

Hydrogeothermal resources of Middle Lithuania

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The main geothermal prospects are related to West Lithuania, while the potential of Middle Lithuania was little considered before. The Cambrian sandstone reservoir was identified as a potential hydrothermal resource in Middle Lithuania. Other large-scale geothermal aquifers have too low temperatures. The study indicates that the effective thickness of the Cambrian geothermal aquifer of Middle Lithuania ranges within 15–58 m, the average porosity of sandstones is 13–20% and permeability averages 370 mD; therefore, these sandstones are classified as a good reservoir. The geothermal potential was calculated for geothermal well doublet. The productivity of the geothermal well doublet is estimated to be as high as 53–175 m³/h in the southern part of the study area, while reaching only 16–43 m³/h in the north. Accordingly, the geothermal energy production of the well doublet varies from 0.44 MWh to 1.37 MWh in the northern area, ranging from 1.69 MWh to 6.02 MWh in the south. The water of the Cambrian formation is of the NaCl type with a high salinity (98–130 g/l). The thermochemical modelling indicates that depending on water composition, either the precipitation of gypsum or carbonates and hydroxides should be expected in the geothermal system, while other major mineral phases remain unsaturated in the geothermal loop.

Analysis of the available geothermal resources and their comparison with the heat energy needs of Middle Lithuanian customers indicate that one or two doublet installations exploiting the Cambrian geothermal aquifer may cover the basic needs in the central heating of towns in the region. It is concluded that the Cambrian geothermal aquifer is highly promising for district heating in Middle Lithuania.

Key words: geothermal, hydrothermal resources, Cambrian, hydrochemistry

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INTRODUCTION

Lithuania is considered as a promising area for hydrothermal energy application. The high geothermal potential of West Lithuania is related to an anomalous heat flow. The nature of this anomaly is explained in terms of mantle processes and high heat generation of crustal lithologies (Šliaupa, Rasteniene, 2000). A number of evaluations of geothermal resources was carried out for West Lithuania (e. g., Kepežinskas et al., 1996; Suveizdis, Rasteniene, 1998; Suveizdis et al., 2000; Zinevičius, Šliaupa, 2010). Geothermal prospects of Middle Lithuania

were little studied, as the heat flow and associated temperatures of the main geothermal aquifers decrease to the east (Rasteniene, 1994; 2003). Nevertheless, it is important to assess the possibility of utilizing the geothermal resources in this marginal part, as there might be some important advantages compared with West Lithuania (reservoir properties, customers profile, etc.).

There are different ways of calculating geothermal resources. The proposed approach is focused on the stakeholders' needs, providing a better interaction among different specialists.

MAJOR GEOTHERMAL AQUIFERS OF LITHUANIA

Lithuania is situated on the eastern flank of the Baltic sedimentary basin overlying the Palaeoproterozoic crystalline basement. The thickness of the sedimentary fill ranges from 0.2 km in the southeast to 2.3 km in the west (Fig. 1). The sedimentary cover is composed of different lithologies representing all geological periods of the Phanerozoic. A number of aquifers is defined in the geological section of the basin (Juodkazis, 1979). Two major geothermal aquifers – Cambrian and Pärnu–Kemeru (Fig. 2)(middle Lower–Middle Devonian) are identified in Lithuania. Their geothermal potential is explained by the large volumes of water formation and high temperatures (Kepežinskas et al., 1996). The Šventoji–Upninkai (Upper–Middle Devonian) aquifer, despite its large water volumes, is presently neglected as a potential geothermal reservoir due to insufficient temperatures, as only in a few local areas the temperature exceeds 35 °C in Middle Lithuania. This temperature was assumed as the lower limit for the economic utilization of hydrothermal resources.

Cambrian geothermal aquifer

Cambrian deposits represent the basal part of the sedimentary cover. Their depth ranges from –100 m to –2100 m (Fig. 1). They consist of Lower and lower-Middle Cambrian marine sandstones, siltstones and shales that show different proportions across the basin (Jankauskas, 2002).

The oldest Cambrian “Blue Clay” formation occurs in the eastern part of Lithuania only. The Trilobitic Lower Cambrian reaches 80 m in thickness and is distributed on the whole Lithuanian territory except its southernmost part. It consists of fine-grained sandstones that grade into siltstones and shale in the west.

Middle Cambrian deposits are documented in the western half of Lithuania and are up to 70–80 m thick. Fine-grained sandstones with sparse argillite and siltstone layers are referred to as the Deimena Regional Stage that overlies about 10 m thick shales of the Kybartai Formation. In the Polish offshore area, these deposits grade into deeper-water siltstones and shales. The younger Paneriai Formation was encountered in a few wells in West Lithuania, constituting small isolated residues several meters thick, whereas it is more widely distributed in the east on the western flank of the Moscow palaeobasin (up to 20–30 m thick). Sandstones and siltstones are the dominant lithologies.

Cambrian sandstones are composed of quartz (95–99%); they are mainly fine-grained, cemented by late diagenetic quartz and carbonates that prevailed respectively in the west and the east (Laškova, 1979).

The thickness of the Cambrian sandstone reservoir is 15–70 m. In the east, it is comprised by the Lower Cambrian, while in West Lithuania the 55–70 m thick reservoir is represented by the Deimena RSt. The effective thickness shows considerable variations in the west; they are largely caused by drastic changes in the content of quartz cement which is increasingly important in the west (Vosylius, 1997; Šliaupa, 2006).

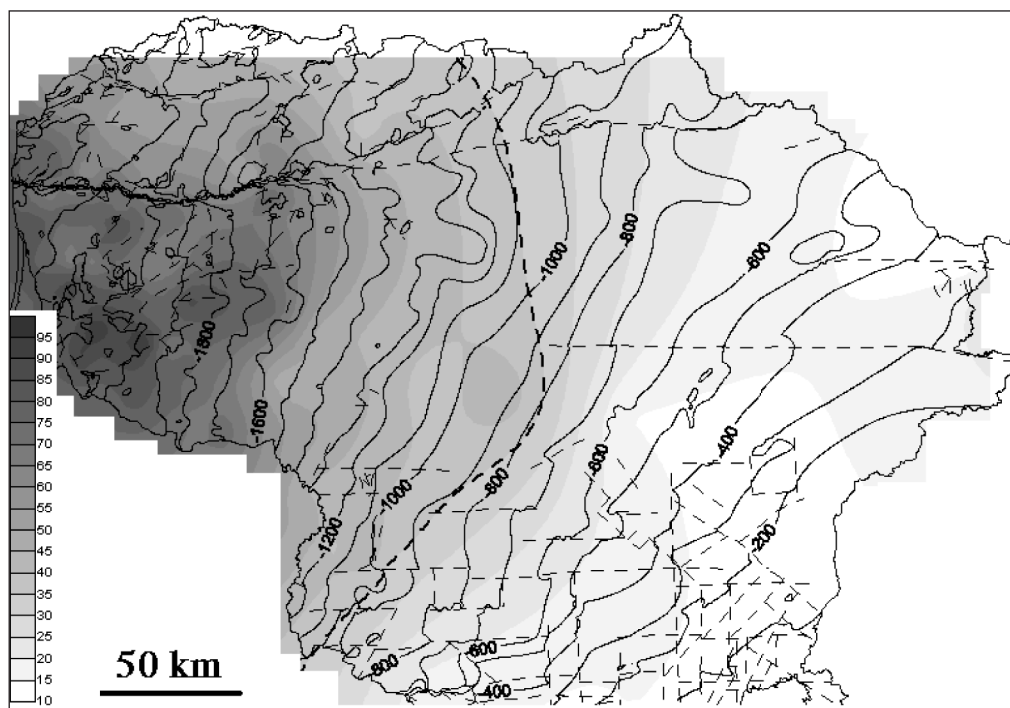


Fig. 1. Depths (contour lines) and temperatures (grey scale) of top of Cambrian geothermal aquifer. Thin dashed lines show faults, thick dashed line marks 35 °C isotherm

1 pav. Kambro kraigo gyliai (izolinijos) ir temperatūros (pilka skalė). Plonos brūkšninės linijos žymi lūžius, stora linija – 35 °C izotermą

The porosity of Cambrian sandstones is in the range 20–25% on the shallow eastern periphery of the basin. The permeability of sandstones ranges within 100–2 300 mD. A reduction from 20 to 15% (permeability 10–2 000 mD) is documented in Middle Lithuania, while it is 3–18% (permeability ranges from <0.01 to 20 mD reaching 300–500 mD) in West Lithuania (Vosylius, 2000).

The temperature of the Cambrian aquifer increases westward with the depth. In East Lithuania, the temperature of the Cambrian aquifer is 7–10 °C (Šliaupa, 2002) (Fig. 1). It sharply increases from 20 °C to 40 °C in Middle Lithuania within a 50–80 km wide zone that is roughly confined to the first-order suture zone of the crystalline basement separating the West Lithuanian Granulites and the East Lithuanian Belt. In West Lithuania, the temperature of the Cambrian aquifer attains 65–96 °C. The eastern limit of the anomaly is rather sharp; the temperature increases from 50 °C to 70 °C within a 10–20 km wide zone. The highest temperatures of the Cambrian aquifer are reported from the southern part of western Lithuania that corresponds to the maximum intensity of the heat flow.

Pärnu–Kemeris geothermal aquifer

The Pärnu–Kemeris aquifer (Fig. 2) is distributed in the major part of the territory of Lithuania except its southern part.

Its thickness reaches up to 160 m. The reservoir is composed of quartz and arkosic fine-grained sandstones (Paškevičius, 1997). They contain subordinate siltstone and shaly layers. The net-to-gross ratio is of the order of 0.65–0.75. The average porosity of sandstones is 26% and the permeability ranges within 500–4 000 mD. The reservoir is covered by 80–120 m thick dolomitic marlstones attributed to the Narva Formation. It is a basin-scale aquitard that separates the Pärnu–Kemeris aquifer from the overlying Šventoji–Upninkai aquifer. The prospective geothermal area is situated in Southwest Lithuania where its temperature exceeds 35 °C and reaches 40–45 °C (Šliaupa, 2002). It is therefore concluded that only the Cambrian geothermal aquifer can be potentially utilised for district heating in Middle Lithuania.

DATA AND METHODS

Data on 23 deep wells penetrating the Cambrian geothermal aquifer of Middle Lithuania were collected from industrial reports. The reservoir properties are characterised by abundant open porosity and permeability measurements. In total, data of 387 samples were used to characterise the reservoir properties of the Cambrian succession. Furthermore, open porosity was defined from gamma ray and sonic velocity logs.

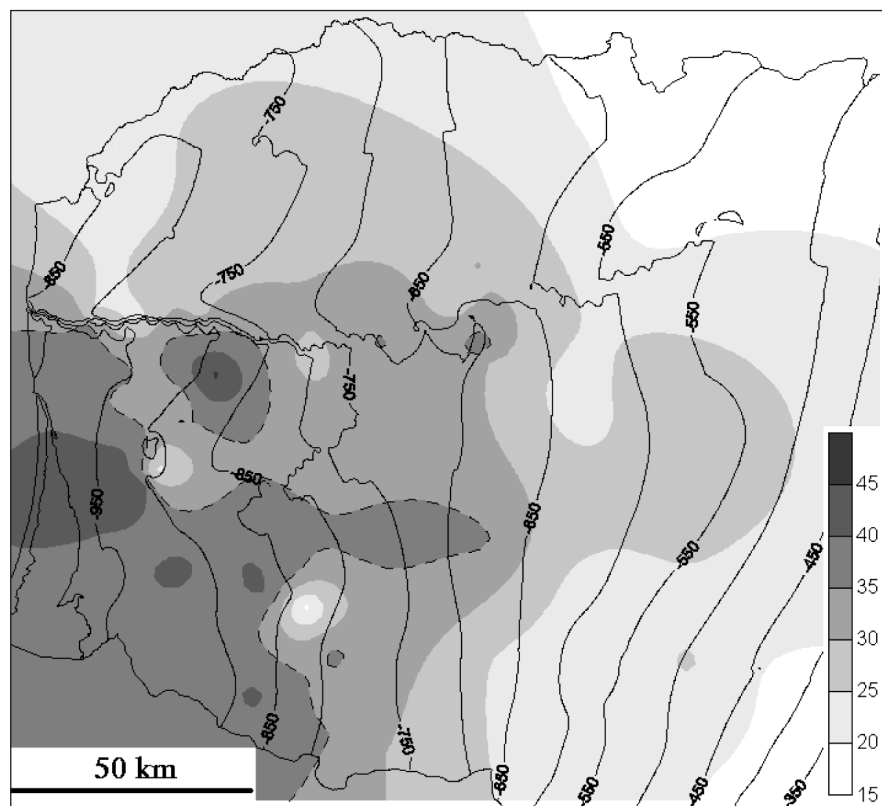


Fig. 2. Depths (contour lines) and temperatures (grey scale) of top of Pärnu–Kemeris geothermal aquifer. Hatched line marks 35 °C isotherm

2 pav. Pärnu–Kemeris vandeningo sluoksnio kraigo gyčiai (izolinijos) ir temperatūros (pilka skalė). Plonos brūkšninės linijos žymi lūžius, stora linija – 35 °C izotermą

The shale content was estimated using gamma ray logging data:

$$V_{sh} = (GR - GR_{min}) / (GR_{max} - GR_{min}), \quad (1)$$

here V_{sh} is the fraction of shale in the rock, GR is the gamma ray intensity (mcr/h).

The open porosity was calculated:

$$\Omega = [(DT - DT_{matrix}) / (DT_{fluid} - DT_{matrix})] \times [1 - V_{sh}], \quad (2)$$

here DT is the sonic velocity ($\mu\text{s} / \text{m}$), DT_{matrix} is the matrix sonic velocity (assumed $170 \mu\text{s}/\text{m}$), DT_{fluid} is the fluid sonic velocity (assumed $600 \mu\text{s}/\text{m}$).

The effective thickness of the Cambrian reservoir was estimated from logging and drill core data.

The Cambrian reservoir temperatures were measured in 21 deep wells drilled in Middle Lithuania (Šliaupa, 2002). Different methods were used (e. g., borehole testing), but mainly thermal logging was applied after temperature equilibrium had been attained in a well (Rastenienė, Šliaupa, 2000).

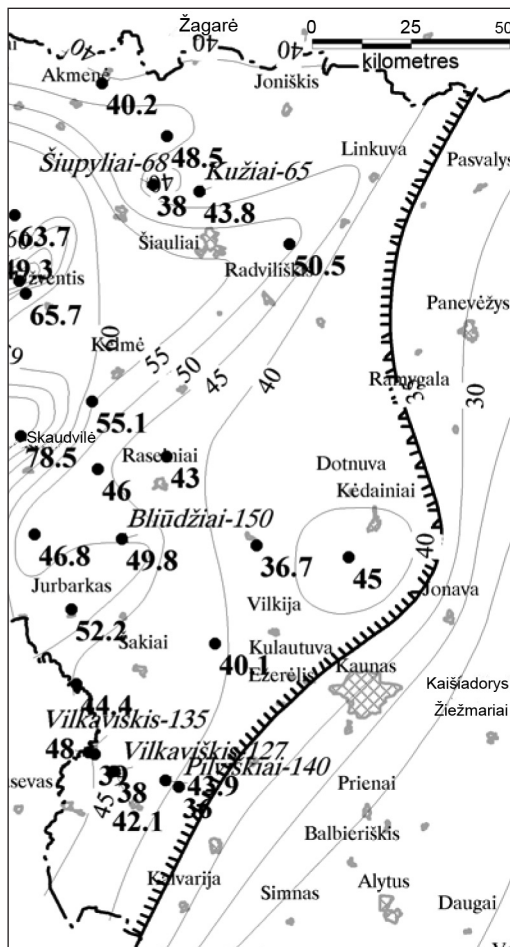


Fig. 3. Temperatures of Cambrian reservoir. Thick line marks 35 °C isotherm. Wells referred to in the text are marked

3 pav. Vidurio Lietuvos kambro sluoksnio temperatūros. Plona linija žymi 35 °C izotermą. Pažymėti gręžiniai minimi tekste

Data on the chemical composition of Cambrian formation water were collected from industrial reports of 21 deep wells.

The well production (injection) rate was calculated:

$$Q = \frac{2 \cdot \pi \cdot k \cdot m \cdot \Delta P}{\mu \cdot \left[\ln \left(\frac{r_e}{r_w} \right) - \frac{1}{2} + S \right]}, \quad (3)$$

here Q is the production (injection) rate (m^3/s), k is the permeability (m^2), m is the effective thickness (m), ΔP is the depression (assumed $4\,000\,000 \text{ Pa}$), μ is water viscosity which depends on temperature and salinity ($\text{Pa}\cdot\text{s}$), r_w is the well diameter (assumed 0.123 m), r_e is the well drainage diameter (assumed 400 m), S is the *Skin* effect (assumed as $+5$).

The heat potential of a well was assessed:

$$Q_{th} = c \times Q \times \rho \times (t_1 - t_2), \quad (4)$$

here Q_{th} is the heat potential (GJ), c is the specific heat of the water ($\text{J}/\text{kg} \times \text{K}$), Q is water volume (m^3), ρ is water density (kg/m^3), t_1 and t_2 (assumed $10 \text{ }^\circ\text{C}$) are temperatures of produced and treated water ($^\circ\text{C}$).

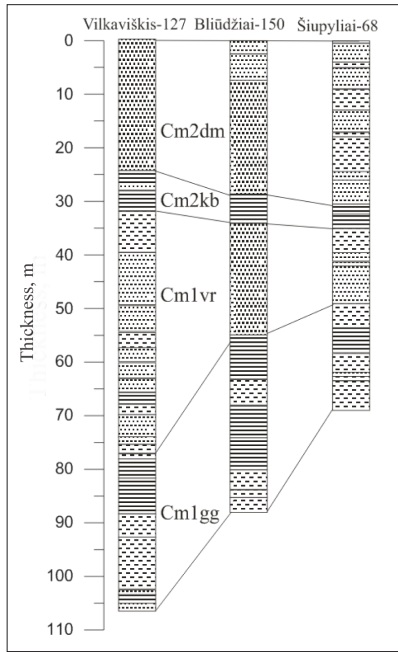
RESULTS

Temperatures of Cambrian geothermal aquifer

The temperatures of the Cambrian geothermal aquifer are rather varying in Middle Lithuania from about $35\text{--}40 \text{ }^\circ\text{C}$ in the eastern part to $50\text{--}78 \text{ }^\circ\text{C}$ in the west (Fig. 3). In particular, temperatures were measured close to the major towns such as Vilkauskis ($43 \text{ }^\circ\text{C}$), Šakiai ($40\text{--}45 \text{ }^\circ\text{C}$), Jurbarkas ($52 \text{ }^\circ\text{C}$), Raseiniai ($40\text{--}45 \text{ }^\circ\text{C}$), Kėdainiai ($45 \text{ }^\circ\text{C}$), Kelmė ($50 \text{ }^\circ\text{C}$), Radviliškis ($50 \text{ }^\circ\text{C}$), Šiauliai ($\sim 44 \text{ }^\circ\text{C}$), Joniškis ($40 \text{ }^\circ\text{C}$). They are sufficient for the operation of geothermal district heating stations. Higher temperatures ($64\text{--}78 \text{ }^\circ\text{C}$) were defined in the north-western part of the area. No geothermal data are available close to the largest cities Kaunas and Panevėžys. Therefore, the geothermal prospects remain unknown here.

Reservoir properties

The Cambrian reservoir is of a complex architecture in Middle Lithuania. Four formations are defined in the Lower-Middle Cambrian (Fig. 4). The Deimena RSt is represented by sandstones with subordinate shaly and silty layers. This sandy package is traced into West Lithuania and the adjacent offshore area. It is $25\text{--}30 \text{ m}$ thick in Middle Lithuania. The basal part of the Middle Cambrian is composed of dark grey shales with rare sandy interlayers. It is attributed to the Kybartai Formation and is $5\text{--}7 \text{ m}$ thick. Two distinct parts are defined in the Lower Cambrian. The upper part is assigned to the Virbalis Formation and ranges from 17 m to 50 m in thickness. It is dominated by sandstones with shaly and silty



interlayers. The abundance of the latter lithologies increases to the west, giving way to the prevailing siltstones with shales in West Lithuania. The lower portion of the Lower Cambrian is represented by siltstones and shales with rare sandstones.

Due to lithological variations, the effective thickness of the Cambrian reservoir varies in Middle Lithuania. The largest thickness (40–58 m) was defined in the southern part and only 15–19 m in the north (Fig. 5). Considerable local variations were also defined between closely spaced wells; they are caused by lithological variations.

The average porosity of Cambrian sandstones also increases (Fig. 6) from 13–14% in the north (Šiauliai area)

Fig. 4. Cambrian lithology of three representative wells (Vilkaviškis-127, south Middle Lithuania, Bliūdžiai-50, central Middle Lithuania, Šiupyliai-68, north Middle Lithuania)

4 pav. Vidurio Lietuvos kambro litologija Vilkaviškio-127, Bliūdžių-150, Šiupylių-68 gręžiniuose

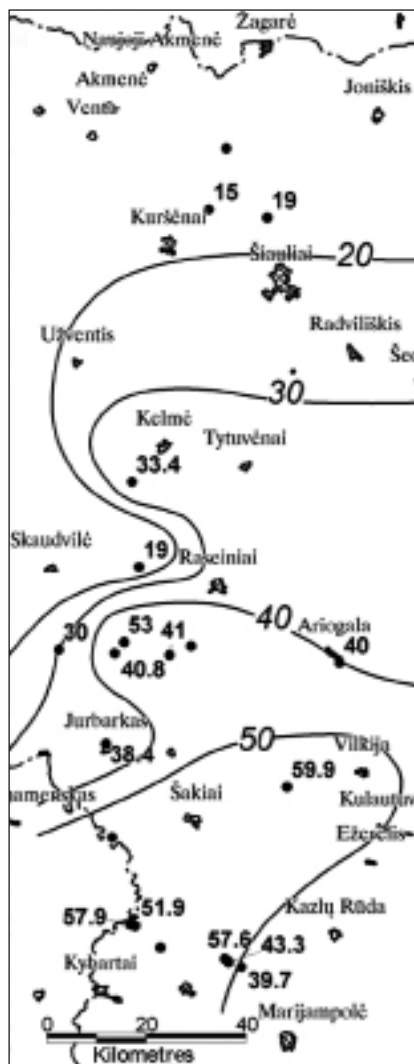


Fig. 5. Effective thickness (m) of Cambrian reservoir
5 pav. Vidurio Lietuvos kambro kolektoriaus efektyvūs storiai m

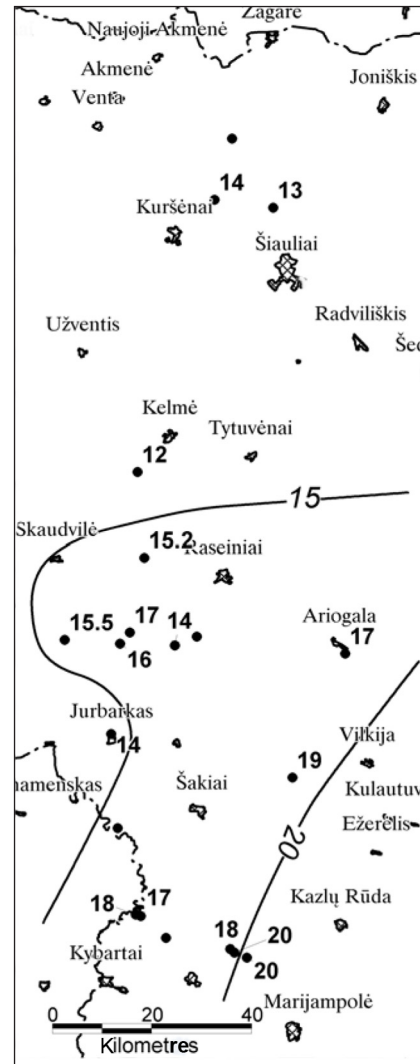


Fig. 6. Average porosity (%) of Cambrian sandstones in wells
6 pav. Vidurio Lietuvos kambro smiltainių poringumas %

to 20% in the south (Marijampolė area). In Central Lithuania, the average values are of the order of 15–17%. The main reservoir bodies are distributed in the upper and middle parts of the Cambrian section (Fig. 7). Locally, the lower part of the Cambrian succession is also represented by a sandstone layer showing good reservoir properties (e. g., the Vilkaviškis-135 well). The porosity variations of sandstones are rather minor because of the minor quartz cementation (several per cents) of sandstones, while quartz cementation is the main factor controlling the dramatic changes in porosity in West Lithuania (Šliaupa et al., 2004). Dolomite cement influences the reservoir properties of sandstones to a minor degree.

Porosity closely correlates with permeability (Fig. 8). The average permeability of sandstones of 10% porosity is about 25 mD and increases to 600–700 mD in sandstones of 22% porosity. The average permeability of Middle Lithuanian sandstones is 370 mD. The ratio of vertical to horizontal permeability ranges within 0.75–1.0, mainly around 0.95.

Productivity of geothermal well doublets

There are different ways of evaluating the geothermal potential of particular regions (e. g., Lavigne, 1978; Muffler, Cataldi, 1978; Hurter, Haenel, 2000; Hajto, Gorecki, 2005). The geothermal potential of Middle Lithuania was assessed by calculating the heat potential of a geothermal well doublet. This approach is more suitable for the practical application of geothermal energy, and this kind of maps is easier comprehended by potential stakeholders.

Based on the defined reservoir properties of the Cambrian reservoir, the potential of well doublets was calculated (Equation 3). The injection rate was assumed to be the main

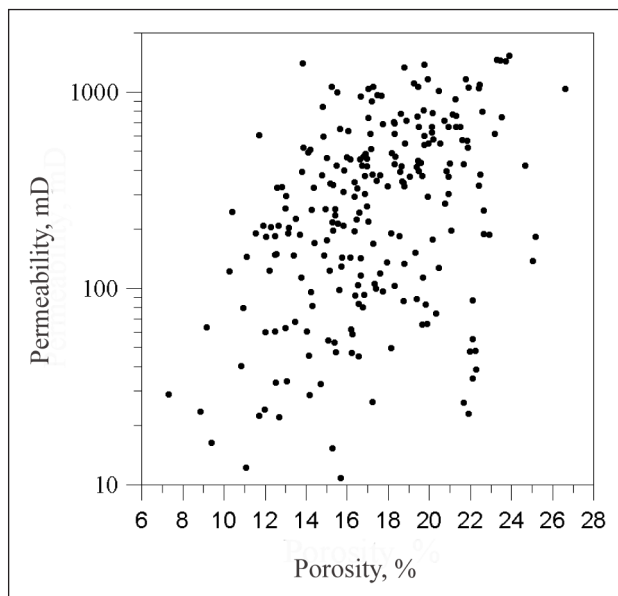


Fig. 8. Porosity vs permeability of Cambrian sandstones in Middle Lithuania
8 pav. Kambro smiltainių poringumo ir skvarbumo palyginimas Vidurio Lietuvoje

parameter for the well doublet potential, as the injectivity is lower than the productivity due to a higher viscosity of cold water. The diameter of geothermal wells was assumed to be 9 5/8". The distance between the doublet wells was 800 m. The temperature of the injected water was accepted to be 11 °C.

Two distinct regions are clear in terms of the well doublet productivity (Figs. 9, 10). The production rate was calculated in the range 22–53 m³/h in the northern and central parts of

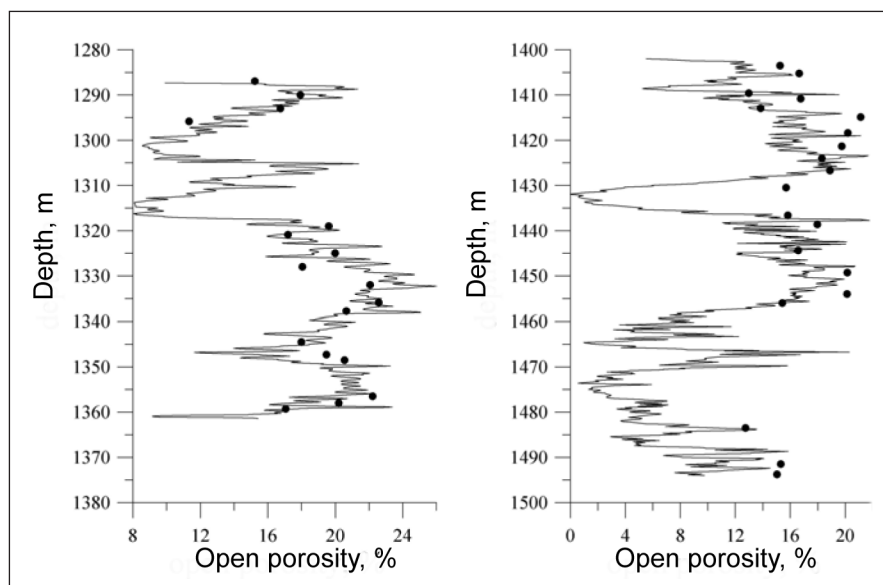


Fig. 7. Porosity of Cambrian reservoir based on logging data (lines) and measurements of rock samples (dots). Vilkaviškis-135 (left) and Bliūdžiai-150 (right) wells

7 pav. Kambro kolektorius poringumas pagal diagramijos duomenis (linija) ir išmatuotas bandinių reikšmes (taškai)

Middle Lithuania. It sharply increased south of Raseiniai (to 70–168 m³/h). This boundary is related mainly to a sharp change in the effective thickness of the Cambrian reservoir which, in turn, is controlled by a change in the shale-siltstone / sandstone ratio. It should be noted that this transition zone is confined to the largest Šilutė–Polotsk tectonic zone crossing the Lithuanian territory from the west to the east. Dramatic local variations were defined in the southern area. It is considered as one of the major exploration risks in siting the geothermal station. For instance, three wells were drilled northeast of the Vilkaviškis town. The injection potential was calculated to be respectively 65, 92 and 168 m³/h. Similarly, two wells drilled close to Kudirkos Naumiestis are evaluated as 56 m³/h and 125 m³/h.

The geothermal potential was calculated using Equation 4. The geothermal potential of the well doublet varied from 0.44 MWh to 1.37 MWh in the northern area and ranged from 1.69 MWh to 6.02 MWh in the south.

Alternatively, another approach can be used. Geothermal resources in an area can be calculated using the following equation (Jichu et al., 2005):

$$Q_r = KHC_r(t_r - t_0), \tag{5}$$

here Q_r is the total geothermal resource that can be harnessed in the area (J/m²), K is the harness coefficient or the fraction of the total geothermal resource that can be extracted, H is the average thickness of the geothermal reservoir (m); C_r is the average volumetric specific heat capacity of the geothermal reservoir (J/m³ °C); t_r is the average temperature of the geothermal reservoir (°C); t_0 is the average atmospheric temperature above the geothermal field (°C).

Based on the analysis of the rock features in the geothermal field, the geothermal harness coefficient of $K=0.2$ is postulated. The average volumetric specific heat capacity was estimated:

$$C_r = \rho_c C_c (1 - \Phi) + \rho_w C_w \Phi, \tag{6}$$

here ρ_c and ρ_w represent the specific density of the reservoir rock and the thermal water, respectively (kg/m³), C_c and C_w represent the specific heat capacity of the reservoir rock and

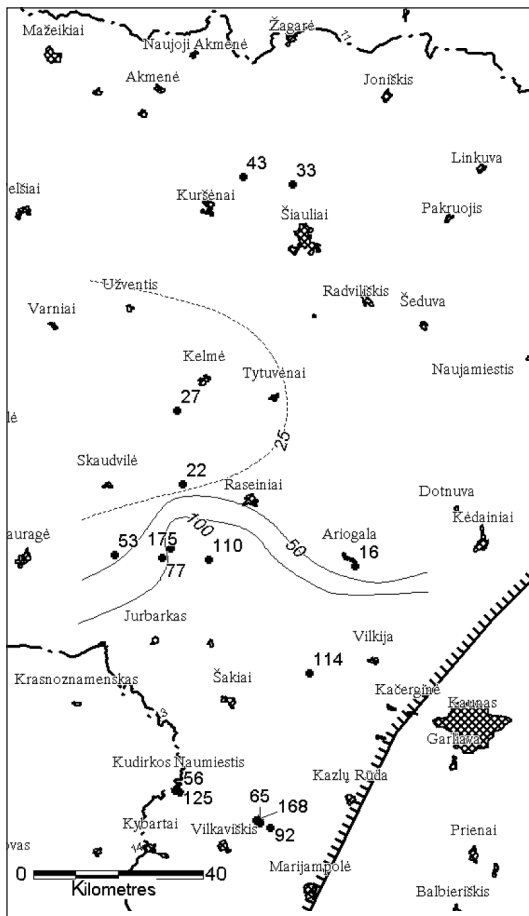


Fig. 9. Productivity (m³/h) of geothermal well doublet (40 bar well head pressure) in Middle Lithuania
 9 pav. Vidurio Lietuvos kambro geoterminio dublento (40 bar slėgis) produktyvumas

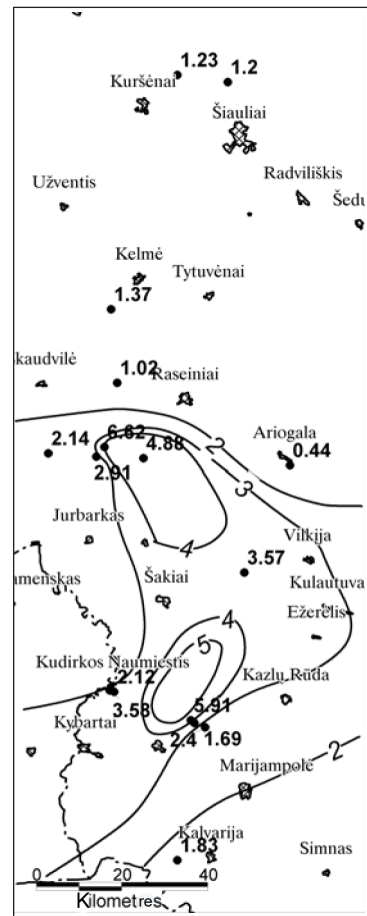


Fig. 10. Heat potential of geothermal well doublet in Middle Lithuania
 10 pav. Vidurio Lietuvos kambro geoterminių gręžinių dublento šilumos energijos potencialas

the thermal water, respectively ($\text{J}/\text{kg}^\circ\text{C}$), and Φ represents the average porosity of the reservoir rock.

The total resources of the Cambrian aquifer that can be harnessed in a unit area range from $0.4\text{--}0.8 \text{ GJ}/\text{m}^2$ in the north to $1.0\text{--}1.3 \text{ GJ}/\text{m}^2$ in the southern part of Middle Lithuania (Fig. 11). This energy parameter was transformed to the oil equivalent for comparison (Fig. 12). The values ranged from $28\text{--}29 \text{ kg}/\text{m}^2$ of oil equivalent in the south to $10\text{--}14 \text{ kg}/\text{m}^2$ in the north.

Cambrian formation water chemistry

The chemical composition of geothermal water is an important factor that should be taken into consideration when planning the exploitation systems. Depending on water chemical composition, it may affect the installations by corrosion and scaling, or reservoir clogging (e. g., Wagner et al.,

2005). The main reasons for water chemistry disequilibria are temperature and pressure variations from production to injection wells.

The salinity of the Cambrian formation water of Middle Lithuania ranges from $98 \text{ g}/\text{l}$ to $128 \text{ g}/\text{l}$. In general, the salinity increases to the west (Fig. 13). Water here is of NaCl type (Fig. 14). The content of Cl varies from 56 to $80 \text{ g}/\text{l}$, the concentration of Na is in the range $15\text{--}39 \text{ g}/\text{l}$. The content of Na and Cl increases with increasing salinity. SO_4 does not show any discernible trend, and its content is about $2\text{--}3 \text{ g}/\text{l}$ in the water. The content of HCO_3 varies from 0.06 to $0.18 \text{ g}/\text{l}$. Ca, K and Mg cations increase in concentration with increasing water salinity. Their concentrations are, respectively, $3\text{--}6 \text{ g}/\text{l}$, $0.25\text{--}0.45 \text{ g}/\text{l}$, and $1\text{--}3 \text{ g}/\text{l}$, silica content being $4\text{--}12 \text{ mg}/\text{l}$. The concentrations of iodine and bromide are low ($0.3\text{--}1.1 \text{ mg}/\text{l}$ and $190\text{--}310 \text{ mg}/\text{l}$, respectively).

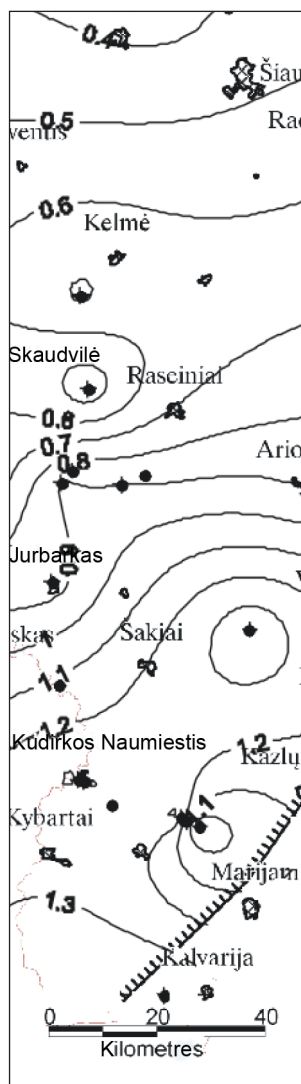


Fig. 11. Geothermal resources of Cambrian aquifer that can be harnessed in a unit area (GJ/m^2) of Middle Lithuania. Hatched line indicates 35°C isotherm

11 pav. Kambro vandeningo sluoksnio geoterminiai išteklių (GJ/m^2) Vidurio Lietuvoje. Pažymėta 35°C izoterma

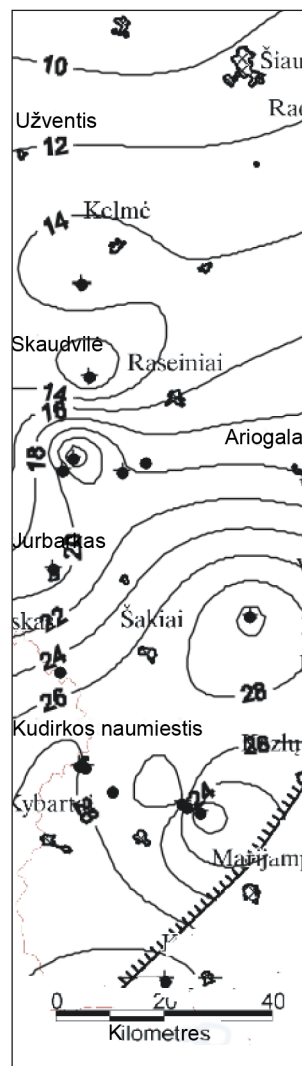


Fig. 12. Geothermal resources of Cambrian aquifer that can be harnessed in a unit area (oil equivalent, kg/m^2) of Middle Lithuania. Hatched line indicates 35°C isotherm

12 pav. Kambro vandeningo sluoksnio geoterminiai išteklių (naftos ekvivalentas kg/m^2) Vidurio Lietuvoje. Pažymėta 35°C izoterma

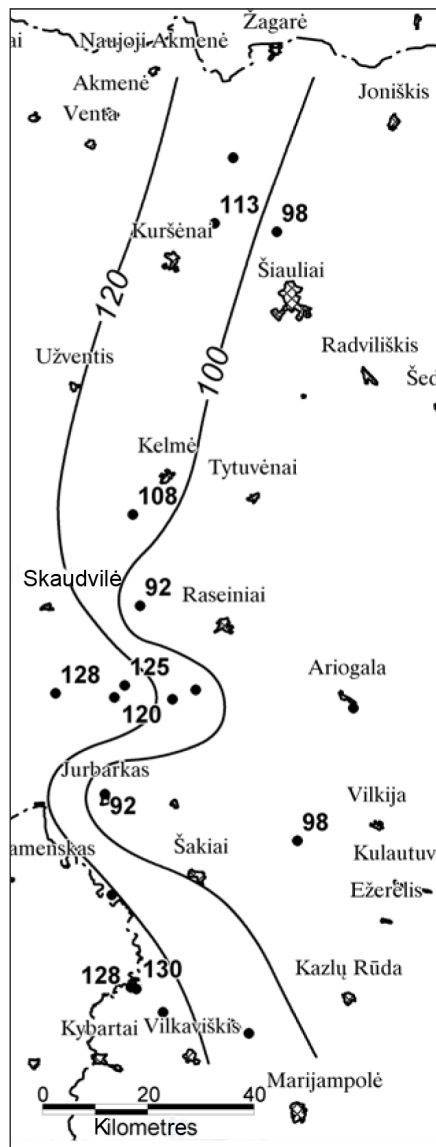


Fig. 13. Salinity (g/l) of Cambrian formation water
13 pav. Vidurio Lietuvos kambro vandens mineralizacija (g/l)

Based on water analyses, the thermochemical modelling of rock composition and the mineral phases that are in equilibrium with water was carried out. The following mineral phases were considered:

- sulphates (gypsum, anhydrite)
- carbonates (calcite, aragonite, dolomite)
- SiO_2 phases (amorphous, chalcedony)
- iron hydroxides (goethite, amorphous $\text{Fe}(\text{OH})_3$).

The modelling was performed using the PHREEQC programme. The saturation indices (SI) were calculated for individual mineral phases and temperatures (Table 1). $\text{SI} > 0$ indicates that the fluid is supersaturated for the mineral phase concerned, thus, the respective mineral precipitates as indicated by the trend that the higher SI, the higher is the saturation. In case $\text{SI} = 0$, the fluid and the mineral phase are in equilibrium, while $\text{SI} < 0$ indicates that the fluid is undersaturated with regard to the relevant mineral phase, so that the corresponding mineral is dissolved.

Two wells were selected for modelling. The Kužiai-65 well is located in the north close to the Šiauliai town; its water salinity is 98 g/l. The Pilviškiai-140 well is situated in the south close to the Vilkaviškis town; its water salinity is as high as 130 g/l.

For the Pilviškiai-140 well, it is shown that gypsum is slightly supersaturated or in equilibrium with the geothermal water at 40 °C, which corresponds approximately to the aquifer temperature (Table 1, Fig. 15). When water cools down to 10 °C, what corresponds approximately to the cooling of the fluid in the surface part of the geothermal station, the saturation indices change. The supersaturation of gypsum increases. After reinjection into the aquifer, the temperatures increase again, however, never achieving the original aquifer temperatures, so that gypsum is supersaturated here. Some silica precipitation may occur in the surface systems. Also, pyrite can be formed in case of bacterial activity. All the rest mineral phases are under saturated in the geothermal water loop.

Table 1. Saturation index vs temperature of different mineral phases (PHREEQC modelling) of Cambrian formation water, Pilviškiai-140 well (close to Vilkaviškis town) and Kužiai-65 well (close to Šiauliai town)

1 lentelė. Skirtingų mineralinių fazių prisotinimo indeksas (PHREEQC modeliavimas), kambro vandeningas sluoksnis, Pilviškių-140 ir Kužių-65 gręžiniai

Minerals	Pilviškiai-140 well				Kužiai-65 well			
	10 °C	20 °C	30 °C	40 °C	10 °C	20 °C	30 °C	40 °C
Anhydrite	0.05	0.01	0.01	0.03	-0.21	-0.25	-0.26	-0.24
Gypsum	0.25	0.19	0.15	0.11	-0.01	-0.07	-0.11	-0.15
Aragonite	-1.15	-1.18	-1.19	-1.19	0.3	0.29	0.29	0.31
Calcite	-0.99	-1.03	-1.05	-1.06	0.46	0.43	0.43	0.44
Dolomite	-2.17	-2.09	-2.01	-1.95	0.74	0.85	0.96	1.06
Chalcedony	0.15	0.03	-0.09	-0.2	0.11	-0.01	-0.13	-0.24
$\text{SiO}_2(\text{a})$	-0.74	-0.83	-0.91	-0.99	-0.78	-0.87	-0.95	-1.03
Pyrite	12.11	11.62	11.15	10.71	12.65	12.12	11.61	11.12
Goethite	-0.78	-0.64	-0.49	-0.32	0.3	0.45	0.62	0.8
$\text{Fe}(\text{OH})_3(\text{a})$	-6.14	-6.38	-6.58	-6.75	-5.05	-5.28	-5.47	-5.62

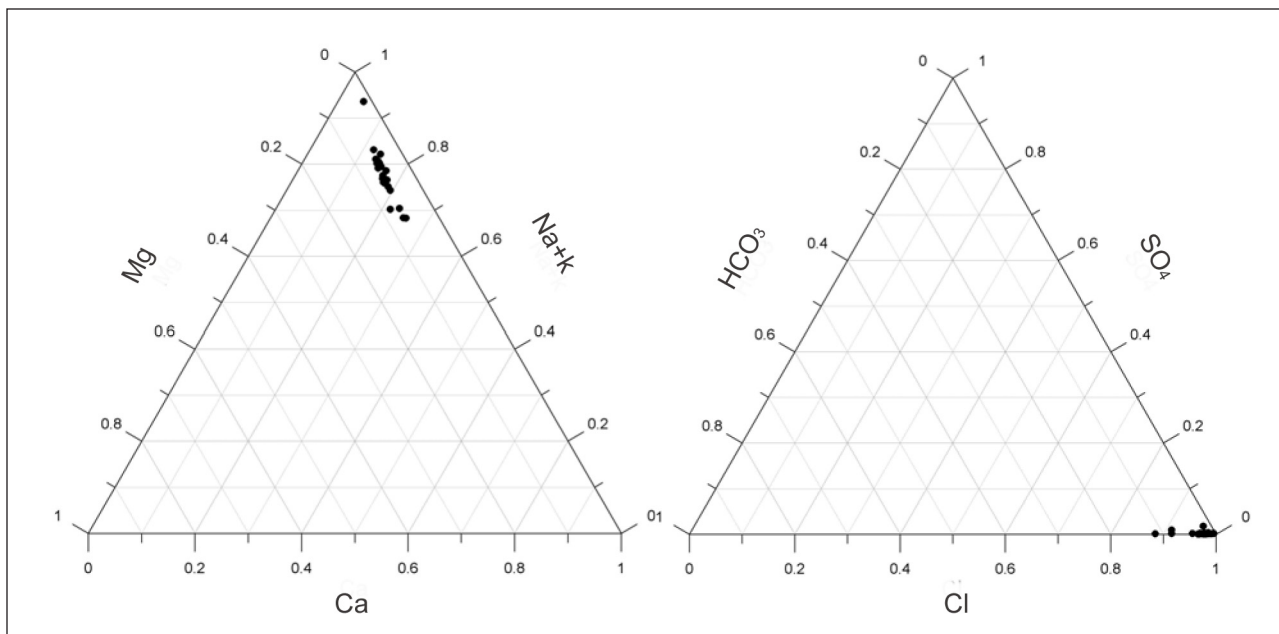


Fig. 14. Plots of chemical composition of Cambrian formation water in Middle Lithuania
 14 pav. Vidurio Lietuvos kambro vandens cheminė sudėtis

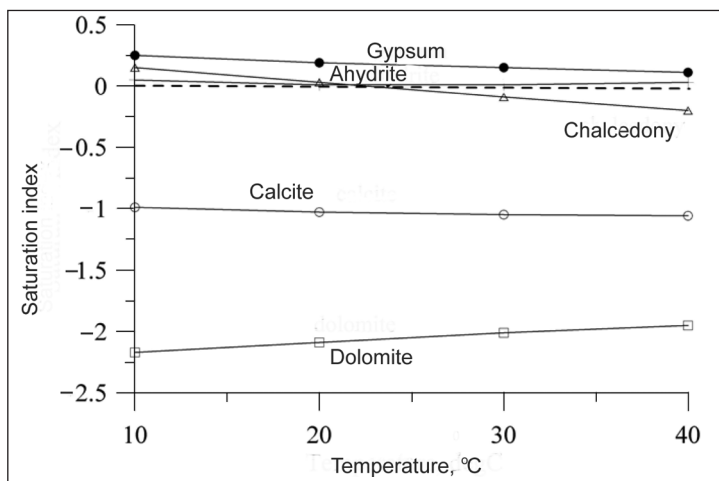


Fig. 15. Temperature vs saturation index of different mineral phases of Cambrian formation water, Pilviškiai-140 well (PHREEQC modelling)

15 pav. Kambro vandens įvairių mineralinių fazių temperatūros ir prisotinimo indekso palyginimas (Pilviškių-140 gręžinys, PHREEQC modeliavimas)

Carbonates and hydroxides are supersaturated mineral phases in less saline water (Kužiai-65 well) (Fig. 16); this fact has to be taken into consideration when planning the exploitation of geothermal wells.

DISCUSSION

The utilisation of geothermal aquifers depends primarily on two basic parameters: geothermal resources and availability of potential customers. Middle Lithuania is densely populated. Central district heating dominates the heat sup-

ply market in the towns; therefore, the application of hydrothermal resources is to be considered a favourable technology.

The needs for heat supply were derived from the annual report (Heat Supply Association of Lithuania, 2011). The minimum consumption of heat energy during the winter season ranges from less than 1 to 9 MWh in Middle Lithuanian towns (Šiauliai town requires 27 MWh) (Table 2). It should be noted that the temperatures of the Cambrian reservoir are too low for direct central heat supply, and additional heating is required. For the temperature range of

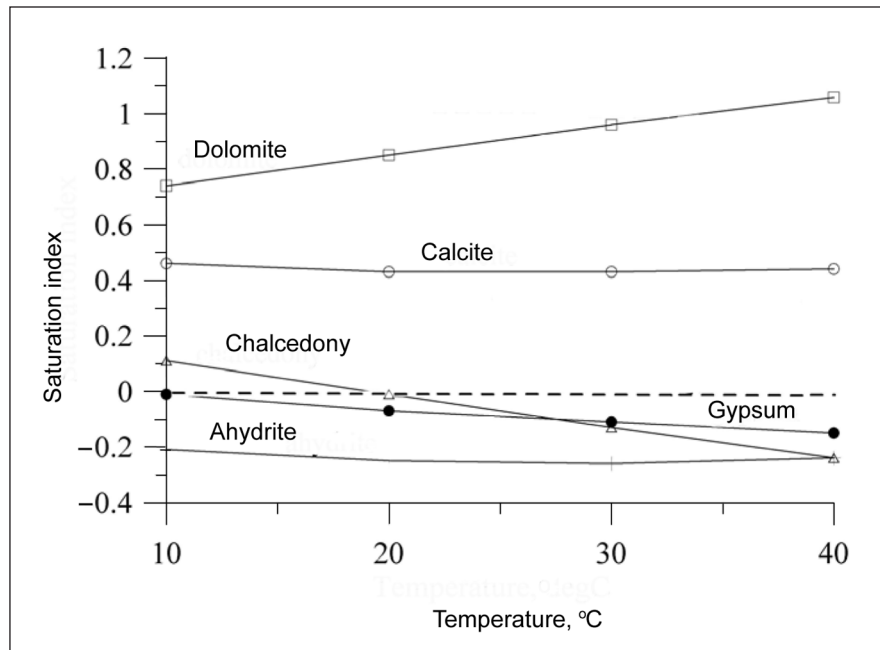


Fig. 16. Temperature vs saturation index of different mineral phases of Cambrian formation water, Kužiai-65 well (PHREEQC modelling)

16 pav. Kambro vandens įvairių mineralinių fazių temperatūros ir prisotinimo indekso palyginimas (Kužiai-65 gręžinys, PHREEQC modeliavimas)

35–60 °C, the application of absorption heat pumps is an efficient technology (applied in the Klaipėda geothermal station). The additional heating (natural or bio-gas) doubles the capacity of a geothermal station, taken into consideration when planning the number of wells for the exploitation of geothermal heat. The heat production rates of well doublets range from 0.44 to 6.02 MWh, i. e. in the same order as that required for the district heating. Accordingly,

the required well doublets are assessed to be one to two in number, in some cases three should be required (Table 2). It shows a high potential of the application of geothermal energy in Middle Lithuania.

There are important advantages of the application of geothermal energy in Middle Lithuania as compared with West Lithuania. The Cambrian reservoir is of much better properties in Middle Lithuania than in the west. Further-

Table 2. Comparison of thermal energy consumption (central heating) of selected towns of Middle Lithuania and well heat production capacity

2 lentelė. Vidurio Lietuvos šiluminės energijos poreikio (centrinis šildymas) ir gręžinių šiluminės energijos potencialo palyginimas

Town	Population	MWh consumption, winter		Capacity of doublet, MWh	Optimum number of doublets
		Max	Min		
Šiauliai	125 461	186	27	1.2	13
Marijampolė	46 261	62	9	2.4	2–3
Radviliškis	19 189	24	4	1.2	2–3
Kalvarija	13 607	10	4	1.83	2–3
Kuršėnai	13 372	12	2	1.23	1–2
Vilkaviškis	12 764	12	5	1.69–5.91	1–2
Raseiniai	12 541	16	3	1.02	1–2
Jurbarkas	12 510	16	3	2.91	1–2
Kelmė	9 967	8	4	1.37	1–2
Kazlų Rūda	6 950	7	2	2.4	1
Šakiai	6 377	3	1	3.57	1
Ariogala	3 332	4	1	0.44	1
Tytuvėnai	2 614	4	2	1.37	2
Ežerėlis	1 959	3	1	3.57	1
Viduklė	1 911	1	–	1.02	1
Kudirkos Naumiestis	1 911	2	1	2.12–3.58	1
Skaidvilė	1 884	2	–	2.14	1
Kulautuva	1 367	2	1	3.57	1
Užventis	811	1	1	1.37	1

more, the architecture of this reservoir is more favourable than that of the Lower Devonian (Kemeris) aquifer which is the main geothermal aquifer considered in West Lithuania. The reservoir part of the Cambrian succession contains a miserable amount of shaly layers; sandstones here are more compacted and have almost no clay admixture which prevents mobilisation of solids.

CONCLUSIONS

The geothermal potential of Middle Lithuania is related to the Cambrian sandstone reservoir which is hot enough for central heat supply. The second largest Pärnu–Kemeris (Devonian) geothermal aquifer has too low temperatures to be considered as a resource.

The study revealed a rather variable geothermal potential of the Cambrian reservoir of Middle Lithuania. In general, two regions which have a different geothermal potential should be considered. The northern part of Middle Lithuania, despite the generally higher temperatures of the Cambrian reservoir, is characterised by a lower geothermal potential than that of the southern part because of the lower reservoir properties (porosity and permeability) of Cambrian sandstones and the smaller effective thickness of the aquifer in the north. The major sandstone bodies are distributed in the upper (Deimena RSt) and middle (Virbalis Formation) parts of the Cambrian succession. The effective thickness of the Cambrian in Middle Lithuania ranges within 15–58 m, the average porosity of sandstones being 13–20% and permeability 370 mD.

The productivity of the geothermal well doublet is estimated to be as high as 53–175 m³/h in the southern part of the study area, while reaching only 16–43 m³/h in the north. These variations in productivity control the geothermal potential of the wells. The geothermal potential of the well doublet varies from 0.44 MWh to 1.37 MWh in the northern area and ranges from 1.69 MWh to 6.02 MWh in the south.

The Cambrian formation water is characterised by a high salinity (98–130 g/l). It is of NaCl type. The thermochemical modelling indicates that gypsum precipitation can be expected in a geothermal system using high salinity water (~130 g/l), while carbonates and hydroxides may precipitate in less saline water (~100 g/l). Accordingly, a special chemical treatment will be required to maintain the geothermal systems. Pyrite may precipitate, essentially in cases of bacterial activity.

A comparison of the geothermal potential to cover heat energy needs of Middle Lithuanian customers indicates that one or two doublet installations exploiting the Cambrian geothermal aquifer may cover the basic needs of central heating of towns (except Šiauliai). It is therefore concluded that the Cambrian geothermal aquifer is highly promising for district heating in Middle Lithuania.

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VIDURIO LIETUVOS HIDROGEOTERMINIAI IŠTEKLIAI

Santrauka

Pagrindinės hidroterminių išteklių panaudojimo perspektyvos daugiausia siejamos su Vakarų Lietuva, tuo tarpu Vidurio Lietuvos geotermis potencialas yra mažai ištirtas. Straipsnyje analizuojami kambro vandeningo sluoksnio ypatumai, svarbūs įvertinant geoterminius išteklius. Kitų geoterminių sluoksnių (devonas) perspektyvumas yra menkas dėl žemos temperatūros. Remiantis esama medžiaga, straipsnyje išsamiai analizuotos kambro uolienų kolektorinės savybės. Nustatyta, kad perspektyvūs smiltainio sluoksniai yra viršutinėje ir vidurinėje kambro stovymės dalyse. Smiltainių vidutinis poringumas gręžiniuose kinta nuo 13 iki 20 %. Vidutinis smiltainių skvarbumas Vidurio Lietuvoje yra 370 mD. Efektyvus storis kinta nuo 15 iki 58 m. Šios pakankamai aukštos reikšmės leidžia eksploatuoti geotermišką vandenį. Geotermio potencialo vertinimas yra grindžiamas vandens ir šilumos išteklių vertinimu gręžiniuose. Tokia metodika yra lengviau suprantama potencialiems geoterminei šilumai vartotojams, leidžia lengviau planuoti ir vertinti geoterminei energijai naudojimą regione. Gręžinių dubletų vandens išteklių pietinėje Vidurio Lietuvos dalyje, įvertinti 53–175 m³/h, šiaurinėje tyrimų ploto dalyje yra mažesni (16–43 m³/h). Atitinkamai skiriasi šių teritorijų geotermis potencialas: 0,44–1,37 MWh šiaurinėje dalyje ir 1,69–6,02 MWh pietinėje dalyje. Palyginimui: Vidurio Lietuvos miestų ir gyvenviečių aprūpinimui šilumos energija pakanka 1–2 geotermiškų gręžinių dubletų. Taigi geoterminei energijai panaudojimo potencialas Vidurio Lietuvoje yra didelis. Kambro vanduo yra stipriai mineralizuotas (98–130 g/l), Na-Cl tipo. Termocheminių procesų modeliavimas rodo, kad pagrindinės geotermio vandens panaudojimo komplikacijos gali būti susijusios su sulfatų išsiskyrimu atšaldžius geotermišką vandenį. Mažesnės vandens mineralizacijos atveju pagrindinė grėsmė siejama su karbonatų ir geležies hidroksido išsiskyrimu.

Raktažodžiai: geotermija, hidroterminiai išteklių, kambras, hidrochemija