močilac, I. K., Jukić, L., Arnaut, M., Vodopić, F., Saftić, B., Sedlar, D. K., and Cvetković, M. (2023): Development of CCUS clusters in Croatia. *International Journal of Greenhouse Gas Control*, *124*, 103857. https://doi.org/10.1016/j.ijggc.2023.103857

Wechsler, A. E. (1992): The Probe Method for Measurement of Thermal Conductivity. In *Compendium of Thermophysical Property Measurement Methods* (pp. 161–185). Springer US. https://doi.org/10.1007/978-1-4615-3286-6_6

Xiaoqing, S., Ming, J., and Peiwen, X. (2018): Analysis of the Thermophysical Properties and Influencing Factors of Various Rock Types From the Guizhou Province. *E3S Web of Conferences*, *53*, 03059. https://doi.org/10.1051/e3sconf/20185303059

Yaşar, E., Erdoğan, Y., and Güneyli, H. (2008): Determination of the thermal conductivity from physico-mechanical properties. *Bulletin of Engineering Geology and the Environment*, *67*(2), 219–225. https://doi.org/10.1007/s10064-008-0126-5

SAŽETAK

Uvid u toplinske vodljivosti stijena Sjevernohrvatskoga bazena temeljem in situ mjerenja

Toplinska vodljivost stijena jedna je od važnih varijabli u istraživanju geotermalnoga potencijala područja na lokalnoj i regionalnoj razini prilikom analize bazena s ciljem procjene ugljikovodičnoga potencijala. Iako se pretpostavlja da metode mjerenja toplinske vodljivosti u stacionarnome stanju daju pouzdanije rezultate, prolazne metode omogućuju mjerenja *in situ*, čime se znatno pojednostavnjuje postupak mjerenja i smanjuje trošak. Ovo istraživanje provedeno je s ciljem poboljšanja razumijevanja toplinske vodljivosti stijena tipičnih za sedimente koji sačinjavaju ispunu Sjevernohrvatskoga bazena (NCB), kao i stijena magmatsko-metamorfnoga kompleksa u podlozi bazena. Izmjerene vrijednosti otkrivaju različite raspone za različite litološke sastave. Vrijednosti toplinske vodljivosti izmjerene na kristalinskim stijenama (graniti, gnajsovi i amfiboliti) prilično su konzistentne, varirajući unutar uskih raspona za svaki litotip: za granit su izmjerene vrijednosti između 2,317 i 2,486 $W\ m^{-1}\ K^{-1}$, raspon vrijednosti za gnajs iznosi između 3,332 i 3,565 $W\ m^{-1}\ K^{-1}$, a toplinska je vodljivost amfibolita u rasponu između 1,549 i 1,623 $W\ m^{-1}\ K^{-1}$. Nasuprot tome, vrijednosti toplinske vodljivosti sedimentnih stijena variraju unutar šireg raspona – vrijednosti u pješčenjacima iznose između 1,778 i 2,433 $W\ m^{-1}\ K^{-1}$, za lapor je registriran raspon između 0,917 i 2,323 $W\ m^{-1}\ K^{-1}$, vrijednosti izmjerene u šejlovima iznose između 0,894 i 2,304 $W\ m^{-1}\ K^{-1}$, a biokalkareniti pokazuju vrijednosti toplinske vodljivosti između 0,990 i 2,023 $W\ m^{-1}\ K^{-1}$. Veća varijabilnost u vrijednostima izmjerenim za sedimentne stijene pripisuje se varijabilnosti poroznosti i zasićenosti fluidima, kao i većoj varijabilnosti mineralnoga sastava. Potrebna su daljnja istraživanja kako bi se utvrdilo koji faktor ima najveći utjecaj na varijabilnost vrijednosti toplinske vodljivosti, odnosno u kojoj mjeri svaki od faktora doprinosi izmjerenim vrijednostima.

Ključne riječi:
toplinska vodljivost stijena, metoda iglene sonde, Sjevernohrvatski bazen

Author's contribution

Iva Kolenković Močilac (1) (assistant professor) conceptualized the study, carried out part of the measurements, and wrote the draft of the manuscript. **Marko Cvetković (2)** (associate professor) helped with study planning, performed part of the measurements, and wrote the draft of the manuscript. **David Rukavina (3)** (senior research assistant) performed part of the measurements, validated the field data; edited the draft of the manuscript. **Josipa Kapuralić (4)** (senior research assistant) performed part of the field work, and edited the draft of the manuscript. **Ana Brcković (5)** (research assistant) performed part of the field work, and edited the draft of the manuscript. **Bruno Saftić (6)** (associate professor) reviewed the draft of the manuscript; **Ivan Cindrić (7)** reviewed the previous research on thermal conductivities of rocks, and performed part of the field work; **Josipa Babić (8)** reviewed the previous research on thermal conductivities of rocks, and performed part of the measurements.