Heliyon 10 (2024) e26360

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Silurian barrier reef in Lithuania: Reservoir properties and low enthalpy geothermal heat potential

Ieva Kaminskaite-Baranauskiene [a,*], Anna Cichon-Pupienis [a,b], Pijus Makauskas [c]

[a] *Vilnius University, Naugarduko st. 24, 03225, Vilnius, Lithuania*
[b] *Nature Research Centre, Akademijos st. 2, 08412, Vilnius, Lithuania*
[c] *Department of Mathematical Modelling, Kaunas University of Technology, K. Donelaicio st. 73, 44249, Kaunas, Lithuania*

ARTICLE INFO

Keywords:
Silurian carbonates
Geothermal doublets
Petrophysical characterisation
Pore types
Repurposing oil wells

ABSTRACT

The Silurian barrier reef zone in Lithuania extends for hundreds of kilometres in the narrow zone in Middle Lithuania continuing from the Saukenai reef in the north to the Vilkupiai reef in the south. After prolific Cambrian sandstone reservoirs, they are considered a secondary oil target in Lithuania. However, drilling data showed that the detected reefogenic bodies are either “dry" or saturated with water and/or viscous oil thus practically no valuable oil supply has been obtained. This study illustrates a review of the existing geological and geophysical data, acquired during oil and gas explorations since the 1960s, specifically re-analysed for geothermal purposes.

The heat production rates of well doublets within the Silurian reefs range from 0.000044 to 0.24 MWh. Within the area of the Kudirka structure, 6 well doublets could be arranged from the existing 16 exploration wells, at the average distance between the producing-injecting wells of around 700 m. Kudirka has the largest reservoir volume and hence the largest reservoir heat potential (250 GWh). At the smallest distance between the doublet wells of 486 m, the thermal breakthrough would be reached after around 30 years of production-injection. Pavasaris reef shows the best geothermal capacity of a well doublet (0.241 MWh). Reservoir properties are especially good in the partially open fracture zone interval. Pavasaris reef has got 2 wells penetrating the reef, thus one doublet could be arranged within the structure. However, the available thermal energy is limited due to hydrogeological closure and small reservoir size (11.2×10^3 MWh). Other reefs (Saukenai, Vilkupiai, North Bliudziai and a reef in the north of the Vadzgirys reef belt) are small isolated structures, thus their heat potential is low. Moreover, they show low flow rates and hence thermal energy that can be extracted at their wellheads in 30 years is well below 1×10^3 MWh. The study indicates that even though the thickness of the reefal build-ups may reach up to *c.*90 m, the effective thickness of the reservoirs rarely reaches 20 m. Analysis of the well logs and the core sections show a high heterogeneity of the structures, and hence low recovery factors of the doublets. The distribution of effective layers is usually associated with processes such as stylolitisation and secondary fracturing with enhanced dissolution. For measured low flow rates (<9 m^3/h), reusing the existing wells shows low economic viability due to the narrow diameters of the boreholes. Therefore, Silurian reefs show low potential for the application of geothermal energy in Middle Lithuania, although small geothermal projects could be achieved in the Kudirka and Pavasaris sites.

---

* Corresponding author.
E-mail address: ieva.kaminskaite-baranauskiene@chgf.vu.lt (I. Kaminskaite-Baranauskiene).

https://doi.org/10.1016/j.heliyon.2024.e26360
Received 26 September 2023; Received in revised form 8 February 2024; Accepted 12 February 2024

1. Introduction

At a time of the Energy Transition, exploration of renewable energy and heat sources are required for society, and natural resources such as geothermal energy are one of the most promising fields for research. Based on the land space and materials or fuels required for power plant building and operation, geothermal energy shows the smallest 'relative aggregate lifecycle footprint' of any energy source [1]. Lithuania shows a high potential for hydrothermal energy application due to an anomalous heat flow in the West of the country. The nature of this anomaly is explained in terms of granitoid intrusions rich in radiogenic elements such as uranium and thorium [2]. Geothermal potential of Devonian and Cambrian aquifers has been evaluated in West Lithuania (e.g. Refs. [3–5]). However, hydrothermal systems in the rest of the country were of low interest, as the heat flow and associated temperatures decrease to the east [5]. Šliaupa and Kežun [6] studied the geothermal potential of Cambrian aquifers in Middle Lithuania. The authors found that geothermal energy production of the well doublet varies between 0.44 MWh and 6.02 MWh depending on the area, with higher values estimated in the south. Middle Lithuania is characterised by Silurian reef reservoirs, which show the highest potential for oil exploration in Lithuania following the Cambrian siliciclastic sandstone reservoirs being a primary oil target in the west of the country. A number of wells drilled during Soviet times showed evidence of oil and possible reservoirs within the Silurian carbonate reefal build-ups ([7–9]). However, due to the high viscosity of oil and hence low oil flow the reservoirs have not been assessed further. The oil exploration works in the area have collected a large amount of data and it is known that the water flow obtained from the reefogenic formations of the Silurian (Pridoli) Minija regional stage reaches up to 6.5–216 m^3/day [10]. Moreover, according to well data documented and maintained by the Lithuanian Geological Survey of Lithuania, there are over 70 exploratory wells drilled through Silurian carbonate formations that are currently indicated as abandoned, plugged, buried and/or inactive. Therefore, a large amount of data, existing infrastructure and never-utilized reservoirs could potentially be used as natural resources for heat energy extraction. The objective of this paper is therefore to investigate the prospect of using abandoned wells reaching Silurian reefs for harvesting low enthalpy geothermal energy. Collected data from the wells provide valuable subsurface information such as lithology, formation porosity and formation water chemistry and temperature. Therefore, 6 reef structures were evaluated in Middle Lithuania, including the productivity of the reservoirs and the geothermal potential of the structures.

Most common petroleum carbonate reservoirs worldwide are reefs, shelf and deep-water carbonates, which are especially productive within fractured fault zones (e.g. Refs. [11–13]). However, carbonate reservoirs are considered somehow less suitable for sustainable energy and subsurface storage projects. This is mainly due to their complex heterogeneity caused by the nature of carbonate sedimentation and chemical reactivity, which subjects them to various pore-destructive hydrothermal deformation processes. However, often, tectonic deformations and the accompanying hydrothermal activities such as dissolution, dolomitization, recrystallization, silicification and Thermochemical Sulfate Reduction (TSR) create productive carbonate reservoirs (e.g. Refs. [14–21]). Deep-burial dolomitization and fracture-controlled dissolution can convert low matrix porosity and permeability rock into a productive reservoir. Therefore, preferential targets for geothermal exploitation in carbonate rocks are fault zones, reef facies that are prone to dolomitization and karstified areas because they are likely to act as conduits to fluid flow (e.g. Refs. [22,23]). Different pore types were analysed affecting the fluid flow within the Silurian reefal units, and hence the most productive rock types were determined. Moreover, a geophysical-geological model was created for the largest Kudirka reef to analyse the reservoir heterogeneity and distribution of lithofacies within the structure.

The biggest costs associated with geothermal resource exploration is the drilling of geothermal wells. Conversion of oil and gas wells to geothermal wells may lower these costs by a substantial amount suddenly making the geothermal projects more financially attractive. Many studies have been performed modelling heat transfer in abandoned hydrocarbon wells, estimating the potential of heat production, and performing sensitivity analysis for optimal conditions of operating the geothermal wells (e.g. Refs. [24–28]). Most of them focus on open-loop systems that have at least one injection and one production well. A fluid is injected into a reservoir through an injection well, where it moves through the rock pores and heats up through the interaction with the hot rock surface and then carries that heated water to the production well. Therefore, geothermal potential was calculated for the doublet systems within the mentioned reef structures. Geothermal models were run to show temperature distribution after a period of injection-production of geothermal fluid between the doublet wells to determine the lifetime of the doublets before the thermal breakthrough takes place. Available water volumes were calculated to determine the thermal capacity limit within the structures. Possible projects for heat utilisation were suggested.

2. Geological and structural setting

During Silurian, the basin was located at the border of the Baltica paleocontinent, which was situated in the Southern Hemisphere within the tropical climate belt, drifting northward and reaching the equator during Silurian [29]. From the late Ordovician through Silurian the main collision between Baltica with Eastern Avalonia and Laurentia occurred causing foreland bending of the western margin of the Baltica or East European Craton, and consequently generating accelerating subsidence and deepening of the basin [30, 31]. The maximum subsidence rate occurred in the late Silurian times which was compensated by the sedimentary load [32]. On the other hand, the late Silurian was characterised by a general sea regression trend and basin infill [31]. The collision of Baltica and Laurentia led to the important phase of basin structural development during the latest Silurian - earliest Devonian namely NW–SE--directed horizontal compression as a result of which two main fault systems were formed, oriented WSW-ENE and SSW-NNE [32]. Silurian sedimentary rocks are deposited across the whole Lithuania, except the south part of the country, where they were eroded during the Carboniferous-early Permian times due to regional uplift events ([30]; Fig. 1).

The structural-tectonic and lithofacial zonation of Silurian divides the Lithuanian territory into three zones, i.e. Baltic Syneclise encompassing Western Lithuania, the Belarusian–Mazurian Anteclise that includes Eastern Lithuania and a transition zone between West and East Lithuania. In the Baltic Syneclise, the Silurian system is dominated by clayey facies, while to a lesser extent by carbonate ones, and the thickness of Silurian sediments may reach over 800 m onland ([37]; Fig. 2). In Eastern Lithuania within Silurian succession carbonate facies are widespread with thickness varying between 50 and 250 m [37]. There is an observed gradual replacement of lithofacies from clayey facies in the west of Lithuania representing marine deep shelf environment to shallow water carbonate, clayey lagoonal and supratidal facies to the east [9]. Moreover, there is also a general progressive lithofacial change upward the Silurian succession from more clayed sediments in the lower part to more carbonate content-rich facies in the upper part, along with a gradual westward shift of the latter. On the basin scale, the Silurian facies belt runs almost parallel to the strike of the basin slope. The transition zone developed between the two aforementioned facies zones and is situated on the eastern slope of the Baltic Syneclise creating favourable conditions for the growth of reef structures in the late Silurian [10]. There is a hypothesis that the distribution and growth of reefal build-ups may be possibly related to paleoflexure zones within the Silurian section [10]. In line with the Silurian facies belt distribution, the reef belt in Lithuania stretches from south to north. In the study area, which is situated within this transition zone, the Silurian sediments are around 400–550 m in thickness [37]. The tectonic evolution of the basin is well demonstrated in the thickness pattern of Silurian sediments that show an increase to the west, and deepening of the top of the Silurian complex to the west within the Lithuanian territory (Fig. 2).

The lithofacial distribution and presence of reefs within the Silurian succession in the Baltic basin led many researchers to the conclusion that the Silurian Baltic basin represents a platform depositional system [41–43]. Although there are different opinions, suggesting that the Pridoli carbonate system shows more characteristics of a ramp rather than a platform, and the central stromatoporoidal facies belt was likely stromatoporoidal biostromes instead of classic reefs [44].

2.1. Silurian reefs

In Lithuania, after the Cambrian sandstone reservoirs as a primary oil target, the Silurian carbonate reefal build-ups and patch reefs of Pridoli Minija regional stage are the most prospective for oil exploration (Fig. 1). Extensive exploration works confirmed the existence of the reefs within the Silurian succession and the presence of oil in them [10]. Gotland (Sweden) and Saaremaa (Estonia) have been major research areas in Europe for Silurian reef-like carbonates as the structures are outcropping at the surface (e.g. Refs. [45,46]). It was determined that the height of the reefs in Gotland varies from 0.5 to 35 m and the width is in a range of 50–150 m (e.g. Refs. [47,48]). Flodén et al. [49], while investigating reefs on the island of Gotland and around the Baltic Sea, observed a distinct facies zonality within reef units, i.e. lagoon, reef barrier, biohermal slope and basin environment, and concluded that such pattern of reef units is probably common to all reefs within the Silurian Baltic basin. It was also observed that younger reefs are consistently displaced seaward, which was interpreted as a consequence of an overall regressive development and the infilling of the basin [49]. However, minor sea-level fluctuations also controlled reef development in nearshore shallow shelf environments [46]. The Pridoli reef belt stretches for hundreds of kilometres from the Saukenai reef in the north to the Vilkupiai reef in the south, covering a narrow zone of a few kilometres in central Lithuania (Fig. 3). In contrast to the general regressive basin evolution mentioned above, the early Pridoli reef units in Lithuania are interpreted as transgressive succession (Fig. 1). Michelevicius et al. [50] suggested, based on the stratigraphic position, lateral distribution of the reefs and seismic attribute maps, that a chain of reefal build-ups of Vadzgirys barrier reef in the

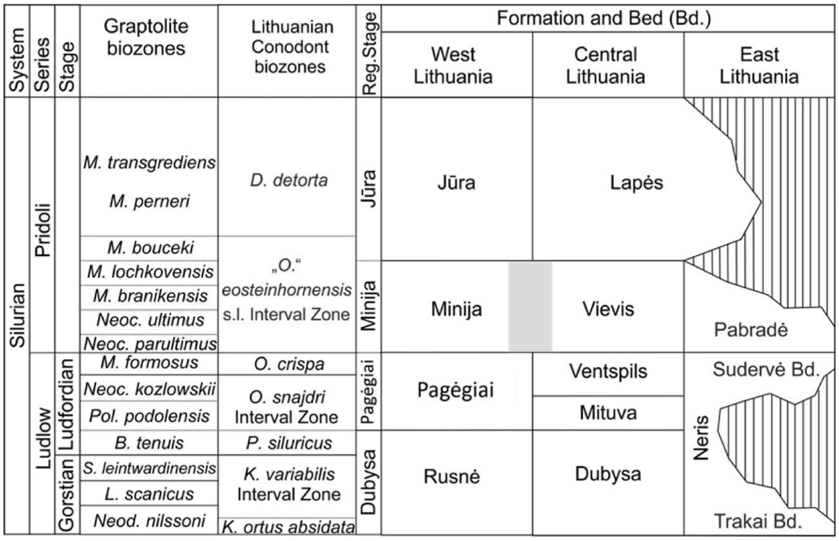

Fig. 1. Ludlow and Pridoli (Silurian) stratigraphic scale with graptolite [33] and conodont [34–36] biozones, Baltic regional stages and formations (after [37,38,39]). Investigated interval is in grey colour.

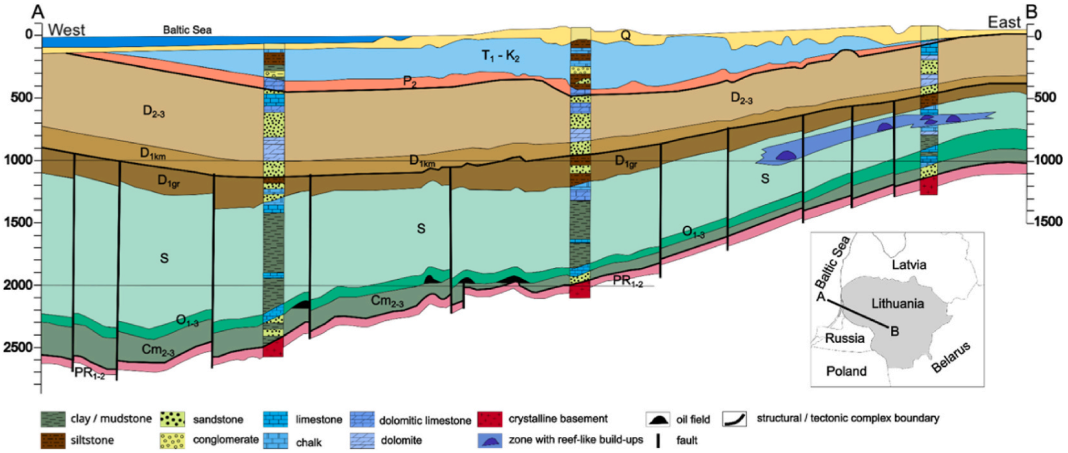

Fig. 2. Generalized geological cross-section throughout Lithuanian territory (A-B profile as marked on the Lithuanian map in the lower right corner) with reefogenic deposits in Central Lithuania (modified after [40]).

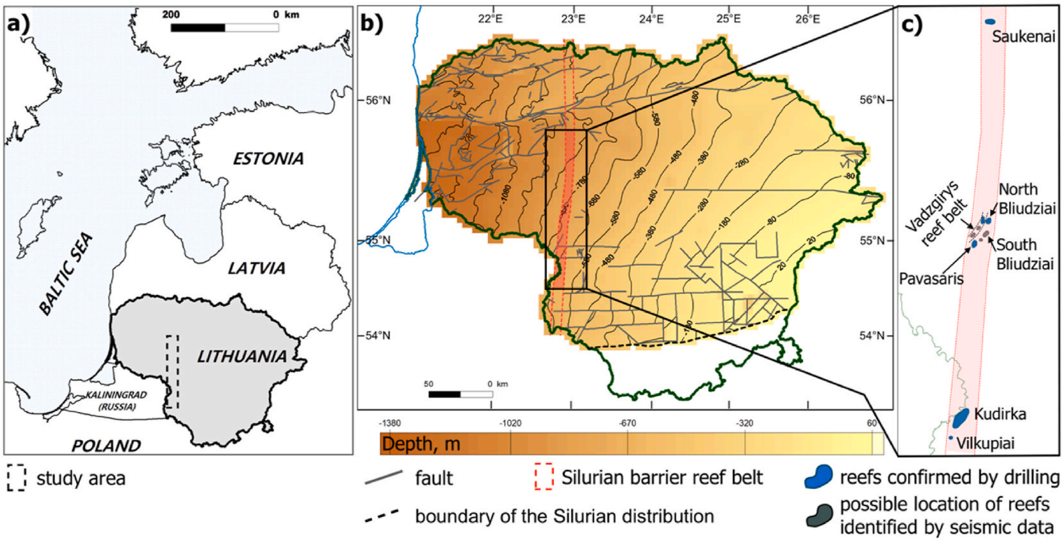

Fig. 3. Study area marked on the a) Baltic region map; b) structural map of the top of the Silurian; and c) a zoomed in map illustrating separate Silurian barrier reef structures (after [50,51]).

western part of the belt was formed earlier (during early Minija regional stage) than the group of the separated reefs (North, South Bliudziai, and Pavasaris reefs), which migrated laterally eastward, thus projected landward, and are placed higher within the Minija regional stage. Such a pattern of the belt evolution was linked to the transgression cycle [50].

Fore-reef, back-reef, interior lagoonal and reef-crest facies have been observed within the reef structures in Lithuania [52]. Oil has mostly accumulated within the reef crest biosparitic and biolithic carbonate rock types and uppermost fore- and back-reef facies. Oil accumulation was discovered in the Kudirka and North Bliudziai reefs, but many signs of oil were also found in the cores of Saukenai, Vadzgirys, Bebirva, Bliudziai, Pavasaris and Vilkupiai reefal structures and surrounding rocks. This indicates intensive oil migration through the Silurian sequence. However, oil manifestations are irregular, the oil intervals are thin and local. Drilling data showed that due to their hydrogeological closure, heterogeneous deposition, recrystallization and dolomitization, the detected reefogenic bodies are either “dry" or saturated with water and/or viscous oil [10]. In the Baltic Syneclise area there is a trend of increasing oil density and viscosity with decreasing depth of oil accumulations, thus Silurian oil is heavier (~0.85–0.908 g/cm^3) in comparison to the Cambrian oil (mostly below 0.840 g/cm^3 [53]). Therefore, the oil has never been produced from the Silurian reefal structures because practically no valuable oil supply has been obtained. The most promising oil quantities, but still not economically valuable, were obtained during formation and production tests in the Kudirka reef performed in the 80s. The oil yield reached 3.4 m^3/day and after stimulation treatment including heating of the beds, the inflow of oil with partial formation water increased to 7.3 m^3/day. However, during the tests gradual decrease of oil inflow and an increase in the water flooding were observed. In recent years, several works, including thermal treatment, were performed which attempted once again to evaluate the potential of reefogenic formation to produce the oil, unfortunately, the tests' results indicated low production rates [54]. Oil spots have also been found in other parts of the Silurian Baltic basin, for example on Gotland Island (33, 54, 55, 9, 51). The search for oil in reefs lacks knowledge about the process of oil migration and the change in properties of the effective layers (diagenetic processes and their extent) in the reef massif itself.

Among the Lithuanian Silurian carbonate organogenic build-ups the Kudirka reef is the largest structure measuring about 4 × 7 km in area and its total thickness according to the well data is 60–90 m [10]. Based on the results of the seismic data analysis, Michelevicius et al. [50] estimated that the Pavasaris and South Bliudziai reefs are similar in shape, i.e., about 1.5 km long and 1 km wide. In comparison, the North Bliudziai reef is smaller and measures 1 km in diameter. The Vadzgirys barrier reef belt is about 10 km long and 1 km wide and probably is composed of 3 isolated reefs, one of which is confirmed by drilling (Bedugnis-1 well). According to Michelevicius et al. [50] the thickness of those structures is up to 30–40 m.

3. Methodology

3.1. Well-log analysis

To constrain the geothermal system and assess the petrophysical properties of the Silurian reefs, well log data, results of drill-stem tests (DST) and core analyses were used from industrial reports prepared for 48 hydrocarbon exploratory wells penetrating the Silurian carbonate reef of Middle Lithuania. The reservoir properties were estimated based on abundant open porosity and permeability measurements, performed both in the laboratory on samples taken from the cores and defined from gamma-ray and sonic velocity logs (equations (1) and (2)). The effective thickness of the Silurian carbonate reef reservoirs was estimated from logging and drill core data. All the data for the study was collected from the industrial reports prepared by the oil industry and held at the Lithuanian Geological Survey of Lithuania.

3.2. Porosity, permeability and well production/injection rate

The permeability was assessed by interpreting the drill-stem tests from the wells together with the values measured on core samples. Open porosity, Φ, was most of all solved using values measured on the core samples, but also, where available, calculated applying acoustic logs corrected for clay content, V_{sh}.

The shale content was measured using gamma-ray logging data according to the standard formula:

$$V_{sh} = \frac{(GR - GR_{min})}{(GR_{max} - GR_{min})} \tag{1}$$

where V_{sh} is the fraction of shale in the rock, GR_{min} and GR_{max} are the gamma ray intensities in clean limestone and clayey intervals (shales) [55].

The open porosity was calculated as:

$$\Phi = \left\{ \frac{DT - DT_{matrix}}{DT_{fluid} - DT_{matrix}} \right\} \times [1 - V_{sh}] \tag{2}$$

where DT is the sonic velocity (μs/m), DT_{matrix} is the matrix sonic velocity, DT_{fluid} is the fluid sonic velocity [56].

The performance of the reservoir is directly controlled by the flow rate, Q, of the geothermal fluid. For the well production (injection) rate, we used values measured during the DST tests.

3.3. Geothermal potential calculations

The primary method for evaluating the production potential of geothermal systems associated to the oil and gas reservoirs is the recently widely used volume method (e.g. Refs. [57–65]). The method calculates useable heat in place, Q_{th}, by means of estimated reservoir volume, rock and fluid characteristics and average formation water temperature, against a reference temperature (equation (3)) [66]. Recoverable heat is calculated using a Recovery Factor, R_g, which is a fraction of a reservoir's thermal energy that can be extracted realistically from production wells using an injection in a liquid-phase reservoir of uniformly porous and permeable rock (equation (8)). The methodology for calculating the resources of one potential doublet of wells (a pair of injection-production wells) is convenient for potential users - when assessing the needs of one or another area, it is possible to predict the required number of wells and, accordingly, the costs of a potential project (equations (4)–(7)) [5].

The reservoir thermal energy is calculated as:

$$Q_{th} = c \times V \times \rho_f \times (t_1 - t_2) \tag{3}$$

where Q_{th} is the heat potential (GJ), c is the volumetric specific heat of the reservoir rock (J/kg · °C), V is the volume of the reservoir (m^3), ρ_f is the fluid density (kg/m^3), t_1 is the reservoir temperature (°C), and t_2 is a reference temperature (we assume injected water temperature of 10 °C). When talking about the realistic amount of energy stored, the real nature of the reservoirs, such as their porosity, density, and the availability of geothermal fluid should be considered. That may be estimated using the enthalpy value, h_{WH} [66]. The thermal energy that can be extracted at the wellhead, q_{WH}, is given by [66]:

$$q_{WH} = m_{WH}(h_{WH} - h_0) \tag{4}$$

where m_{WH} is the extractable mass, h_{WH} is the enthalpy of the extracted fluid, and h_0 is the enthalpy at a reference temperature. Here [66]:

$$m_{WH} = Q \times \rho_f \times t_{life} \tag{5}$$

$$h_{WH} = c_f \times t_1 \tag{6}$$

$$h_0 = c_f \times t_2 \tag{7}$$

where Q is the maximum water yield per well (m^3/h); ρ_f and c_f are the density (g/m^3) and specific heat capacity (kJ/kg · °C) of the fluid, respectively, and t_{life} is the time needed to reach a thermal breakthrough or the maximum pressure drawdown limit in the production well (converted to hours). Thermal breakthrough time between the injector and producer wells was determined by geothermal modelling (see section on Petrophysical and geothermal modelling) [67].

Recovery Factor, R_g, is then defined as [66]:

$$R_g = \frac{q_{WH}}{Q_{th}} = \frac{V \times \Phi_r \times \rho_f(h_{WH} - h_0)}{c \times V \times \rho_f(t_1 - t_2)} \tag{8}$$

3.3.1. *Reservoir temperature*

The Silurian reservoir temperatures were measured in 15 wells drilled in Middle Lithuania by using thermal logging applied after temperature equilibrium had been achieved in a well. Reservoir temperature data was taken from the database collected at the Lithuanian Geological Survey [68] as well as industrial reports for individual studied wells. Temperature data was used to calculate geothermal temperature gradient in the region as well as average temperature of the studied structures.

3.3.2. *Specific heat capacity and thermal conductivity of rocks*

The specific heat capacity as well as thermal conductivity of rocks depend on a number of different factors, such as chemical composition of the rock, density of fractures, porosity, particle size, etc. Therefore, it is most reliable to determine these parameters by directly measuring it on core samples. In this study, we used values determined by Balakauskas et al. [69] at the Lithuanian Geological Survey. The authors collected and summarized the data for the main types of rocks in Lithuania using the data presented in the literature. In cases of contradictions, the averages between the data of different sources were used, and the specific heat capacity and thermal conductivity values for rocks composed of different minerals were calculated according to their proportions in the evaluated rock (Table 1).

3.4. *Petrophysical and geothermal modelling*

V_{sh}, porosity and permeability models were done using Petrel subsurface software, and geothermal simulations were performed using a reservoir modelling platform tNavigator. Petrophysical models were created by uploading calculated V_{sh} and Φ logs of boreholes penetrating the structures studied and the porosity/permeability values measured on the cores taken from these wells. The cell size of these models is 50 x 50 × 50 m.

The geothermal models have the main reservoir properties (such as thickness, net to gross, porosity, permeability, etc.) implemented assuming a simplified rectangular-shaped reservoir with no flow boundaries. The model has around 300,000 cells (8.1 x 8.1 × 3 m size each) and it is more finely discretized along the Oz axis. Permeability in this direction is also assumed to be 3 times lower. Both doublet wells are completely perforated throughout the whole reservoir length and the permeability distribution is created at random given lower-higher boundaries as well as its estimated average. The 3D temperature distribution was simulated for well doublets injecting 10 °C water back into the reservoirs. Thermal breakthrough time was determined when the cold water front reached the production well and the bottom hole temperature started to decline.

Table 1
Specific heat capacity and thermal conductivity of different types of carbonate rocks in Lithuania (after [69]).

Rock type	Specific heat capacity of the rock (kJ/kg · °C)	Thermal conductivity of the rock (W/m · °C)	Proportion of different minerals in the rock
pure limestone	1.05	2.56	mean value
pure dolomite	1.07	3.09	mean value
dolomitic limestone	1.06	2.78	0.6 limestone; 0.4 dolomite
clayey limestone	1.43	2.15	0.6 limestone: 0.4 clay
clayey dolomite	1.44	2.47	0.6 dolomite: 0.4 clay
clayey dolomitic limestone	1.25	2.47	0.6 limestone: 0.2 dolomite: 0.2 clay
clayey limestone-rich dolomite	1.25	2.68	0.6 dolomite: 0.2 clay: 0.2 limestone

3.5. *Core and microstructural analysis*

The core intervals were analysed from 48 wells that penetrate the Silurian reef carbonate deposits (Minija regional stage) to provide appropriate descriptions and analyses of different rock types within the reefs. 125 hand specimens were collected and examined. A total of 78 thin sections were prepared from core samples and examined under plane-polarized and cross-polarized light using a Nikon Eclipse LV100 N POL microscope.

4. Results

4.1. *Depth and temperature*

The depth of the Silurian succession varies significantly throughout Lithuania, in the east they are at a depth of 90 m and deepens towards the west, where it reaches depths of *c.*1400 m. A wide range of temperatures is associated with the changing depth: from 9 to 10 °C in the east Lithuania to 50–60 °C in the west, up to 80–90 °C within the geothermal anomaly area (data of 94 measurements [68]; Fig. 4). The geothermal gradient varies from 1.7 to 6.5 °C/100 m. The top of the Silurian reef structures of interest are at the depths of 750–1100 m. Temperature for the top depth of the Silurian succession ranges from 25 to 38 °C (Fig. 4). The average temperatures of the reefogenic bodies are slightly higher. For the study of the largest Kudirka reef, temperature was measured in 8 wells drilled in the Vilkaviskis region. The measured temperature in Vilkaviskis-127 well at the depth of 657 m is 25.6 °C, in Kudirka-144, 145, 147 and Vilkaviskis-132,136 wells at the depths of 770–783 m temperature is between 28 and 32 °C, in Vilkaviskis-135 well it is around 36 °C at the depth of 773 m, and in Vilkaviskis-129 well temperature is around 41 °C at the depth of 800 m. Taking a wide range of temperatures measured at a short distance and depth, the conservative average reef temperature is assumed as 30 °C. In Vilkupiai reef, the maximum temperature recorded at the depth of 778–796 m was 25 °C. The central barrier reef belt within the studied area showed temperatures of 27.4 °C at the depth of 835 m (Bliudziai-150 well), 28.4 °C at the depth of 952 m (Vidukle-62 well), average temperature of 31 °C at the depth interval of 887–940 m (Tidikas-1 well), and 31.5 °C at the depth of 942 m (Bedugnis-1 well). Temperatures in the Saukenai reef showed a large discrepancy between the measured values: temperature in the Saukenai-75 well was 23.1 °C at the depth of 1046 m, and in the Saukenai-91 well it was 37.6 °C at the depth of 1043.5 m. However, based on a regional isotherm map, the latter temperature for the reef reservoir is more likely (Fig. 4).

4.2. *Reservoir lithological characterisation*

Silurian reefal build-ups in Lithuania are composed of several different rock types, mostly stromatoporous - crinoid limestone, detrital limestone, clayey carbonates with admixture of fauna such as brachiopods and corals as well as microcrystalline limestone. Different rock types are described in the following paragraphs.

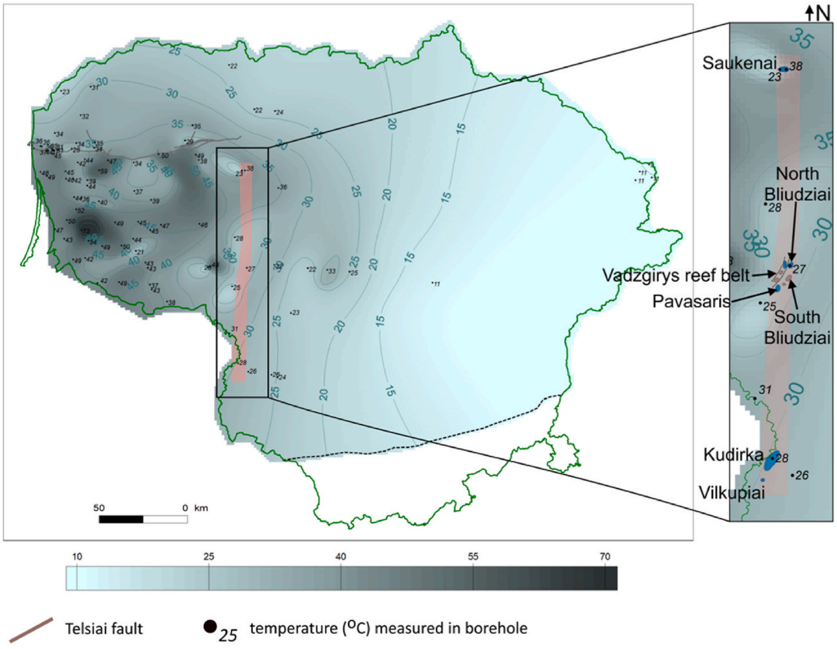

Fig. 4. Temperature map for the top depth of the Silurian succession in Lithuania. Temperatures measured at isolated wells are also marked on the map.

4.2.1. Stromatoporous limestone

Stromatoporous limestone is composed of lamellar (up to 3 cm) and massive (up to 25 cm) stromatopore clasts, making up 50–80 % of the rocks' volume (Fig. 5, b; Fig. 6, a). It is boundstone based on Dunham's classification of carbonate rocks [70]. The clasts are cemented by a sorted organogenic matrix, which is rich in crinoids, tabulate corals, skeletons of spongia and fragments of stromatoporoids. Unevenly clayey marl interlayers are also common. Stromatoporous limestone has intra-fossil and interparticle porosity. The limestone is unevenly fractured, in some places, there are caverns of up to 3 cm in diameter. Effective porosity is 0.70–13.8 %, permeability is < 0.1–2725 mD. Highly fractured parts of the cores showed permeability of up to 4485 mD.

4.2.2. Crinoid limestone

Crinoid limestone is rudstone and grainstone based on Dunham's classification. Crinoid fragments are between 0.5 and 5 mm in diameter and account for as much as 80 % of the rocks' volume (Fig. 5, c). These grains are largely cemented by syntaxial calcite cement. The grains are also encrusted with calcite spar. Crinoid limestone has interparticle and moldic porosity. Effective porosity

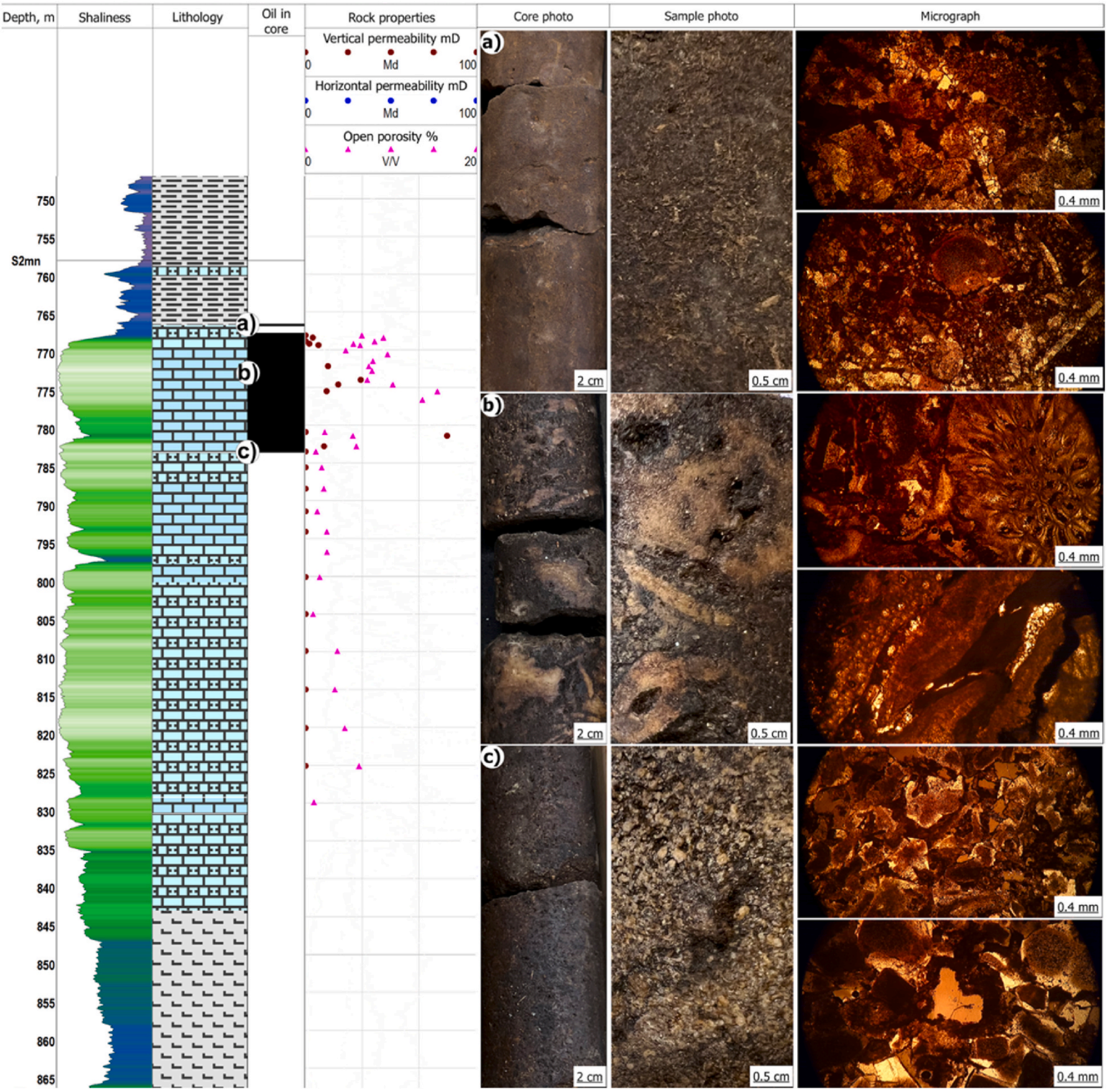

Fig. 5. The characteristics of petrology, logging response and physical properties of the oil-saturated part of the Kudirka reef structure (Vilkaviskis-139 well). The locations of the cores and samples are shown in the 'Oil in core' column. Note the oil stains in black in the core and sample photos. The sample shown in a) is a microporous detrital limestone; b) intra-porous stromatoporoid limestone; and c) inter-porous crinoidal limestone.

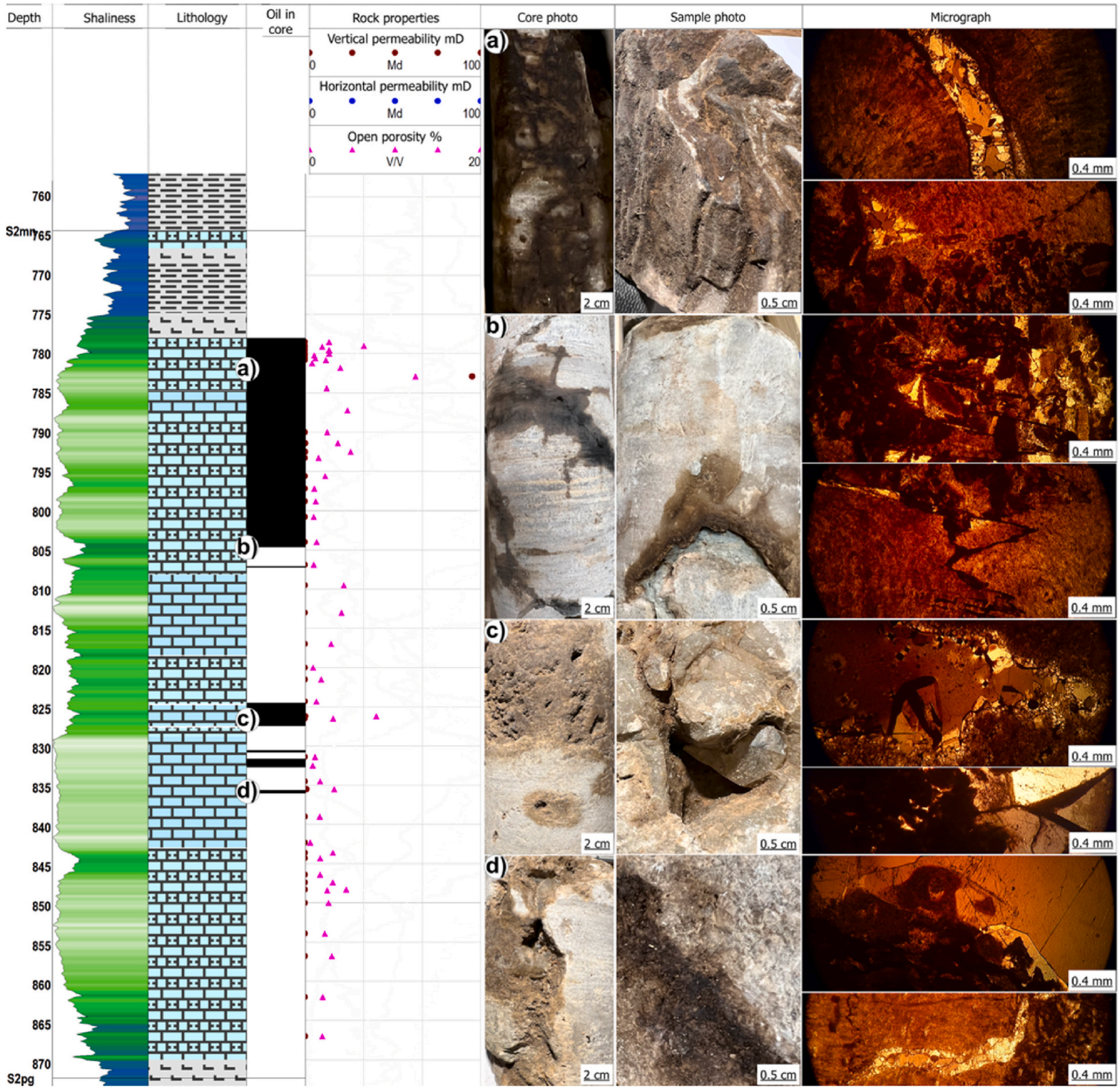

Fig. 6. The characteristics of petrology, logging response and physical properties of the oil-saturated part of the Kudirka reef structure (Vilkaviskis-136 well). The locations of the cores and samples are shown in the 'Oil in core' column. Note the oil stains in black in the core and sample photos. The sample shown in a) is an intra-porous stromatoporoid limestone; b) microporous clayey micrograin limestone with an oil-saturated stylolite structure; c) cavernous micrograin limestone and d) fractured micrograin limestone.

accounts for 1.34–10.15 %, and permeability is < 0.001–135 mD.

4.2.3. *Detrital limestone*

Organogenic detrital limestone is massive and horizontally and diagonally laminated. It mainly consists of 0.01–2.5 mm fragments of crinoids and to a lesser extent brachiopods, trilobites, skeletons of spongia, as well as micro-grain fragments and intraclasts. It is packstone and grainstone based on Dunham's classification (Fig. 5, a). The insoluble residue such as silty-clay substance makes up 0.5–10 % of the rocks' volume. During the lithogenesis of these rocks, calcitic cement filled abundant primary voids. Effective porosity is between 0.33 and 11.1%, and permeability is < 0.01–36.6 mD.

4.2.4. *Dolomitic limestone*

Dolomitic limestone is a massive rock, it is mudstone and crystalline limestone based on Dunham's classification. Most of the pores in the dolomitic part of the rock are micro-intercrystalline and moldic, and some fenestral pore types were also observed. The admixture of clay material does not exceed 20 %. Effective porosity is between 1.4 and 13.5%, permeability is 0.01–5 mD.

4.2.5. *Clayey micrograin limestone*

Clayey micrograin limestone usually consists of micro-grained (<0.01 mm) calcite crystals and unevenly scattered debris of trilobites, ostracods, brachiopods, pellicypods and fragments of stromatoporoids of 1–2 mm, less often <4 cm in diameter, the amount of which does not exceed 50 % of the rocks' volume. It is mudstone and wackestone based on Dunham's classification (Fig. 5, b; Fig. 6, c). The amount of clayey matter makes up 6–35 % of the rocks' volume. Clayey micrograin limestone has microporosity, rarely vuggy and fracture porosity (fractures are most often cemented with calcite). Effective porosity is between 0.18 and 9.8 %, and permeability is < 0.001–60 mD.

4.3. *Reservoir petrophysical characterisation*

Porosity and permeability as well as carbonate content values measured on core samples were plotted against depth and against each other for all studied reef structures (Fig. 7, a-c). Porosities up to 5% and permeabilities below 1 mD prevail within the measured values and there is no obvious relationship between these two parameters.

Porosity and permeability show no correlation with the depth along the reef sections and have similar ranges for all the reefs. However, the Saukenai reef which is the deepest reef, shows very low porosity. Kudirka structure shows a high range of permeabilities in the upper part of the reef and has several layers showing very good porperm values (Fig. 7, a). Carbonate content shows no clear correlation with the petrophysical properties, except for the Kudirka reef which has a high carbonate content and best petrophysical properties (Fig. 7, d). However, that may be not because of direct correlation, but rather be related to structural and/or diagenetic effects.

Porosity and permeability values for different types of lithofacies are widely scattered, however, general trends may be observed (Fig. 8, a-b). Stromatoporous and crinoidal limestones have good reservoir quality, their mean effective porosity is around 10 and 8 %, and their mean horizontal permeability is *c.*103 and 43 mD, respectively. Detrital limestone has a similar mean effective porosity (8 %), but a lower mean permeability (1.4 mD). Dolomitic limestone has a good mean effective porosity (5.5–6.7 %). However, its mean horizontal permeability is only around 2.2 mD. Micrograin and clayey limestones have the lowest mean porosity and permeability values, *c.*4 % and *c.*0.1 mD, respectively. Permeability anisotropy is observed within the effective layers, where horizontal permeability is 10–100 times higher than vertical. That is due to the textural properties of the rocks. As horizontal permeability increases, so does its ratio to vertical permeability.

4.3.1. *Pore types*

The complexity of porous spaces are well illustrated by a more extensive set of laboratory analysis of recently recovered cores from Vilkupiai and Kudirka reef carbonates. Fig. 9 (a) shows pore size distribution and percentage of porosity occupied by vugs in the samples. Total porosity ranges from *c.*2% to 31 %, while the volume of vugs is in the range of 15–61 % of total porosity (measurements

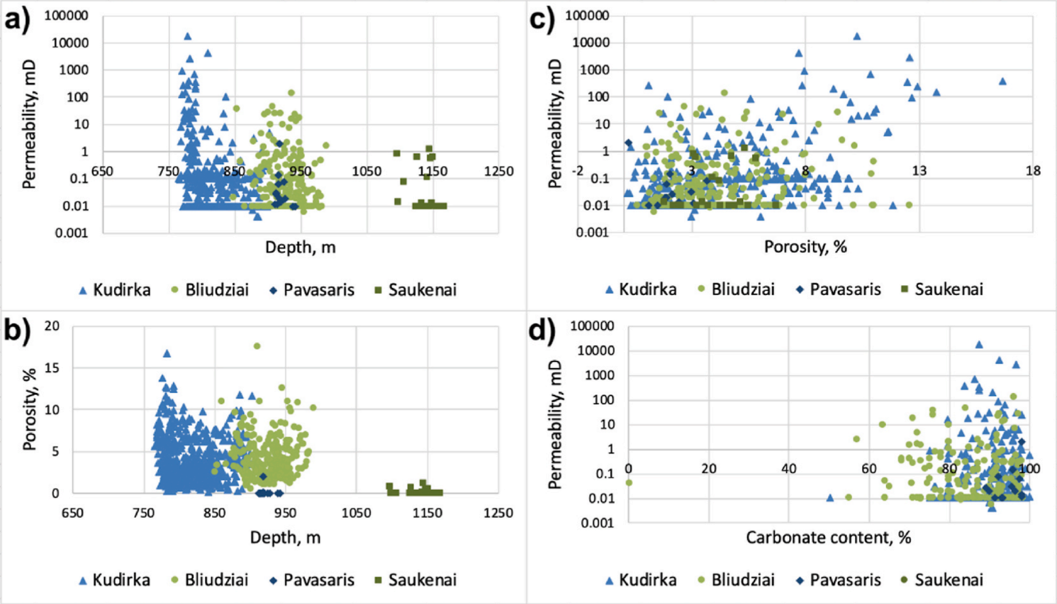

Fig. 7. a) Permeability (logarithmic scale) and b) porosity dependency of depth for the tested and cored intervals within the Silurian reef structures. b) Permeability as a function of porosity; and d) carbonate content.

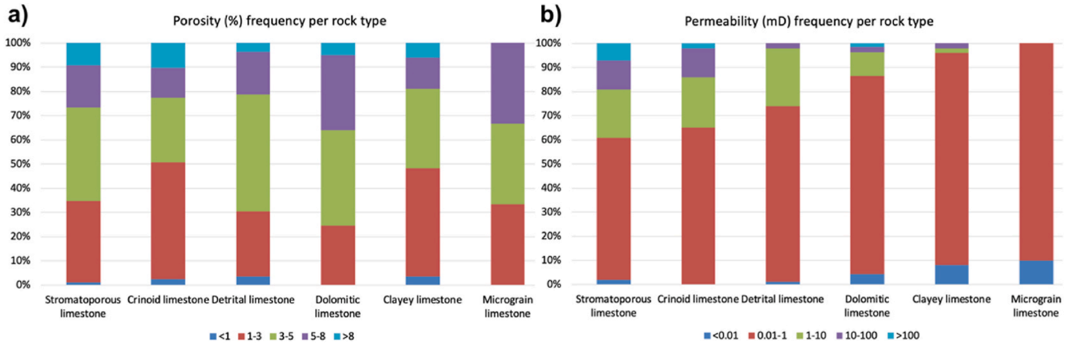

Fig. 8. Histograms of a) effective porosity (%), and b) permeability (mD) frequencies for the Silurian carbonate rocks in Lithuania. The values are classified into different types of carbonate lithofacies that are the most commonly observed within the studied reef structures.

done on 31 samples). However, even if a relatively large volume of vugs is present, it does not guaranty good fluid conductivity in rocks. Among the studied samples, a large part of them show reduced permeability (Fig. 9, b). Poor permeability is linked to the high content of pores with pore sizes <1 μm that prevent fluid transport between vugs and mega-pores (Fig. 9, a). Therefore, an overall trend can be observed implying a reduction in permeability with a decreasing volume of pores with pore sizes >1 μm (Fig. 9, c [71,72]).

4.3.2. Petrophysical models: Kudirka reef

Kudirka reef shows the best coverage of geological-geophysical data from all the studied reefs, allowing it to create its geophysical-geological model in order to find out reservoir properties distribution within the structure (Fig. 10, a-c). The structure is made of fore-reef, back-reef, interior lagoonal and reef-crest facies [52]. The oil is mostly accumulated within the upper part of the reservoir which is comprised of stromatoporoid-crinoid build-ups and organogenic detrital limestone representing the reef-crest facies. Analysis of the well logs as well as the core sections showed a high reservoir heterogeneity of the layers over a short distance (Fig. 10). Lithology changes between the inter-porous crinoidal limestone, the thickness of which reaches up to *c.*10 m, a 0.2–5 m thin intra-porous stromatoporous limestone layer and <7 m thin inter-porous and micro-porous detrital limestones at the top of the reef structures.

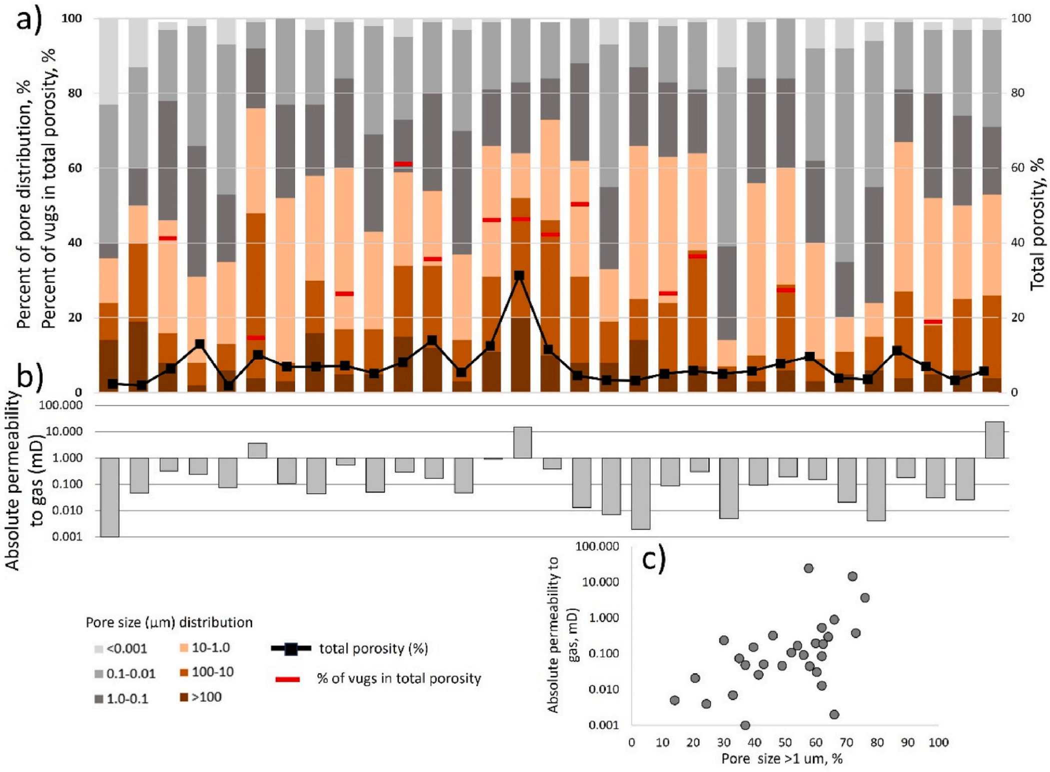

Fig. 9. a) Total porosity (%) of reefogenic carbonates with corresponding distribution of pore size (%)and percent of vugs in total porosity (%); b) permeability (mD) distribution, c) permeability (mD) vs volume of pores > 1 μm (% (data from Refs. [71,72]).

Then deeper down they are followed by micro-porous clayey micrograin limestone and/or crystalline dolostone and dolomitic limestone layers, that may be up to 30 m in thickness.

Porosity and permeability are higher within the central part of the reef, reef crest or individual thin layers across the structure (Fig. 10, b-c). The distribution of effective layers is usually associated with the lithologies commonly characterised by good petrophysical properties such as crinoid-stromatoporoid-detrital limestones, and/or the layers affected by secondary processes such as fracturing or enhanced dissolution forming vuggy porosity (Fig. 5; Fig. 6). The effective properties of the rocks sharply decrease towards the open paleobasin, where the size and quantity of debris decrease, the clay content increases as well as the degree of recrystallization and cementation. Despite the presence of effective intervals distinguished along the well profiles, there is a limited connection between them, caused by diagenetic barriers. Oil and formation water flow measured in the central part of the Kudirka reef (Vilkaviskis-135) shows that petrophysical properties are good in the near proximity of the well, however, they decrease going 10–20 m away from the well and eventually fluid almost stops flowing (Fig. 11 [54]). That is in agreement with the petrophysical models showing high reservoir heterogeneity of the layers and poor connectivity between different types of porosity such as vugs and intraporosity system and different rock types show different types of pore systems.

4.4. Reef structures

4.4.1. Kudirka reef

Kudirka reef is the largest reef within the Silurian reef belt in Lithuania. It is an atoll-like structure being almost up to 90 m in thickness. The highest point of the reef top is at a depth of 762 m and was determined by drilling. The reef consists of detrital crinoid, crinoid - stromatoporous and microcrystalline limestone, partly dolomitic. The rocks are unevenly fissured. Effective porosity is 0.70–18 %, permeability 0.04–833 mD, rarely reaches 4290 mD, while fracture permeability is 0.01–491 mD. The most effective intervals are located in the uppermost part (up to 10–12 m) of the reef, while the lower part of the structure contains a much tighter

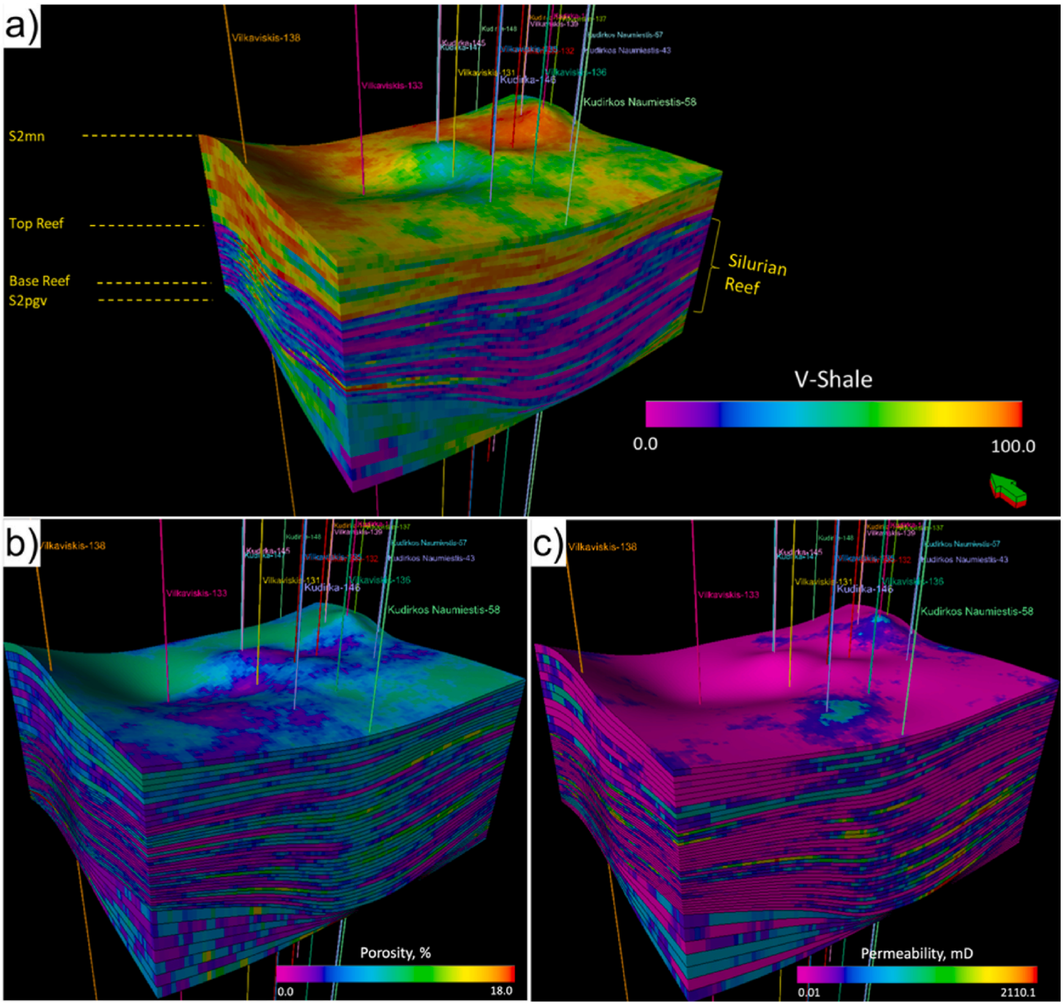

Fig. 10. Petrophysical models demonstrating distribution of a) clay content, V_{sh}; b) porosity and c) permeability within the Kudirka reef.

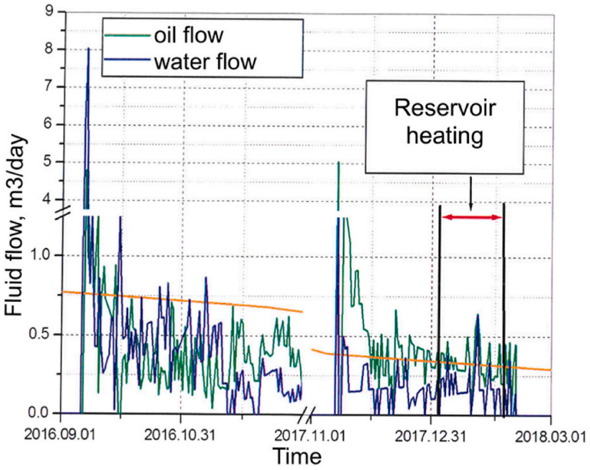

Fig. 11. Oil and formation water flow measured in Vilkaviskis-135 well within the Kudirka reef (modified from Ref. [54]).

rock. The distribution of effective layers is usually associated with crinoid-stromatoporoid-detrital limestones and the secondary processes such as secondary fracturing with enhanced dissolution. Only the upper part of the reef is saturated with oil, oil saturation may reach 92%. Hydrodynamic tests yielded up to 7.3 m^3/day of oil (Vilkaviškis-135 well) and up to 75.6 m^3/day of formation water (K. Naumiestis-58). The reef is surrounded by a clayey column consisting of argillite and marl with interlayers of dense, clayey crystalline limestone, and is clearly distinguished on the V_{sh} distribution model (Fig. 5; Fig. 6; Fig. 10, a).

4.4.2. *Vilkupiai reef*

Vilkupiai reef is located 2 km southwest of the Kudirka reef. The top of the reef is at a depth of 765 m, and the determined thickness of the reef is around 62 m, where 40 m of the uppermost part was cored. The reef body consists mainly of coarse-grained stromatoporoid limestone, but also contains coarse-grained coral, crinoid and detrital, as well as fine-grained detrital layers. Effective porosity within the reef ranges between 1 to almost 20 %, however, an average value is only around 5%. Permeability values are generally very low (less than 1 mD) and only a few samples show fair permeability quality. The oil saturation in the reef varies from intensively saturated layers to patchily saturated layers. Hydrodynamic tests recorded up to 0.775 m^3/day fluid inflow.

4.4.3. *North Bliudziai reef*

Isolated North Bliudziai reef is within the central Silurian reef belt (Fig. 3) and is confirmed by 3 wells. The top of the reef is at a depth of around 917 m. It is up to 40 m in thickness and consists of coarse-grained stromatoporous crinoid debris limestone. The thickness of the effective layer is *c.*20 m. Here open porosity is around 5–9 % (average 6 %), permeability 0.19–134 mD. Hydrodynamic tests yielded up to 0.1 m^3/day of oil and water inflow.

4.4.4. *Pavasaris reef*

Pavasaris reef is a small, isolated reef in the central part of the Silurian reef belt (Fig. 3) and it was confirmed by 2 wells. Its thickness is around 45 m. The highest point of the reef top was determined during drilling at *c.*903 m. The effective porosity of the limestone is 0.80–9 %, and permeability in most samples is below 1 mD. In rare cases, the effective porosity of the rocks increases up to 26 %, and permeability up to 36 mD. A reef body is composed mainly of coarse-grained detrital, stromatoporoid, crinoidal, brachiopodial and coralline limestone. Fractures are quite common and are single or create more complex systems. In Tidikas-1 well fracture systems are often related to stylolites, which can be open or filled with clay minerals. Typically, stylolites are only partly filled creating conduits to fluid flow. Cores in Bliudziai-156 well show fracture zone with wide fracture apertures (up to 2 cm in thickness), in places enlarged by dissolution forming caverns, that are partially filled with large calcite crystals. In fractured zones, permeability can reach up to 4202 mD. The reef is unevenly saturated with oil. Hydrodynamic tests from the upper part of the reef in the Bliudziai-156 well yielded 17.28 m^3/day inflow of formation water with an oil film layer, and near the well bottom, the well began to fountain at the 192–216 m^3/day water inflow.

4.4.5. *Vadzgirys reef belt (Bedugnis)*

This isolated reef structure was identified and mapped based on 3D seismic survey in a northern part of the Vadzgirys reef belt ([51]; Fig. 3), and successively drilled with Bedugnis-1 well. It is located west of the North Bliudziai reef. The top depth of the reef is at around 958 m and its thickness is *c.*20 m. The uppermost 16 m of the reef was cored. The reef is composed of detrital limestone, rich in fragments of crinoids, corals, stromatoporoids, brachiopods, bryozoans and rarely trilobites. Porosity is low – mostly below 4%, with equally poor permeability quality (around 0.12–0.55 mD). Signs of oil have been detected in pores and fractures. Fractures are rare and usually related to clay intersections/stylolites, and are often partly filled with clay minerals. During the hydrodynamic test, the inflow of formation water with an oil film from the interval encompassing the upper half of the reef was only minor.

4.4.6. *Saukenai reef*

The isolated Saukenai reef is located in the north of the studied Silurian reef belt at a depth of around 1130 m. It occupies a small area and has a thickness of 18 m. The reef consists of stromatoporoid-crinoid limestone with an effective porosity of 1.14–3.85 %, and permeability $<$0.9 mD. 0.03 m^3/day oil inflow was obtained during the hydrodynamic tests.

4.5. *Silurian formation water chemistry*

Data on the chemical composition of Silurian formation water were collected from industrial reports archived in the Geological Survey of Lithuania. The total mineralization of the water is 74.1–131 g/l, and it is slightly acidic (pH of 6.4–6.7). Formation water at the largest Kudirka reservoir shows the lowest mineralization of 74.1 g/l. Silurian water is rich in chlorides, calcium and magnesium, it is a chloride-calcium type based on Sulin's classification. Sulfates are at low concentrations, the sulfate content is 0.19–2.68 g/l. In the water the biophile constituents (bromides and iodides) are present which is characteristic of waters accompanying petroleum deposits. Based on values of hydrogeochemical indicators the formation water can be characterised as relic salty water. That means that the water has been metamorphosed since primary deposition and is accumulated in well-isolated layers. The degree of metamorphism is 0.49–0.78 (Na/Cl). Electrical conductivity is around 97.6–113 mS/cm, and specific gravity is 1.053–1.071 g/cm^3.

4.6. *Utilisation of existing wells*

For the oil exploration of the largest Kudirka reef, 16 wells have been drilled in Vilkaviskis region. In total, 6 well doublets could be arranged within the area of the Kudirka structure, at the smallest distance between the wells of 486 m (Kudirka-144 and Vilkaviskis-137) and at the largest distance of 860 m (Kudirka-146 and Vilkaviskis-136). Pavasaris reef has got 2 wells penetrating the reef (Bliudziai-156 and Tidikas-1) the distance between which is 710 m. Three wells reach North Bliudziai reef, thus 1 doublet could be arranged with a distance between the wells at around 600 m. Each Vilkupiai and Bedugnis structure has only 1 exploration well drilled, therefore a doublet is not possible by reusing the existing wells, and investments to drill an extra well would be needed. Saukenai reef has got 2 wells penetrating the structure (Saukenai-75 and Saukenai-92) and 1 well doublet could be arranged within the area at a distance between each other of around 1000 m.

Boreholes that penetrate the Silurian reefs typically have a 93 mm diameter within the target interval, sometimes slightly larger (102–114 mm), or rarely even 190 mm. New boreholes drilled in the last decade or so (Kudirka-1, Vilkupiai-1, Bedugnis-1, Tidikas-1) have larger open holes (155.6 mm).

4.7. *Geothermal potential*

Kudirka reef has the largest reservoir volume and hence the largest reservoir heat potential (250,000 MWh) (Table 2). However, due to large heterogeneity, the recovery factor is only 11 %. Taking the smallest distance of 486 m between the injecting and producing wells, the thermal breakthrough would be reached after around the 30-year period, where the cold water front reaches the production well and the bottom hole temperature starts to decline. Fig. 12 shows a possible scenario of temperature distribution after 30 years of injection/production of geothermal fluid. Pavasaris reef shows the best geothermal capacity of a well doublet (0.241 MWh). The reservoir has a reasonable temperature and injection/production rate. However, the available thermal energy is limited due to hydrogeological closure and small reservoir size (11.2×10^3 MWh), and if run at full capacity, the maximum pressure drawdown limit in the production well would be reached after around 15 years of production. Even though the Saukenai reef has the highest formation temperature, it shows the lowest geothermal potential due to the extremely low petrophysical properties of the reservoir rock. Other reefs (Vilkupiai, North Bliudziai and a reef in the north of the Vadzgirys reef belt) are small isolated structures, thus their heat potential is low. Moreover, they show low flow rates and hence thermal energy that can be extracted at their wellheads in 30 years is well below 1×10^3 MWh.

5. Discussion

Silurian reefs in the Middle Lithuania were widely studied by the oil industry because they show potential for oil exploration. However, the oil production proved uneconomical due to low oil flows. Large amount of data collected, and numerous abandoned wells drilled within the area may serve as a treasure if reused for geoenergy purposes. For this reason, we evaluated the data for

Table 2
Geothermal potential calculations for the studied Silurian reefs.

Reef structure	Reservoir volume, km^3	Reservoir thermal energy, MWh	Geothermal capacity of a well doublet, MWh
Kudirka	0.025	250×10^3	0.11
Vilkupiai	0.00019	1.11×10^3	0.00062
North Bliudziai	0.00053	3.5×10^3	0.000093
Pavasaris	0.00096	11.2×10^3	0.241
Reef in Vadzgirys (Bedugnis)	0.00011	0.89×10^3	0.00067
Saukenai	0.0012	12.39×10^3	0.000044

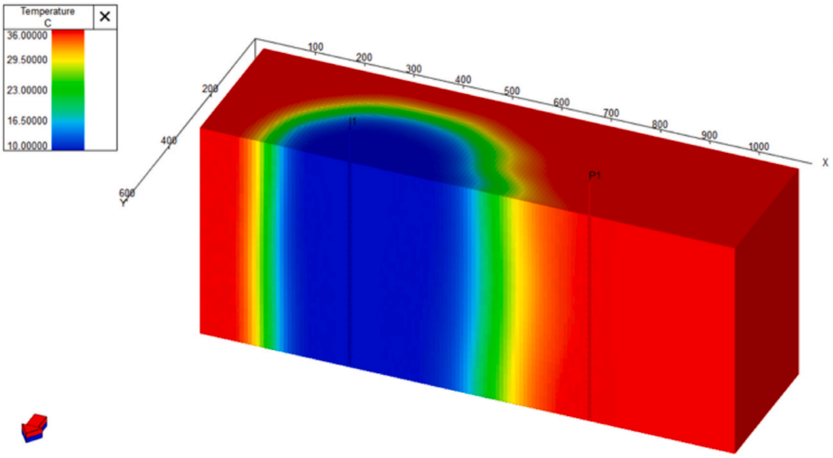

Fig. 12. 3D temperature distribution graph of a simulated Kudirka reservoir after 30 years of cool water injection.

Silurian carbonate formations in the light of geothermal energy utilisation. Central district heating in the small Middle Lithuania towns dominates the heat supply market. Therefore, the application of hydrothermal resources may be a favourable technology.

5.1. Petrophysical properties of the Silurian reefs in Lithuania

Carbonates show a wide range of porosities varying between nearly 0 % in tightly cemented rocks to about 35 % in unconsolidated deposits [73]. Porosity can be primary or secondary. Primary porosity forms between grains during the time of deposition (e.g., interparticle-, intraparticle-, growth framework-, shelter- and fenestral porosity), and secondary porosity forms after deposition due to structural, geological and/or diagenetic processes (e.g., moldic-, channel-, intercrystalline-, fracture- and vuggy porosity) [73]. Cementation and compaction are the main processes reducing porosity in carbonates even at shallow depths (e.g. Refs. [74,75]), whereas dolomitization and dissolution often increase the porosity (e.g. Refs. [14,21,23,72,76]). Therefore, it is difficult to find any relationship between porosity and permeability for carbonate rocks. During the dolomitization, permeability and porosity increase because the volume of dolomite is lower than that of calcite. Karstification also leads to an increase in reservoir properties due to dissolution of grains or the existing pore space including enlargement of fractures and bedding plane surfaces. Carbonate reefs are often considered a suitable target for geothermal exploitation because they are prone to dolomitization and karstification (e.g. Ref. [77]). The reefs often show improved hydraulic properties because groundwater mainly flows along karst cavities, joints, fractures, and fault zones, and less often along bedding planes. Late diagenetic leaching forming vugs and caverns has enhanced the reservoir quality within some of the wells within the Silurian reef formations. Sutured seam contacts and pressure solution structures also acted as pathways to aggressive fluids forming numerous micron-scale solution pores and small vugs. Intra- and intergranular pores as well as some tension gashes were also solution-enlarged. In the Silurian reefs, intercrystalline and microporosity within the micrograin and dolomitic limestones create comparably high porosity, however, the small pores and pore throats between the crystals and grains do not allow for high permeability. Caverns within the tight limestone create higher porosity, however, they do not increase permeability by much due to their poor connectivity. Matrix ability to transfer fluids is necessary even in fractured systems, because it creates a pathway for fluids accumulated in the matrix pores towards fractures [78]. Stromaporoid limestone layers are very thin, however, their intrafossil and intergrain porosity show the best petrophysical properties. That is because it contains the least amount of fine matrix containing microporosity compared to other lithofacies. At larger scale, crinoidal limestone is more effective than stromatoporoid limestone as it is more homogeneous over larger distances. Crinoid limestone has high permeability, however, syntaxial cement and calcite sparite encrustations greatly reduce the porosity of the rock.

The study indicates that even though the thickness of the reefal build-ups may reach up to *c.*90 m, the effective thickness of the reservoirs ranges within several meters and rarely reaches 20 m. That is because of the high heterogeneity of the structures. A good example is the Pavasaris reef which was penetrated by two boreholes at about 700 m distance from each other, and only one of the boreholes demonstrated particularly good reservoir properties (Bliudziai-156). The effective interval within the Bliudziai-156 well is only a few metres thick, but it is characterised by open fractures and caverns, often filled with viscous oil. Irregular open fractures and caverns are present almost throughout the entire reef interval and thus contribute to the flow of fluid within the reservoir. However, the second Tidikas-1 well demonstrates the tight nature of the rock and contains very few fractures. Similarly, in the Kudirka reef, a several-meter thick porous and oil-saturated limestone cap was determined at the top of the structure, where fluid transfer is partly restricted to thin layers that retain its primary rock deposition or contain fractures. In general, the studied reservoir rocks of reefal build-ups are mainly composed of stromatoporoid - crinoid limestone, partly clayey, with the admixture of fauna such as brachiopods and corals as well as microcrystalline limestone. Open porosity of these limestones is mainly between 5 and 10 %, and the permeability is usually negligible, whereas the highest values (up to few Darcy) and flow rates are mostly linked to fractured zones, stylolitisation and intense dissolution forming extensive vug systems (Fig. 6 b-d).

5.2. Geothermal potential of the Silurian reefs in Lithuania

Temperatures of the Silurian reef reservoirs are too low for direct central heat supply, and additional heating is required. The additional heating increases the capacity of a geothermal plant, which should be taken into consideration when planning the number of wells for the exploitation of geothermal heat. The heat production rates of well doublets within the Silurian reefs range from 0.000044 to 0.24 MWh, with only two reservoirs worth considering: Kudirka and Pavasaris reefs. They are the only reefs that have sufficient flow rates and high enough water availability within the closed structures. Other reefs (Vilkupiai, North Bliudziai and a reef in the north of the Vadzgirys reef belt) have low heat potential because they are hydrogeologically closed and thermal energy from the available water can produce less than 1×10^3 MWh. Moreover, the flow rates of these reefs are too low to make them economically viable cases for geothermal projects. Saukenai reef has the highest formation temperature, however, due to extremely low petrophysical properties of the reservoir rock, it shows the lowest geothermal potential.

Kudirka and Pavasaris reefs could make economically viable geothermal heat projects. 6 well doublets within the Kudirka structure would produce 2836 MWh during the heating season, whereas the closest Vilkaviskis town with 9444 population would require around 10,000 MWh. Heating to the required district heating temperatures of >60 °C (e.g., using gas boilers) would increase the capacity of the doublets to around 1,580,000 MWh, which would cover the heating needs of the nearby towns and more. A doublet within the Pavasaris structure would produce 1056 MWh during the heating season, and the towns nearby (Šimkaičiai, Vadžgirys, Girdžiai) with >1000 population would require around the same amount of thermal energy. Another possibility is to use this low-enthalpy geothermal fluid to heat water to the target temperature for aquatic species in raceways, ponds and tanks. The water temperature depends on the species used, varying from 13 to 30 °C (e.g. Ref. [79]), making Silurian reef formation water suitable for geothermal aquaculture using heat exchanger technology.

Reservoirs such as the reefal build-ups have a limit on the available water for extraction because they are lithologically and hence hydraulically bound from the continuous supply of water from the aquifers. That proved a limiting factor for the majority of Silurian reefs in Middle Lithuania. Moreover, the diameters of the existing wells are between 93 and 190 mm, and with such low flow rates, they should be at least double the size. Therefore, reusing the existing wells penetrating the Silurian reef reservoirs shows low potential for geothermal heat extraction. However, for the Kudirka reef, which can have at least 6 well doublets arranged from the existing exploration wells, a reasonable water production could be achieved for an economically viable project. Despite the fact that it is a bound small reservoir (1.5 km long and 1 km wide), Pavasaris structure also provides an economically feasible case, because it shows good flow rates and has two existing wells penetrating the reef at a distance of 710 m. Moreover, the well that showed lower flow rates (Tidikas-1) has a larger open hole (155.6 mm) which would contribute towards better production/injection rates. Therefore, these two structures could be utilized for small geothermal projects (i.e., fish farms or district heating for a small town such as Vilkaviskis).

Doublet wells within the Silurian reefs show lower geothermal potential (<0.24 MWh) compared to Cambrian aquifers (<6.02 MWh) in Middle Lithuania [6]. However, proven oil reservoirs play safer options for geo-energy resource production compared to aquifers due to possible groundwater contamination in the latter case. That is because accumulation of oil provides evidence of good sealing properties of reservoir cap rock, and hence low risk of leakage to groundwater. Moreover, extensive drilling works for the exploration of oil within the Silurian reefs provide both the data for more accurate predictions of geothermal potential, as well as existing infrastructure to reduce the costs of drilling. Such economic evaluation should be done for Cambrian aquifers, i.e. finding out whether there are a potential number of existing wells for the arrangement of producer–injector doublets penetrating the Cambrian sandstone formations close to towns in need of district heating. Moreover, technical and economical evaluation of the wells should be done for the wells penetrating both the Silurian reefs as well as Cambrian sandstone aquifers, investigating their state (corrosion, scaling etc.) and investment needed to make them reusable for the geothermal purposes. The majority of the wells in Middle Lithuania were drilled in the Soviet times and no such evaluation has been done yet, especially for the abandoned and plugged boreholes.

6. Conclusions

This study illustrates an integrated review of the existing geological and geophysical data of the Middle Lithuanian Silurian barrier reef system, collected during oil and gas explorations since the 1960s, specifically re-analysed for geothermal purposes. The geothermal potential was calculated for a geothermal well doublet. The heat production rates of well doublets within the Silurian reefs range from 0.000044 to 0.24 MWh, with only two reservoirs worth considering: Kudirka and Pavasaris reefs. Within the area of the Kudirka structure, 6 well doublets could be arranged from the existing 16 exploration wells, at the average distance between the producing-injecting wells of around 700 m. Kudirka has the largest reservoir volume and hence the largest reservoir heat potential (250,000 MWh). With the additional heating of geothermal water to temperatures of >60 °C, the Kudirka reservoir could produce around 1,580,000 MWh during the heating season, which would cover the heating needs of the nearby towns and more. Pavasaris reef has got 2 wells penetrating the reef, thus one doublet could be arranged within the structure. Pavasaris reef shows the best geothermal capacity of a well doublet (0.241 MWh). Reservoir properties are especially good due to the presence of partially open fractures within reef intervals. However, the available thermal energy is limited due to hydrogeological closure and small reservoir size (11.2×10^3 MWh), and if run at full capacity, the maximum pressure drawdown limit in the production well would be reached after around 15 years of production. However, utilising the existing wells could make geothermal heat extraction from the reservoir economically viable at least for a small geothermal project such as a fish farm. Other reefs (Saukenai, Vilkupiai, North Bliudziai and a reef in the north of the Vadzgirys reef belt) are small isolated structures, thus their heat potential is low. Moreover, they show low flow rates and hence thermal energy that can be extracted at their wellheads in 30 years is well below 1×10^3 MWh.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Ieva Kaminskaite-Baranauskiene: Writing – original draft, Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anna Cichon-Pupienis:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation. **Pijus Makauskas:** Writing – review & editing, Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project has received funding from the Research Council of Lithuania (LMTLT), agreement No S-MIP-22-49. The authors would like to thank prof S. Radzevičius at Vilnius University for constructive comments on the stratigraphic distribution of Pridoli in Lithuania, and Roderick Perez Altamar for helping with the petrophysical modelling part.

References

[1] D. Matuszewska, M. Kuta, J. Górski, The environmental impact of renewable energy technologies shown in case of ORC-Based Geothermal Power Plant, in: IOP Conference Series: Earth and Environmental Science, vol. 214, 2019 012142, 1.
[2] S. Šliaupa, V. Rastenienė, Heat flow and heat production of crystalline basement rocks in Lithuania, Geologija 31 (2000) 24–34.
[3] K. Kepezinskas, V. Rasteniene, P. Suveizdis, West Lithuanian Geothermal Anomaly. Monograpfy, Institute of Geology, Vilnius, 1996, p. 68.
[4] P. Suveizdis, V. Rasteniene, F. Zinevicius, Geothermal potential of Lithuania and outlook for its utilization, in: Proceedings of the World Geothermal Congress, vol. 28, Kyushu-Tohoku, Japan, 2000.
[5] S. Šliaupa, A. Zuzevičius, V. Rastenienė, A. Baliukevičius, F. Zinevičius, J. Gudzinskas, K. Buinevičius, Vakarų Lietuvos regione esančių geoterminės energijos resursų potencialo išaiškinimas ir pagrindimas, bei galimybės jų panaudojimui energijos gamybai, Geology and geography institute, Vilnius, 2008.
[6] S. Šliaupa, J. Kežun, Hydrogeothermal resources of Middle Lithuania, Geologija 53 (2) (2011).
[7] P. Lapinskas, J. Smilgis, Prospects of revelation of reefogenic buildups in paleozoic rocks of south east baltic, in: Materialy Dokladov Vtorogo Seminara Neftepoiskovykh Kriteriev Pribaltiki [Presentations at the Second Seminar on Oil-Prospecting Criteria in the East Baltic, 1972, pp. 37–39, 37-39. Vilnius, Lithuania [translated from Russian].
[8] P. Lapinskas, Z.B. Chechavichius, The task of geological investigations of Silurianrocks with good prospects for oil in the Eastern Borderland of Baltic Depression, in: J. Paltanavicius (Ed.), Dostizheniya I Zadachi Issledovaniy Po Geologii Litovskoi SSR, 1981, pp. 105–107. Vilnius.
[9] P. Lapinskas, Lietuvos Silūro Sandara Ir Naftingumas. Structure and Petroliferosity of the Silurian in Lithuania, 2000. Vilnius.
[10] O. Zdanavičiūtė, J. Jacyna, Mokslinio tyrimo darbo ‚Silūro rifų paplitimo dėsningumų ir jų naftos perspektyvų įvertinimas bei pasiūlymų tolimesniems naftos darbams vykdyti pateikimas", vol. 2600, Industrial report of UAB „Minijos nafta", Geology and geography institute, Vilnius, 2003, p. 13.
[11] A.S. Alsharhan, K. Magara, Nature and distribution of porosity and permeability in Jurassic carbonate reservoirs of the Arabian Gulf Basin, Facies 32 (1995) 237–253.
[12] M. Shepherd, Carbonate reservoirs, in: M. Shepherd (Ed.), Oil Field Production Geology: AAPG Memoir 91, 2009, pp. 301–309.
[13] D.A. Martyushev, P.O. Chalova, S. Davoodi, U. Ashraf, Evaluation of facies heterogeneity in reef carbonate reservoirs: a case study from the oil field, Perm Krai, Central-Eastern Russia, Geoenergy Science and Engineering 227 (2023) 211814.
[14] D. Zhu, Z. Jin, W. Hu, Hydrothermal recrystallization of the Lower Ordovician dolomite and its significance to reservoir in northern Tarim Basin, Sci. China Earth Sci. 53 (3) (2010) 368–381.
[15] X. Zhang, T. Guo, B. Liu, X. Fu, S. Wu, Porosity formation and evolution of the deeply buried lower Triassic Feixianguan Formation, Puguang gas field, NE Sichuan Basin, China, Open J. Geol. 3 (4) (2013) 13, 2013), Article ID:35145.
[16] L. Jiang, W. Pan, C. Cai, L. Jia, L. Pan, T. Wang, H. Li, S. Chen, Y. Chen, Fluid mixing induced by hydrothermal activity in the Ordovician carbonates in Tarim Basin, China, Geofluids 15 (3) (2015) 483–498.
[17] B.C. Biehl, L. Reuning, J. Schoenherr, V. Lüders, P.A. Kukla, Impacts of hydrothermal dolomitization and thermochemical sulfate reduction on secondary porosity creation in deeply buried carbonates: a case study from the Lower Saxony Basin, northwest Germany, AAPG (Am. Assoc. Pet. Geol.) Bull. 100 (4) (2016) 597–621.
[18] A. Brogi, D. Liotta, G. Ruggieri, E. Capezzuoli, M. Meccheri, A. Dini, An overview on the characteristics of geothermal carbonate reservoirs in southern Tuscany, Italian Journal of Geosciences 135 (1) (2016) 17–29.
[19] D. You, J. Han, W. Hu, Y. Qian, Q. Chen, B. Xi, H. Ma, Characteristics and formation mechanisms of silicified carbonate reservoirs in well SN4 of the Tarim Basin, Energy Explor. Exploit. 36 (4) (2018) 820–849.
[20] C.P. Menezes, F.H. Bezerra, F. Balsamo, M. Mozafari, M.M. Vieira, N.K. Srivastava, D.L. de Castro, Hydrothermal silicification along faults affecting carbonate-sandstone units and its impact on reservoir quality, Potiguar Basin, Brazil, Mar. Petrol. Geol. 110 (2019) 198–217.
[21] B. Jiu, W. Huang, N. Mu, M. He, Effect of hydrothermal fluids on the ultra-deep Ordovician carbonate rocks in Tarim Basin, China, J. Petrol. Sci. Eng. (2020) 107445.
[22] I. Moeck, T. Bloch, R. Graf, S. Heuberger, P. Kuhn, H. Naef, M. Sonderegger, S. Uhlig, M. Wolfgramm, The St. Gallen project: development of fault controlled geothermal systems in urban areas, in: Proceedings World Geothermal Congress, 2015, April, p. 5.
[23] I.S. Moeck, M. Dussel, J. Weber, T. Schintgen, M. Wolfgramm, Geothermal play typing in Germany, case study Molasse Basin: a modern concept to categorise geothermal resources related to crustal permeability, Neth. J. Geosci. 98 (2019) e14.
[24] A.N. Toth, P. Szucs, J. Pap, A. Nyikos, D.K. Fenerty, Converting abandoned Hungarian oil and gas wells into geothermal sources, in: Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, 2018, February, pp. 1–8.
[25] K. Wang, B. Yuan, G. Ji, X. Wu, A comprehensive review of geothermal energy extraction and utilization in oilfields, J. Petrol. Sci. Eng. 168 (2018) 465–477.
[26] A. Mehmood, J. Yao, D. Fan, K. Bongole, J. Liu, X. Zhang, Potential for heat production by retrofitting abandoned gas wells into geothermal wells, PLoS One 14 (8) (2019) e0220128, 19.

[27] X. Hu, J. Banks, L. Wu, W.V. Liu, Numerical Modeling of a Coaxial Borehole Heat Exchanger to Exploit Geothermal Energy from Abandoned Petroleum Wells in Hinton, Alberta, vol. 148, Renewable Energy, 2020, pp. 1110–1123.

[28] J.C. Kurnia, Z.A. Putra, O. Muraza, S.A. Ghoreishi-Madiseh, A.P. Sasmito, Numerical evaluation, process design and techno-economic analysis of geothermal energy extraction from abandoned oil wells in Malaysia, Renew. Energy 175 (2021) 868–879.

[29] L.R.M. Cocks, T.H. Torsvik, Baltica from the late Precambrian to mid-Palaeozoic times: the gain and loss of a terrane's identity, Earth Sci. Rev. 72 (1–2) (2005) 39–66.

[30] P. Poprawa, S. Šliaupa, R. Stephenson, J. Lazauskienė, Late Vendian–Early Palaeozoic tectonic evolution of the Baltic Basin: regional tectonic implications from subsidence analysis, Tectonophysics 314 (1–3) (1999) 219–239.

[31] J. Lazauskienė, R. Stephenson, S. Šliaupa, J.D. van Wees, 3-D flexural modelling of the silurian Baltic basin, Tectonophysics 346 (1–2) (2002) 115–135.

[32] S. Šliaupa, P. Hoth, Geological evolution and resources of the Baltic Sea area from the precambrian to the quaternary, The Baltic Sea Basin (2011) 13–51.

[33] M.J. Melchin, P.M. Sadler, B.D. Cramer, The Silurian period, in: Geologic Time Scale 2020, Elsevier, 2020, pp. 695–732.

[34] A. Spiridonov, A. Brazauskas, S. Radzevičius, Dynamics of abundance of the mid- to late Pridoli conodonts from the eastern part of the Silurian Baltic basin: multifractals, state shifts, and oscillations, Am. J. Sci. 316 (4) (2016) 363–400.

[35] A. Spiridonov, R. Stankevič, T. Gečas, T. Šilinskas, A. Brazauskas, T. Meidla, L. Ainsaar, P. Musteikis, S. Radzevičius, Integrated record of Ludlow (Upper Silurian) oceanic geobioevents–Coordination of changes in conodont, and brachiopod faunas, and stable isotopes, Gondwana Res. 51 (2017) 272–288.

[36] A. Spiridonov, J. Samsonė, A. Brazauskas, R. Stankevič, T. Meidla, L. Ainsaar, S. Radzevičius, Quantifying the community turnover of the uppermost wenlock and ludlow (silurian) conodonts in the Baltic basin, Palaeogeogr. Palaeoclimatol. Palaeoecol. 549 (2020) 109128, 18.

[37] J. Paškevičius, P. Lapinskas, A. Brazauskas, P. Musteikis, J. Jacyna, Stratigraphic revision of the regional stages of the upper silurian part in the Baltic basin, Geologija 17 (1994) 64–87.

[38] S. Radzevičius, A. Spiridonov, A. Brazauskas, D. Dankina, A. Rimkus, G. Bičkauskas, D. Kaminskas, T. Meidla, L. Ainsaar, Integrated stratigraphy, conodont turnover and palaeoenvironments of the upper Wenlock and Ludlow in the shallow marine succession of the Vilkaviškis-134 core (Lithuania), Newsl. Stratigr. 49 (2) (2016) 321–336.

[39] T. Želvys, A. Brazauskas, A. Spiridonov, M. Balčiūnas, A. Garbaras, S. Radzevičius, Stable carbon isotope stratigraphy of the Silurian in the Jočionys-299 borehole (eastern Lithuania), Est. J. Earth Sci. 71 (3) (2022) 127–134.

[40] J. Jacyna, O. Lauritzen, O. Zdanaviciute, S. Šliaupa, V. Nasedkin, Lithuania-petroleum Potential and Exploration Opportunities, Lithuanian Geological Survey, Vilnius, 1997.

[41] S. Laufeld, M.G. Bassett, Gotland: the anatomy of a Silurian carbonate platform, Episodes Journal of International Geoscience 4 (2) (1981) 23–27.

[42] V. Nestor, R. Einasto, Correlation of some wenlock outcrop sections of Gotland with the ohesaare section of Saaremaa, Estonia, in: Proceedings of the Estonian Academy of Sciences, Geology, vol. 46, Estonian Academy Publishers, 1997, pp. 155–168, 4.

[43] M. Calner, L. Jeppsson, A. Munnecke, The Silurian of Gotland—Part I: Review of the Stratigraphic Framework, Event Stratigraphy, and Stable Carbon and Oxygen Isotope Development, vol. 5, Erlanger geologische Abhandlungen, 2004, pp. 113–131. Sonderband.

[44] G. Bičkauskas, Sedimentology and Diagenesis of Minija Regional Stage (Silurian) Carbonates in Lithuania, Vilnius university, 2017. Doctoral dissertation.

[45] A. Hadding, Silurian reefs of Gotland, J. Geol. 58 (4) (1950) 402–409.

[46] I. Tuuling, T. Flodén, Silurian reefs off Saaremaa and their extension towards Gotland, central Baltic Sea, Geol. Mag. 150 (5) (2013) 923–936.

[47] S. Kershaw, Sedimentation control on growth of stromatoporoid reefs in the Silurian of Gotland, Sweden, J. Geol. Soc. 150 (1) (1993) 197–205.

[48] N.R. Watts, R. Riding, Growth of rigid high-relief patch reefs, mid-Silurian, Gotland, Sweden, Sedimentology 47 (5) (2000) 979–994.

[49] T. Flodén, M. Bjerkéus, I. Tuuling, M. Eriksson, A silurian reefal succession in the Gotland area, Baltic Sea, GFF 123 (3) (2001) 137–152.

[50] D. Michelevicius, D. Kaminskas, N. Blažauskas, The Silurian barrier reef structures of the Baltic petroleum basin (Lithuania) according to recent 3D seismic results, in: IX Congreso de Exploración y Desarrollo de Hidrocarburos, Instituto Argentino del Petróleo y el Gas, 2014, pp. 527–538.

[51] D. Kaminskas, D. Michelevičius, N. Blažauskas, New evidence of an early Pridoli barrier reef in the southern part of the Baltic Silurian basin based on three-dimensional seismic survey, Lithuania, Est. J. Earth Sci. 64 (1) (2015) 47–55.

[52] N. Stentoft, P. Lapinskas, P. Musteikis, Diagenesis of Silurian reefal carbonates, Kudirka oilfield, Lithuania, J. Petrol. Geol. 26 (4) (2003) 381–402.

[53] O. Zdanavičiūtė, K. Sakalauskas, Petroleum Geology of Lithuania and Southeastern Baltic, Institute of Geology, Vilnius, 2001.

[54] I. Vaičeliūnas, L. Jakaitė, A. Cichon-Pupienis, V. Lubys, R. Kirvelis, Tradicinių Angliavandenilių (Naftos) Parengtinė Žvalgyba (Gręžinio Vilkaviškis-135 Tyrimas). Atliktų Hidrodinaminių Tyrimų Gręžinyje Vilkaviškis-135 Informacinė Ataskaita [Priedas: Oil and Reservoir Water Analyses from Vilkaviskis 135 Well with Interpretation], Reports of Oil and Gas Institute – National Research Institute, UAB „Minijos nafta", 2016.

[55] A. Poupon, R. Gaymard, The evaluation of clay content from logs, in: SPWLA Annual Logging Symposium, SPWLA, 1970, May SPWLA-1970.

[56] M.R.J. Wyllie, A.R. Gregory, L.W. Gardner, Elastic wave velocities in heterogeneous and porous media, Geophysics 21 (1) (1956) 41–70.

[57] P. Muffler, R. Cataldi, Methods for regional assessment of geothermal resources, Geothermics 7 (2–4) (1978) 53–89.

[58] R. Cataldi, A. Lazzarotto, P. Muffler, P. Squarci, G. Stefani, Assessment of geothermal potential of central and southern Tuscany, Geothermics 7 (2–4) (1978) 91–131.

[59] C.F. Williams, Development of revised techniques for assessing geothermal resources, in: Proceedings, 29th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 2004, January, p. 7p.

[60] M. Doveri, M. Lelli, L. Marini, B. Raco, Revision, calibration, and application of the volume method to evaluate the geothermal potential of some recent volcanic areas of Latium, Italy. Geothermics 39 (3) (2010) 260–269.

[61] N.A. Zaigham, Z.A. Nayyar, Renewable hot dry rock geothermal energy source and its potential in Pakistan, Renew. Sustain. Energy Rev. 14 (3) (2010) 1124–1129.

[62] C.R. Chamorro, J.L. García-Cuesta, M.E. Mondéjar, M.M. Linares, An estimation of the enhanced geothermal systems potential for the Iberian Peninsula, Renew. Energy 66 (2014) 1–14.

[63] J. Limberger, P. Calcagno, A. Manzella, E. Trumpy, T. Boxem, M. Pluymaekers, J.D. van Wees, Assessing the prospective resource base for enhanced geothermal systems in Europe, Geothermal Energy Science 2 (1) (2014) 55–71.

[64] E. Trumpy, S. Botteghi, F. Caiozzi, A. Donato, G. Gola, D. Montanari, M.P.D. Pluymaekers, A. Santilano, J.D. Van Wees, A. Manzella, Geothermal potential assessment for a low carbon strategy: a new systematic approach applied in southern Italy, Energy 103 (2016) 167–181.

[65] C. Alimonti, E. Soldo, D. Scrocca, Looking forward to a decarbonized era: geothermal potential assessment for oil & gas fields in Italy, Geothermics 93 (2021) 102070.

[66] A. Franco, F. Donatini, Methods for the estimation of the energy stored in geothermal reservoirs, in: Journal of Physics: Conference Series, vol. 796, IOP Publishing, 2017 012025. No. 1.

[67] Y. Fan, S. Zhang, Y. Huang, Z. Pang, H. Li, Determining the recoverable geothermal resources using a numerical thermo-hydraulic coupled modeling in geothermal reservoirs, Front. Earth Sci. 9 (2022) 1–12, 787133.

[68] S. Šliaupa, G. Sneigienė, J. Jacyna, Geoterminių Duomenų Rinkimas Ir Sisteminimas, Lithuanian Geological Survey. Industry report, 2001. No. 5769.

[69] L. Balakauskas, A. Baliukevičius, A. Čečys, Žemės Gelmių Geoterminės Energijos Išteklių Skaičiavimo Metodikos Parengimas, Lithuanian Geological Survey. Industry report, 2017. No. 24670.

[70] R.J. Dunham, Classification of Carbonate Rocks According to Depositional Textures, 1962.

[71] R. Cicha-Szot, P. Budak, Special analysis of cores from Kudirka-1 well with interpretation (Industry report No. DK- 4100-133/18), in: I. Vaičeliūnas, L. Jakaitė, V. Lubys (Eds.), 2018. Tradicinių Angliavandenilių (Naftos) Parengtinė Žvalgyba. Žvalgybos Gręžinio Kudirka-1 Gręžimo (Įrengimo) Ataskaita, Oil and Gas Institute – National Research Institute, 2018 (in Lithuanian). Industry report of UAB "Minijos Nafta". Retrieved from Lithuanian Geological Survey archive, report No. 25010: unpublished.

[72] R. Cicha-Szot, P. Budak, Special analysis of cores from Vilkupiai-1 well with interpretation (Industry report No. DK- 4100-134/18), in: V. Lubys, L. Jakaitė, A. Cichon-Pupienis, R. Kirvelis, I. Vaičeliūnas (Eds.), 2018. Tradicinių Angliavandenilių (Naftos) Parengtinė Žvalgyba. Žvalgybos Gręžinio Vilkupiai-1 Gręžimo

(Įrengimo) Ataskaita, Oil and Gas Institute – National Research Institute, 2018 (in Lithuanian). Industry report of UAB "Minijos Nafta". Retrieved from Lithuanian Geological Survey archive, report No. 25009: unpublished.

[73] F.J. Lucia, Petrophysical Rock Properties. Carbonate Reservoir Characterization: an Integrated Approach, 2007, pp. 1–27.

[74] J.W. Schmoker, R.B. Halley, Carbonate porosity versus depth: a predictable relation for south Florida, AAPG Bull. 66 (12) (1982) 2561–2570.

[75] S. Homuth, A.E. Götz, I. Sass, Lithofacies and depth dependency of thermo-and petrophysical rock parameters of the Upper Jurassic geothermal carbonate reservoirs of the Molasse Basin, Z. Dtsch. Ges. Geowiss. (2014) 469–486.

[76] E. Mraz, M. Wolfgramm, I. Moeck, K. Thuro, Detailed Fluid Inclusion and Stable Isotope Analysis on Deep Carbonates from the North Alpine Foreland Basin to Constrain Paleofluid Evolution, vol. 2019, Geofluids, 2019, pp. 1–23. Article ID 8980794.

[77] S.H. Wadas, H. von Hartmann, Porosity estimation of a geothermal carbonate reservoir in the German Molasse Basin based on seismic amplitude inversion, Geoth. Energy 10 (1) (2022) 1–40.

[78] A. Cardona, J.C. Santamarina, Carbonate rocks: matrix permeability estimation, AAPG (Am. Assoc. Pet. Geol.) Bull. 104 (1) (2020) 131–144.

[79] Á. Ragnarsson, Geothermal energy in aquaculture. Geothermal training programme "short course VI on utilization of low- and medium-enthalpy geothermal resources and financial aspects of utilization", organized by UNU-gtp and LaGeo, in: Santa Tecla, El Salvador, March 23-29, 2014, 2014.