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POTENTIAL TEPID AND HOT WATER RESOURCES IN THE TOKAJ MOUNTAINS

ZOLTÁN FEJES–PÉTER SZŰCS
MTA-ME Research Group of Geoengineering,
Department of Hydrogeology and Engineering Geology,
University of Miskolc

ABSTRACT

Thermal water exploration in volcanic areas is a more complex task than in porous systems. The literature has negligible information about potential thermal reservoirs of the Tokaj Mountains; furthermore, the hydraulic parameters of the volcanic rocks are also unknown. In our study the possible occurrences, locations and hydrogeological parameters of potential thermal water aquifers Tokaj Mountains will be investigated. The geothermal gradient and hydraulic parameters of volcanic formations were calculated by several methods to find the best method. According to our calculations the aquifers associate with fissured rocks and the highest discharge is experienced along fault lines. The final aim of our research is to provide information and data to plan the geothermal water supply in the region.

INTRODUCTION

The Tokaj Mountain range, located in the north-eastern part of Hungary as part of the Carpathian Basin, is one of the most famous volcanic mountains of Hungary. Its strike is to the north-south, and it is approximately 100–120 km long. The mountain runs between Tokaj and Eperjes (Prešov) [1]. The thermal and geothermal research in the Tokaj Mountains has always had secondary importance from the point of view of hydrogeologists, due to its complex geological structure and the insufficient number of deep exploration wells. In 2012 the Department of Hydrogeology and Engineering Geology at the University of Miskolc started a very detailed hydrogeological survey of the wells of the entire Northern Hungary region. During our research we have observed that many potential thermal aquifers can be found in the investigated area, despite the complex geological structure. The aim of our research was to characterize the hydrological parameters of the thermal aquifers and the geothermal gradient of the area with numerical methods.

MATERIALS AND METHODS

We have defined the investigated area mainly by natural boundaries. The boundary in the North is the Hungarian–Slovak border, while the western boundary runs along the Hernád Valley, which is a north-northeast south-southwest structural line, known also as the ALCAPA-Tisza tectonic line, a part of the Central Hungarian lineament. The southern boundaries of the area are the Tisza and Sajó Rivers. Finally, the eastern borders are the Tisza and Bodrog Rivers (*Figure 1*). The geological structure of the Tokaj Mountains is very complicated and elaborated. The depth and the material of the basement are still in question, although many of basement maps show that it is at approximately 1500–2000 m depth, and the material of the basement is probably metamorphic mica.

Concerning the geological structure of the investigated area, it has been proved by the thermal karst of Sárospatak and Bükk that shallow marine carbonate sediments were deposited in the research area in the Triassic. Neogene vulcanite formations settled to the basement materials with hundreds or – in some places thousands – of meters in thickness. The reason for the extraordinary thickness is that the volcanism started in the Miocene and ended in the Lower-Pannonian. The Pannonian Lake gradually lost its salinity, and it was charge by the river-drift. The Upper Pannonian clastic sediments pinched out on the southern part of the research area, but toward the Great Plains their thickness increases. In several areas above the Pannonian layers Pleistocene fluvial sediments have settled in large thickness. In those areas the Holocene formations are negligible.

The hydrogeology of the research area is very diverse and complex, confirm the geological structure. We have classified potential groundwater bodies by the 2010 Watershed Management Plan (WMP). The WMP divides the Tokaj Mountains into two parts: the northeastern part is the Tokaj Foothills and the southwestern part is the watershed of the Hernád and Takta rivers. Four groundwater body types can contain potential hot water aquifer formations. *Table 1* shows the groundwater bodies in the research area [2].

Table 1

Potential warm water aquifers in Tokaj Mountains

Type of groundwater body	Name of area	Surface
Mountainous	Zemplén Mountains–Hernád Watershed Zemplén Mountains–BodrogWatershed	504.1 km^2 615.1 km^2
Porous	Sajó–Hernád Valley Sajó–Takta Valley, Hortobágy Bodrogköz	458.2 km^2 303.1 km^2 61.9 km^2
Porous thermal	Basins of the Northern Mountains Northern Great Plains	1142.6 km^2 28.7 km^2
Thermal karst	Thermal karst in Sárospatak Thermal karst in the Bükk Mountains	62.2 km^2 174.3 km^2

It is a difficult task to define precisely the boundaries of the groundwater bodies boundaries, but estimated values show the potential hot water reserves in each area. In the last few years, many wells have been screened to these groundwater bodies, and their effluent water temperature was warm (25–37 °C) or sometimes hot (37–60 °C). *Figure 1* shows the wells in the research area, which have an effluent water temperature, higher than 18 °C. The temperature limits are corresponding with the temperature classification of Bél-teky–Papp–Schmidt [3] (75 p.). As the first step of the geothermal exploration of the research area, we defined the geothermal gradient using four different numerical methods from the bottom-tempe-rature values of 18 wells. With the resulted geothermal gradient values we calculated the bottom temperatures, and by the comparison of the calculated and measured bottom-temperature values we got the variance

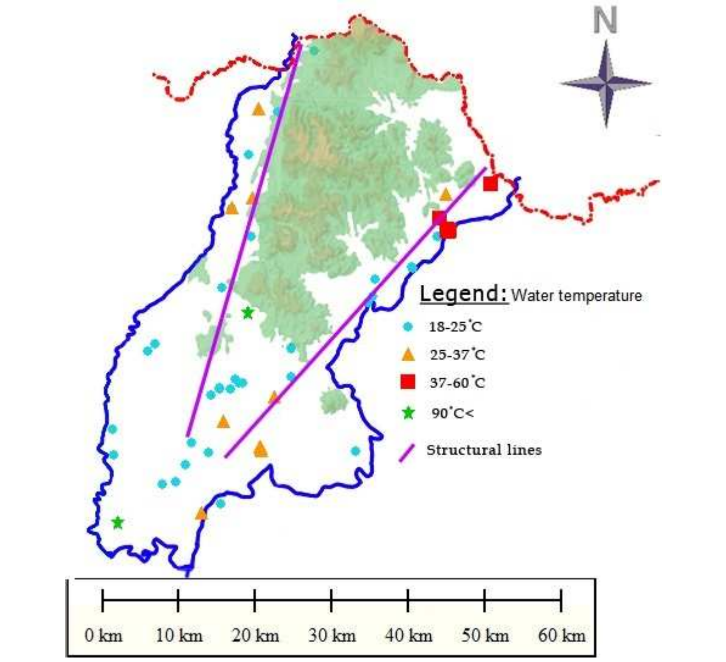

Figure 1.
Tepid- and warm water wells in the Tokaj Mountains with the main structure lines

and applicability of the different numerical methods. The geothermal gradients were calculated using the following approaches:

1. *Bobok–Tóth* equation [4]

$$gg = \frac{T_z - 11}{z} \cdot 100 \tag{1}$$

2. *Szlabóczky* formula [5]

$$gg* = \frac{z - 20}{T_z - 10} \tag{2}$$

3. *Depth vs. bottom-temperature method*: The measured bottom temperatures versus the depth of the wells have been plotted. We have fitted a linear regression curve to the points; the slope of the curve gave the geothermal gradient of the area.

$$T_z = \frac{z + 337{,}75}{18{,}127} \tag{3}$$

4. *The effluent water temperature vs. bottom-temperature method*: From the measured bottom temperature and the effluent water temperature values of the wells we could calculate an average cooling coefficient for the investigated area.

$$h* = \frac{100 \cdot (T_z - T_{out})}{z} \tag{4}$$

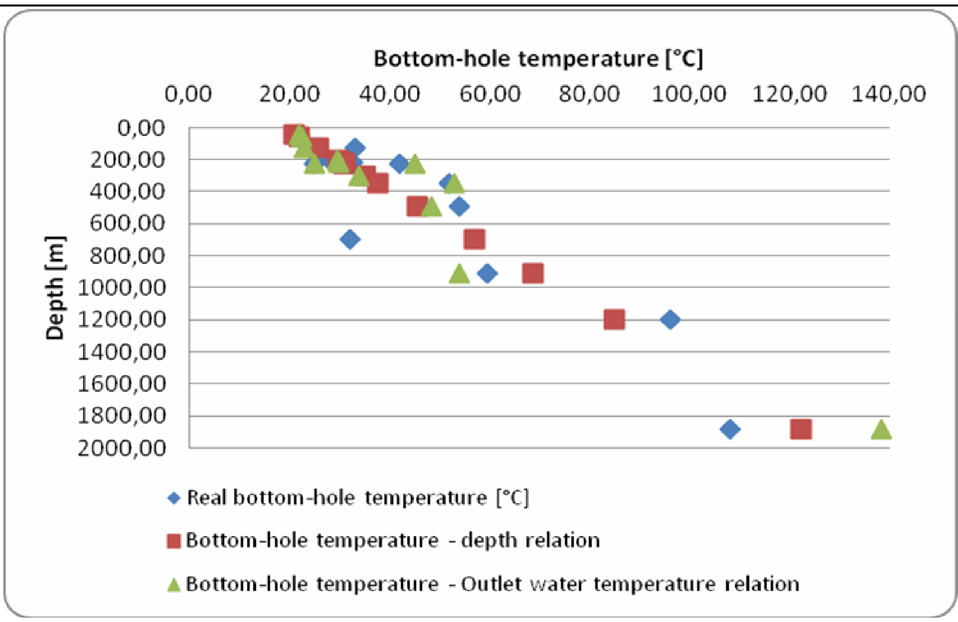

Figure 2.
The measured and calculated bottom temperature values vs. depth

The measured and calculated geothermal gradient values showed that the depth vs. bottom temperature and the bottom temperature vs. effluent water-temperature equations shown in *Figure 2* gave the most precise values of the four approaches (all of correlation coefficient are higher, than 0,9, but the bottom temperature vs. effluent water-temperature equations have the best maximum difference value [25,03 °C]). *Figure 1* shows, that all wells located in the edge of the mountains. In the research area, there are many thermal water aquifer formations. Wells in the southern part of the research area are dominantly screened to porous aquifers (Pleistocene and Pannonian layers), the thicknesses of these layers are increasing to the increases southwards; therefore, the effluent water temperature is also increasing. These Pleistocene and Pannonian formations are excellent aquifers, they consist of high porosity sediment layers with good porosity and excellent aquifer properties, but they are too shallow, and the geothermal gradient cannot prevail. Only in the southern parts of the area did the Pannonian layer reach a sufficiently large depth to provide hot water.

By using the results of pumping tests, we have determined with different methods the average hydraulic conductivity of the Upper Pannonian formations:

1. *Logan–Schieder* equation [3] (299 p.):

$$k = 3.11 \cdot \frac{Q}{s_0 \cdot l}. \tag{5}$$

2. Dupuit–Thiem equation with iteration [3] (291 p.):

$$Q = \frac{2 \cdot m \cdot \pi \cdot k \cdot \left(H - h_0\right)}{\ln \frac{R}{r_0}} \tag{6}$$

$$R = 5000 \cdot \sqrt{k} \cdot s_0. \tag{7}$$

3. *Krasznopolszkij* equation [5]:

$$k = \frac{Q}{2 \cdot \pi \cdot m \cdot \sqrt{s_0 \cdot r_0}}. \tag{8}$$

The calculated hydraulic conductivity values of Pannonian sediments are presented in the next section. Within the research area main aquifers are Pleistocene sands and Upper Pannonian sand and gravel. The yield of these aquifers is high (k = ~4,1 m/d) (*Table 2*) and increases with depth, but the recharge of the wells is limited, due to the poor infiltration conditions from the mountain side. The groundwater level can dramatically decrease because of the inadequate production rates of the wells. (In the case of Prügy Waterworks, the dynamic water level sinkage was 43 m!). In spite of its favorable hydrological and geothermal conditions, only a few deep wells were settled in the south part of the investigated area. In Kesznyéten and Girincs the depth of the wells did not reach 100 m, but the bottom of the Upper Pannonian formation is at more than 1000 m depth. From the calculated geothermal gradient, at this depth we can expect the water temperature to be approximately 70 °C with a yield of 900–1100 l/min.

The most significant Neogene thermal aquifer formations are cracked tuff layers, in which thermal water flows in a rift system to the wells. At the research area thermal wells are located along the Hernád and Bodrog tectonic lines; thermal water updraft is possible through these wells (*Figure 1*). The greater part of the Tokaj Mountains was formed from high and medium strength porous Miocene (Tertiary) volcanic rocks and debris [5]. These rocks have medium hydraulic conductivity (k = ~0,2 m/d) (*Table 2*). The lava rocks (rhyolite, dacite and andesite) and tuffs store fissure water, with their hydraulic conductivity depending on the fracture system. It is important to take into consideration that hydrogeological and geothermal properties of host rocks cannot be determined with single values; the change in their parameters can be described with frequency curves. The curve requires a great deal of data, but for the characterization of the rocks this is the most accurate method. In the case that measured data is lacking, the characterization is made using the minimum, maximum and the most frequent values.

Due to weathering, the lava rocks near the surface crack and their porosity increases, however, deep lava rocks are very poor porosity. In these rocks, the groundwater could leak into micro-fissures. The temperature of the subsurface lava rock can be higher than its surroundings; in Vajdácska the 200 m deep andesite formation raised the water temperature of the overlying aquifer (*Figure 3*).

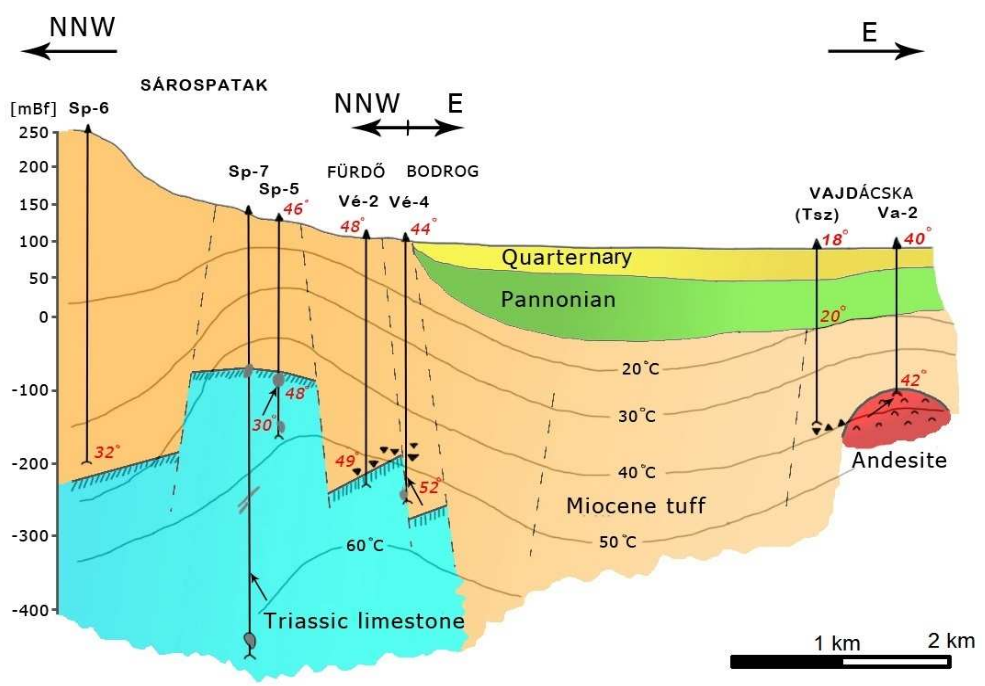

Figure 3.
Geothermal profile between Sárospatak and Vajdácska [6]

Characterization of hydraulic properties of subsurface lava rocks was carried out from the literature and from the evaluation of the pumping tests evaluation on Tállya-15 well. The pumping-test equations presume a porous, homogenous aquifer; therefore, the calculated values are equivalent hydraulic conductivities. The equivalent hydraulic conductivity was determined by the pumping tests of wells screened to the tuff formations. Hydraulic properties of a fractured system depend on the depth, the tectonic effects and the ratio of clay minerals. The water warms up in the subvolcanic formations, the silica content increases, and thereafter flows upward through a fracture system. During the flow, the water cools and the silica precipitates along the flow path. The most conspicuous occurrence of these formations is the top of Árpád Roof in Szerencs. Electrical Resistance Survey (ERS) measurement detected hydrothermal quartzite lead; the estimated sinkage of the lead is determined by the surface outcrops and the data of deep-wells *(Figure 4).* The hydraulic conductivity depends on the rate of the clogging, the lead could behave as an aquitard if clay minerals fill the lithoclases.

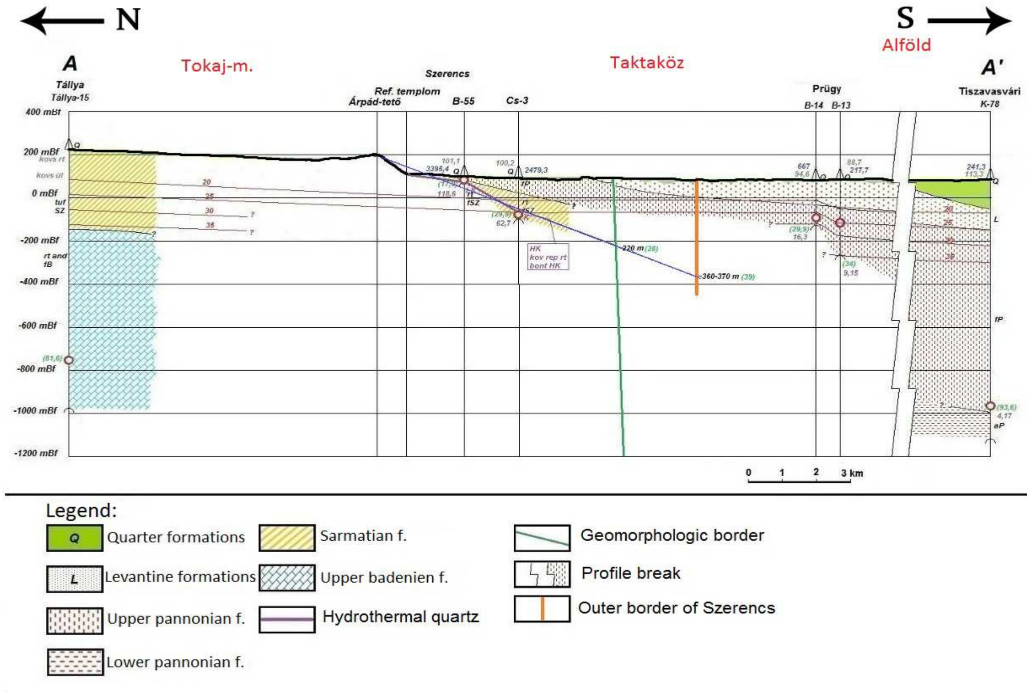

Figure 4.
The estimated sinkage of the hydrothermal quartzite

The covered thermal karst aquifers in the northeastern and southwestern part of the investigated area have the maximum water temperature values; the effluent water temperature is about 40 to 70 °C from the depth of 300–1000 m. The deeper wells (1800–2000 m) of the thermal karst give higher temperature water. The Bükk karst formation and Sárospatak karst formation have quite different recharge conditions. The Bükk karst bodies have high recharge from the Bükk, but the Sárospatak karst has very poor recharge conditions from the Tokaj Mountains, and thus the static water level has been decreasing for years in the thermal wells in Végardó thermal wells (Vé-2, Vé-4) *(Figure 3)* [7]. The equivalent hydraulic conductivity has been determined by the pumping tests of the wells of Végardó screened to the karst aquifer formations.

RESULTS

We have performed hydrogeological investigations on many thermal water aquifers of the Tokaj Mountains to characterize hydraulic properties of the formations. The calculated values (geothermal gradient and hydraulic conductivity) can provide a good basis for the further geothermal exploration of the area. *Table 2* presents hydrogeological parameters of groundwater aquifer formations in the research area.

Table 2

Hydrogeological parameters of potential warm water aquifers in the Tokaj Mountains

Formation	**Hydraulic conductivity [m/d]**	**Permeability [m^2]**	**Transmissivity [m^2/s]**		
			min.	**max.**	**med.**
Pannonian sand	4.1	2×10^{-9}	3	300	77
Miocene tuff	0,2	1.9×10^{-8}	-	-	-
Miocene rock (compact)	4.6×10^{-3}	-	8.7×10^{-5}	4.3	0.3
Hydrothermal quartzite	8.1	1.3×10^{-7}	3	289	118
Carbonate rock	0.9	2.3×10^{-9}	3.8	68	20

Results were as follows:

- The average cooling coefficient for the investigated area is 2.3 °C/100 m, but there was high variance in the average cooling coefficient values; therefore we used **7.4 °C/100 m** for the geothermal gradient, based on the depth vs. bottom-temperature equation.
- From the calculated geothermal gradient value, the isotherm of 30 °C temperature is located at a depth of 270–280 m. *Figure 5* shows the depth of the Upper Pannonian formations in the southern part of the Tokaj Mountains (based on the map of Csíky G. et al. [8]); formations that are potential thermal aquifers are highlighted in green.
- We performed infiltration tests in Szerencs to characterize the vertical hydraulic conductivity of the upper weathered part of the tuff. Based on these measurements the values of hydraulic conductivity were in the range of 2.7–5.1 m/d.
- The temperature of the water in the quartzite strike is approximately 30 °C, with a yield of 1500–1700 l/min.

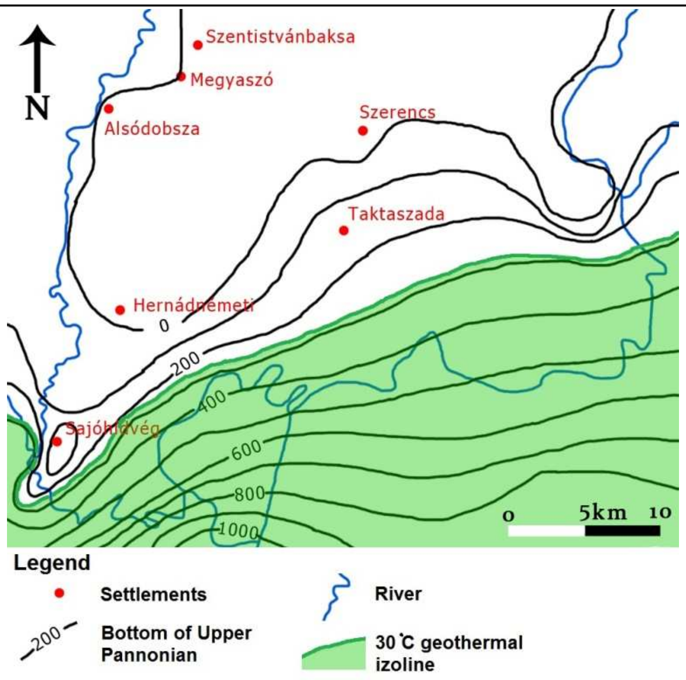

Figure 5.
Depth of the Upper Pannonian formations in the southern part of the Tokaj Mountains

DISCUSSION

The calculated geothermal gradient value corresponds to the geo-isotherm map of Dövényi and Horváth [9]. The geothermal gradient value is 6.5–7 °C/100m on the geo-isotherm map. It gives good agreement with the calculated value. Many hydrogeological parameter values of volcanic formations were collected from the literature. The most important measurements were the hydraulic conductivity, permeability and transmissivity of the lava rock aquifers. The transmissivity of subvulcanic andesite is in the range of 2.7×10^{-6} – 4×10^{-4} m^2/s [3] (318 p.). Szilágyi [10] determined this value to be between 10^{-9} and 5×10^{-5} m^2/s. The hydraulic conductivity value of the lava rocks proved that the andesite formation is solid, and contains micro-fissures *(Figure 6)* [11]. We have compared the results with the measured values of Szűcs and Ritter [7], and according to these data the equivalent hydraulic conductivity of tuff for the investigated area is 0.85 m/d. Our measured values agree well with those in the literature.

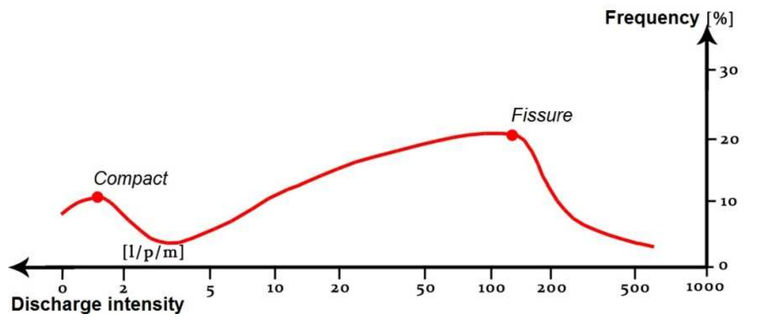

Figure 6.
Discharge intensity in lava rocks

CONCLUSIONS

The Tokaj Mountains have the most complex structure of any of the mountains in Hungary. Until now, the Tokaj Mountains were not the main target of warm water exploration, due to the poor hydraulic information on the formations and the large thickness of the volcanic sequence.

However, the different geophysical methods and the wells screened in the Pannonian, Miocene and Karst aquifers proved that we can discover warm-water aquifers with sufficient geological and hydrogeological properties within the investigated area.

LIST OF SYMBOLS

Variable	Name	Unit
z	depth	[m]
gg	geothermal gradient	[°C/100m]
gg*	geothermal step	[m/°C]
H	static water level	[m]
h*	cooling	[°C/100m]
h_0	measured water level in the well	[m]
k	hydraulic conductivity of aquifer	[m/s]
l	thickness of the screened layer	[m]
m	thickness of the aquifer layer	[m]
R	distance from piezometer to the pumping well	[m]
r_0	radius of the pumping well	[m]
s_0	depression	[m]
T_{out}	effluent water temperature	[°C]
T_z	bottom-temperature	[°C]

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