

**Evaluation of clay formations for the deep geological repository
of radioactive wastes in Lithuania**

Roma Kanopienė

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Abstract. The construction of a deep geological repository (DGR) for the spent nuclear fuel and high-level long-lived radioactive wastes is prescribed in Lithuanian legislation. Therefore, geological investigations for DGR host formation and site selection are being carried out. This paper presents a comparative suitability evaluation of two potentially suitable Lithuanian clayey formations. The suitability evaluation of Lower Cambrian and Lower Triassic clays was performed using the data set of laboratory test results from two decades. The results of laboratory investigations performed on clay material obtained from the unpreserved cores of nine boreholes were analysed in order to quantify the parameters relevant to the formation suitability. The data set contains the results of hydraulic conductivity measurements of several samples, mineralogical analysis of clay minerals, determination of Atterberg limits, chemical analysis (EDS method), and particle specific surface area measurements (BET method). Analysis of laboratory test results allow to compare the suitability for DGR installation of two Lithuanian clayey formations according to several properties. The clay fraction of the Lower Triassic potentially suitable formation is dominated by smectite/montmorillonite group minerals (60–88%), and the dominance of illite (60–95%) is characteristic of Lower Cambrian clay. The determination of Atterberg limits indicates a similar (medium) plasticity of both formations. The specific surface area of particles ranges from 30.9 to 54.8 m²/g in Lower Triassic samples and from 28.0 to 32.7 m²/g in Lower Cambrian samples. A higher smectite content and a larger specific surface area show a greater swelling and sorption capacity of Lower Triassic clay. Clay swelling and sorption capacity are important features causing geological environment suitability for the DGR. Although the tests were conducted on unpreserved and degraded samples, their results support the conclusion that the suitability of the Lower Triassic potentially suitable formation is comparatively greater.

Keywords: DGR programme; suitability for DGR; clayey formations; unpreserved core; milled samples

✉ *Roma Kanopienė* (defamor@hotmail.com),  <https://orcid.org/0000-0001-8704-8143>;

Vilnius University Institute of Geosciences, M. K. Čiurlionio str. 21, LT-03101, Vilnius; Lithuanian Geological Survey, S. Konarskio str. 35, LT-03123, Vilnius

INTRODUCTION

According to the European Council Directive 2011/70/Euratom of 19 July 2011 all radioactive wastes should be managed and finally disposed in the territory of the country where those are produced. The construction of a DGR for the spent nuclear fuel and high-level long-lived radioactive wastes is planned in Lithuania (Lithuanian...2016). Geological investigations for the recent stages of the Lithuanian DGR programme mainly consist of the desktop studies. All the data about geological structure of Lithuania are ac-

cumulated at the Lithuanian Geological Survey under the Ministry of Environment (LGT). The available information could be divided into four main groups: 1) borehole data, 2) geological and geophysical mapping data, 3) raw material prospecting and exploration data, and 4) results of technical geological investigations summarised in various reports. Based on these datasets, the site selection process for the Lithuanian DGR was initiated, and reports on potentially suitable geological formations, site suitability criteria, and the prioritization of candidate locations were prepared (Čyžienė *et al.* 2022, 2023).

A dedicated methodology for evaluating the suitability of geological formations for the DGR was developed in 2022 (Kanopienė, Gadeikis 2022). The created methodology relies on the safety requirements and recommendations established by the International Atomic Energy Agency (IAEA 1994, 2011). The systematic approach, world-wide generally applied criteria (Mallants *et al.* 2018), geological data available in Lithuania and multiple criteria analysis were used as a basis of the created methodology. Created methodology allows to use qualitative criteria together with quantitative ones. The results of the application of the mentioned methodology showed that the clayey geological formations of the Cambrian and the Triassic are more suitable for the Lithuanian DGR than other formations. This supports the suggestion to concentrate further geological investigations on those two clayey formations in Lithuania.

There are no recently drilled boreholes penetrating Lower Triassic and Lower Cambrian potential formations in Lithuania. Clayey rock material could not be taken from the core of the natural conditions. However, several tests of the clayey formations' samples taken from the old unpreserved altered cores had been performed for the quantitative evaluation of the formation's suitability for the DGR and the determination of several key parameters required for subsequent DGR performance assessment. Core material from nine boreholes provided clayey material which had been sampled, and laboratory tests had been performed using the crushed bulk material of the rocks. The properties or features of clayey rocks that do not depend very much on the moisture content and other natural conditions have been determined. The results of laboratory tests from the initial stages of the Lithuanian DGR programme have been analysed together with the results of recently performed investigations with the purpose of the quantitative evaluation of the clayey formations suitability for the DGR and preparation of the data sets for the further stages of the DGR sitting process, and features, events and processes (FEPs) analysis that is a safety assessment method for the geological disposal of radioactive waste.

PREVIOUS INVESTIGATIONS

There are 1148 core-drilled deep (depth more than 200 m) boreholes (total length about 140 km) in Lithuania. Borehole cores are available at the core storage of the Underground Information Centre. The drill cores are unpreserved (not protected from oxidation and drying-out) and are altered. The properties of rocks that depend on moisture content and oxidising conditions differ very much from the natural ones. Information about the deep geological structure of Lithuania is related to the boreholes of oil prospecting, structural investigations and deep geological

mapping. Geological mapping at a scale of 1: 200,000 covers all the territory of Lithuania. This scale was selected as a working scale for the graphical information of the desktop studies of the recent DGR site selection project stages. Some geological formations (systems) are investigated in detail during oil, rock salt, anhydrite and other mineral resources prospecting and exploration. The results of these investigations have been analysed as basic quantitative data about the potentially suitable geological formations. The data summarised in the technical reports of different geological investigations have been constantly used in the recent selection process of geological formations and sites for the Lithuanian DGR.

The prospective investigations for the DGR started in Lithuania in the beginning of recent century. Between 2001 and 2006, Lithuania conducted small-scale geological investigations related to the establishment of the DGR. These tasks were carried out by the LGT in collaboration with the Lithuanian Radioactive Waste Management Agency (RATA), the Institute of Geology and Geography, Lithuanian Energy Institute (LEI) and other institutions.

By 2003, a very general overview of the geological conditions across Lithuania was completed, including the positive and negative screening of the territory for the DGR site selection. Positive screening utilized areas where potentially suitable geological formations occurred. The geological bodies of sufficient thickness (more than 50 m) laying at a depth greater than 200 m and consisting of the rocks which are considered suitable in advanced foreign DGR programmes were defined as potentially suitable formations. Negative screening relied on the data concerning protected areas, mineral resource deposits, groundwater well-fields, potentially active neotectonic zones, deep palaeoincisions (deep valleys), and territories near the state borders (Kanopienė, Gadeikis 2023).

In 2004, the disposing possibilities for the spent nuclear fuel and long-lived radioactive waste in Lithuania's crystalline rocks were analysed. The most critical geological issues related to both crystalline and sedimentary rocks were identified. The tectonic movements and faulting of the Lithuanian crystalline basement were examined in detail. Additionally, the lithology and lithofacies of the potentially suitable sedimentary rocks were analysed (Čyžienė *et al.* 2005), and detailed geological and lithological cross-sections were elaborated (Kanopienė *et al.* 2005). The geological studies of 2005 focused on evaluating the suitability of Lower Triassic clay for the DGR installation. Beyond reviewing previous investigation results and old borehole core, several tests on clay samples were performed. Several samples were taken from old cores of the boreholes drilled in the areas with suitable depths of formation occurrence. Analy-

ses of grain size distribution, plasticity, and mineralogical composition were carried out in Lithuanian laboratories. Experiments to establish pore water chemistry and hydraulic conductivity were conducted at the Belgian Nuclear Research Centre (SCK-CEN).

According to the results of performed tests, the quantity of the grains (133 samples tested) smaller than 0.002 mm in diameter (fines) varied from 10% up to 60% (statistic average 31.6%). The average plasticity (plasticity index I_p) of the fine fraction (27 samples tested) was 0,193. The results of X-ray diffraction analysis indicated the dominance of smectite among clay minerals in the Lower Triassic samples.

Although the experiments for pore water chemistry and hydraulic conductivity determination did not fully meet standard requirements, the results suggested that the pore water type might be sodium sulphate (only 3 samples tested), and the hydraulic conductivity varied from 3.33×10^{-12} to 8.12×10^{-12} m/s.

The region of Ignalina Nuclear Power Plant (INPP), as the major producer of Lithuanian radioactive waste, was named as highly convenient for DGR installation from a socioeconomic perspective. In 2006, a project was conducted to evaluate the suitability of geological environment for DGR installation in this region. A desktop study was performed on the basis of results of comprehensive geological mapping at a scale of 1:50,000 (Marcinkevičius *et al.* 1995). The entire sequence of the sedimentary cover was characterised by 6 deep boreholes drilled to the depths of 750–800 m and reaching the crystalline basement rocks. The geological column in this area consists of the Lower Proterozoic crystalline basement, Baikalian (Vendian, Lower Cambrian), Caledonian (Lower-Middle Cambrian, Ordovician, Lower Silurian) and Hercynian (Middle and Upper Devonian) structural complexes covered by Quarternary deposits (Marcinkevičius, Laškovas 2007). The results of the mentioned mapping presented the evaluation of the hydrogeological conditions of the region based on hydrodynamic well testing. During the 2006 project, a hydrodynamic scheme of the INPP region was compiled (Kanopienė, Gadeikis 2023), which provides the vertical directions of the hydraulic gradient and would be useful for the hydrogeological modelling of the region.

METHODOLOGY AND RESULTS

Core sampling

The descriptions of 145 boreholes were reviewed in the technical reports and the digital information system in order to select samples for additional laboratory testing. Most of them were related to Triassic clayey rocks. Only 11 boreholes penetrating the entire Lower Cambrian potentially suitable formation were found in the documents. After the desktop revision of the descriptions, the availability of the drill cores was checked. Only 30 boreholes (20 of the Lower Triassic and 10 of the Lower Cambrian) were evaluated as suitable for sampling. After considering the possibilities to cover larger areas of occurrence of both potential formations, to sample all the sequence of them, and to get a similar amount of data for their suitability evaluation, the total number of boreholes was reduced to 9. Old drill cores collected from 5 boreholes crossed the Lower Cambrian clays and were distributed in east Lithuania, while Lower Triassic clays (mudstones) samples were collected from 4 boreholes distributed in the western part of Lithuania. (Fig. 1). The names, registry numbers, coordinates of borehole location and the number of samples taken are presented in Table 1.

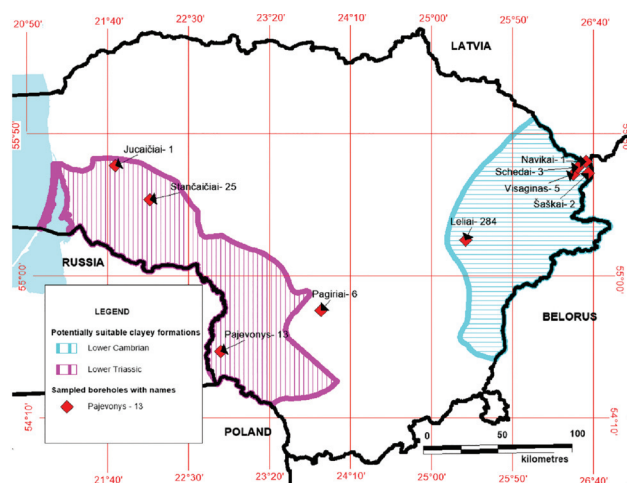


Fig. 1 Location of the sampled boreholes and potential areas for DGR

Table 1 Tested samples

No	Borehole name	Register No	Coordinates in LKS 94 system		Sampled depth interval, m	Geological index	Amount of tested samples
			X	Y			
1.	Jucaičiai-1	25112	6170576	358247	273–455	T_1	7
2.	Stančiai-25	10415	6147623	379821	320–400	T_1	1
3.	Pajevonys-13	26301	6047241	424555	440–670	T_1	6
4.	Pagiriai-6	20448	6073553	491303	250–290	T_1	2
5.	Šaškai-2	20555	6166398	664504	495–530	C_1	5
6.	Navikai-1	20554	6173929	663083	510–570	C_1	3
7.	Leliai-284	8081	6120477	585987	560–620	C_1	6
8.	Visaginas-5	20558	6165189	655138	500–510	C_1	1
9.	Schedai-3	20556	6170022	657854	510–550	C_1	2

A different number of samples were tested for various features. The material for the determination of plasticity was taken directly from the samples. Other analyses needed a special form of the clay material. The latter were prepared for the tests at the LGT laboratory. During sample preparation procedure, 10 g of a sample were crushed using a ball mill Fritsch Pulverisette 6; the milling process lasted for 25 min (14 samples) and 45 min (12 samples). The produced powder of clay material was provided for the tests of chemical composition (EDS method) and specific surface area (BET method).

Analysis of clayey rock composition

The clayey rock material of unpreserved core altered during the 30–50 year period of its storage. It was assumed that rock mineralogy and the chemical composition of rock material could be the features which are relatively less sensitive to these changes. That was a reason to perform the mineralogical and chemical analyses of the core samples.

Summarising previous and recent investigations, analysis of mineralogical composition was performed on two kinds of clay samples. The first one contained the samples of separated clay fraction, and the second one contained the samples of the bulk rock material.

The X-ray diffraction (XRD) analysis of a separate clay fraction was performed during previous investigations. The tests of Lower Cambrian clay (22 samples from 3 boreholes analysed) were performed during the comprehensive geological mapping at a scale of 1: 50,000 in the region of INPP (Marcinkevičius *et al.* 1995). The results of this analysis show a very strong dominance of illite (60–95%) among clay minerals. The part of kaolinite ranges from 5 to 10% and sometimes reaches 40% (2 samples from the largest depth). Several percent of chlorite were determined in the material of 14 samples. The clay fraction of Lower Triassic clay (26 samples from 3 boreholes tested) was analysed during a special scientific study for the characterisation of Lower Triassic clay mineralogical composition (Špokauskas 2005). The results of this study show that smectite (montmorillonite) dominates in the clay fraction of Lower Triassic samples, and its part varies from 60% up to 88%. The part of illite minerals varies from 7% to 25%, and chlorite comprises about 10%.

The XRD analyses of the bulk rock material of Lower Cambrian clay (10 samples from 4 boreholes analysed) were performed during previous investigations at Belgian SCK CEN (3 samples) and recently at the Vilnius University Institute of Chemistry (7 samples). Together with the XRD analysis of 3 Lower Cambrian samples the cation-exchange capacity (CEC) was measured. It varied from 9 to

12 meq/100 g in Lower Cambrian clay material. Clayey rock material (7 samples) of the Lower Triassic have also been recently analysed at Vilnius University. The results of bulk rock material analyses show the dominance of the same clay minerals as of the investigations of separate clay fractions. The smectite group is characteristic of Lower Triassic clay samples, and mica with chlorite is characteristic of Lower Cambrian samples. The quartz and K-feldspar are the principal non-clay minerals in all tested samples, and quite a high amount of dolomite is characteristic only of Lower Triassic clay.

In addition to XRD, the determination of chemical composition was performed on the same milled samples (13 of the Lower Cambrian and 13 of the Lower Triassic). The method of Energy-Dispersive X-ray Spectroscopy (EDS) was used to determine chemical elements in the samples. The method is based on the principal that each element has a characteristic atomic structure. During the analysis, a focused beam of high-energy electrons from an instrument strikes the sample. Consequently, the atoms in the material emit characteristic X-rays. The EDS detector sorts the X-rays by energy, creating a spectrum and specific software, calculates and provides the elemental composition of the sample. The EDS analysis was performed at 3 points of each sample, which means 21 measurements of each clayey formation. The summarised data on elemental composition is presented in Table 2.

The EDS analysis showed a similar content of the elements that form the clay minerals – carbon, silica and aluminium (C, Si, Al). The difference was noticed in magnesium (Mg) and calcium (Ca). A higher content of these elements reaching 6.84% of Mg and 5.84% of Ca in Lower Triassic clay samples might be caused by small inserts and lenses (Fig. 2) of carbonates (calcite, dolomite) or fluid migration from the dolomite-rich

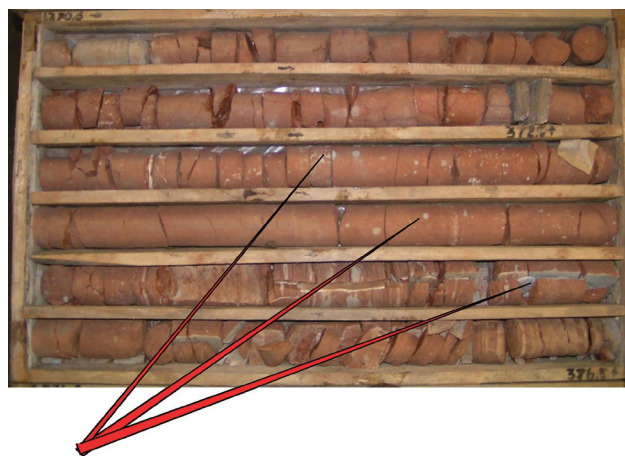


Fig. 2 Pointers indicating the spots and insertions of carbonates visible in Lower Triassic clay core. The length of the core box is 1 meter (photo by author)

Table 2 Elemental composition of clay samples (Kanopienė, 2024)

Element	Min. weight %	Max. weight %	Average weight %	Number of measurements
Lower Triassic. Interval of depth 260.0–422.5 m				
C	3.69	22.7	8.56	19
O	46.49	61.82	55.34	20
Na	0.16	1.59	0.57	19
Mg	0.38	6.84	2.75	20
Al	3.76	11.25	6.99	19
Si	11.89	31.99	18.44	20
S	0.15	1.12	0.48	5
K	1.13	4.13	2.05	19
Ca	0.2	5.84	2.46	19
Ti	0.16	1.29	0.37	19
Fe	2.23	7.39	3.67	19
Lower Cambrian. Interval of depth 516.8–558.4 m				
C	3.41	22.57	9.06	18
O	47.52	60.55	54.27	20
Na	0.18	1.41	0.44	19
Mg	0.31	4.49	0.85	19
Al	2.25	11.40	7.83	20
Si	14.02	31.03	20.56	20
S	0.10	0.41	0.20	6
K	1.15	9.05	3.65	19
Ti	0.10	0.57	0.28	16
Fe	0.82	7.71	4.03	19

layers. The results of the tests performed are suitable only for the comparative evaluation of samples, because the chemical and mineralogical composition of clayey rocks could be changed due to material alteration in oxidising conditions (Churchman, Lowe 2012), and secondary minerals could be formed during a quite long alteration period (Evans 1992). Furthermore, it is impossible to assign elements to certain minerals because of unknown natural state of the samples. However, the chemical and mineralogical composition of tested clay material could be comparable between two groups of samples because the core storage conditions were the same for all of them.

Plasticity

The characteristic properties of clay (plasticity, cohesiveness) are caused by particles smaller than 0.002 mm (clayey substance). When examined under a microscope, their crystalline structure can be observed. The clays of lower purity, especially more plastic ones, contain very fine, shapeless particles formed from disintegrated crystals. Each particle of the plastic clay is covered by water film. When the clay is drying it loses plasticity. Many physical and mechanic properties of clayey rocks depend on the natural water content. Nevertheless, the plastic and liquid limits could be determined using the old core samples. In addition to previously performed tests of Lower Triassic clay, recently the determination of the Atterberg limits has been carried out on 7 samples of

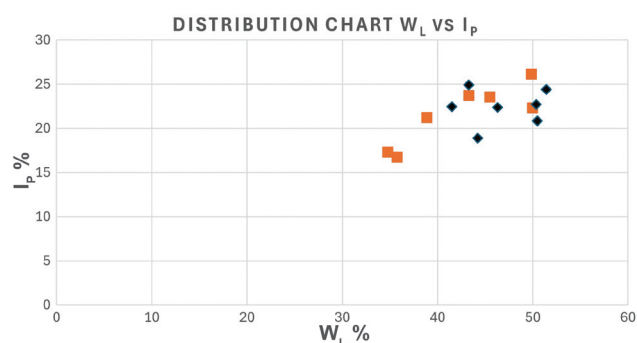


Fig. 3 Distribution of liquid limit and plasticity index ratio. Brown squares – Lower Triassic samples, blue rhombuses – Lower Cambrian samples

the Lower Cambrian clay core. The tests were performed in the LGT laboratory according to the standard LST CEN ISO/ TS 17892-12: 2018. The liquid limit (w_L) was determined using a method of cone penetration at 4 points. The mass of the cone was 80 g, and the angle of the cone apex was 30°. The plastic limit (w_p) was determined by a rolling method. The results of Lower Cambrian samples testing are quite similar to the ones of the Lower Triassic. For comparison, Table 3 and Fig. 3 were compiled.

Surface area of particles

The determination of the specific particle surface area was performed at Vilnius University Institute of Chemistry by using the BET analyser by Micromerit-

Table 3 Results of plasticity tests (Kanopienė 2024)

Borehole	Depth, m	w _L , %	w _p , %	I _p , %	Lithology
Lower Triassic					
Jucaičiai-1	261.8–261.9	43.3	19.6	23.7	Medium plasticity clay
Jucaičiai-1	305.4–305.5	35.8	19.1	16.7	Medium plasticity clay
Stančiai-25	228.7–228.9	50.0	27.7	22.3	Medium plasticity clay
Stančiai-25	293.4–293.5	38.9	17.7	21.2	Medium plasticity clay
Stančiai-25	322.8–323.0	49.9	23.8	26.1	Medium plasticity clay
Pagiriai-6	221	45.5	22.0	23.5	Medium plasticity clay
Pagiriai-6	260	34.8	17.5	17.3	Low plasticity clay
Lower Cambrian					
Schedai-3	535.0–535.2	43.27	18.36	24.91	Medium plasticity clay
Schedai-3	516.8–517.0	50.37	27.36	22.71	Medium plasticity clay
Šaškai-2	527.6–527.8	46.29	23.91	22.38	Medium plasticity clay
Navikai-1	558.2–558.4	50.48	29.64	20.84	Medium plasticity clay
Navikai-1	526.7–526.9	41.52	19.06	22.46	Medium plasticity clay
Navikai-1	514.3–514.5	51.43	27.03	24.40	Medium plasticity clay
Visaginas-5	503.0–503.2	44.2	25.28	18.91	Medium plasticity clay

Table 4 Summarised results of specific surface area measurements

No	Sample name	Geological index	Specific surface area, m ² /g
1	Juc 1-10/1	T ₁	54.80
2	Pag 6-16/3	T ₁	30.88
3	Juc 1-20/6	T ₁	46.32
4	Sched 3-12/16	C ₁	30.6
5	Nav 1-3/20	C ₁	32.74
6	Vis 5-10/21	C ₁	28.04

ics Instrument Corporation “TriStar II 3020 V1.03”. BET is an abbreviation of the scientists Stephen Brunauer, Paul Hugh Emmett, and Edward Teller names. The BET theory applies to the systems of multilayer adsorption that usually utilizes probing gas (called the adsorbate) that does not react chemically with the adsorbent (the material to which gas attaches) to quantify the specific surface area. Nitrogen is the most employed gaseous adsorbate for probing surface, and it was used for the current measurements. Gas temperature was -195.850 °C and saturation pressure was about 101.3 kPa during measurements. The same samples of the clayey rock core as for the EDS analysis were used. The specific surface area of particles was measured in 3 samples of Lower Cambrian clay and 3 samples of Lower Triassic clay (Table 4).

Specific surface area was defined to be somewhat larger for the Lower Triassic, which correlates with the predominance of smectite clay, while kaolinite mineral was typically characterized by a lower value (Macht *et al.* 2011). The specific surface area of the particles in the material is an important feature for DGR safety because of its strong relation with the sorption capacity. A larger particle surface area means there are more active sites available for the substance to be adsorbed or absorbed onto, leading to a higher sorption capacity. Due to a very small number of the

tested samples, the specific surface area determination results could be used only as indicators in suitability evaluation.

EVALUATION OF CLAYEY ROCKS' SUITABILITY FOR DGR INSTALLATION

Clay rocks, or rocks with a high clay content, offer promising isolation properties over time periods that are as long as the age of their host geological formations. Constructing a repository in such material does not significantly change the clay's isolation properties, which is a great advantage (Grambow 2016). Clay formations are considered potentially suitable for DGRs in many countries, such as Switzerland, France, and Belgium. In several other countries (Canada, Hungary, Japan, Germany), clays still are under consideration (NEA 2020). The selection of the most suitable geological formation for a DGR is a very important decision worldwide. Making such a decision as early as possible is even more important because it could save financial and other resources in the DGR sitting process. Two clayey formations, Lower Cambrian and Lower Triassic, have been evaluated as potentially suitable for the DGR in Lithuania. Currently known features, events and processes of these Lithuanian formations correspond to the hypotheses suggested to be highly relevant in establishing confidence in formation suitability to host a DGR (NEA 2022). The methodology of suitability evaluation including 23 criteria (Kanopienė, Gadeikis 2022) was applied to the mentioned formations. The criteria for the suitability evaluation in the mentioned methodology were determined according to the best international practice and characterise geological factors which are most important for the DGR safety. For the comparison of two Lithuanian clayey formations, quantitative data are needed. The laboratory tests of

the core samples are only the first steps in the quantification of the suitability evaluation in Lithuania.

The results of the investigations described above show that the mineralogical composition of the Lower Triassic clay formation is more suitable for the DGR than the Lower Cambrian formation because of a higher content of smectite. This feature could be an additional suitability evaluation criterion. The smectite content relatively shows the swelling ability or capacity of the rock which is important for the healing of fissures and fractures and makes the rock less permeable for fluids. The plasticity of both clayey formations is quite similar, and the suitability of both formations could be evaluated as equal according to this parameter if used as an evaluation criterion.

The specific surface area of particles might be used for the suitability evaluation for the DGR only as an indicator because of very few samples tested. This feature relatively shows the sorption capacity of the material important for the retardation of radionuclides. Their specific surface area of particles is larger in Lower Triassic samples, and this formation could be evaluated as relatively more suitable for DGR according to this indicator.

The results of Lithuanian clayey rocks tests fall within the range of values determined for the clayey formations considered suitable for DGRs in different countries (NEA 2022).

CONCLUSIONS

Only limited data are available in Lithuania to assess the suitability of its geological formations for hosting a GDR. Hence, it is difficult to compare the suitability of clayey formations quantitatively because of the lack of well-preserved samples, the lack of tests results, and various details of research. The necessity of the drilling of new boreholes and getting the samples of fresh cores had been stressed many times before (IAEA 2023; Kanopienė, Gadeikis 2023).

The composition investigations of borehole core material of the Lower Triassic formation show the smectite group minerals dominance among the clayey fraction minerals and a significant amount of dolomite among non-clay minerals. The investigations of the Lower Cambrian clay material composition show the dominance of mica group and chlorite among the clay minerals. The non-clayey part consists mostly of quartz and feldspar in the samples of both formations. Smectite content might be determined as a criterion for the suitability evaluation, and Lower Triassic clay could be evaluated as relatively more suitable for the DGR according to this criterion.

The investigations of Atterberg limits showed that the plasticity of the samples for both formations is similar. However, this feature might be determined

as a criterion for a further quantitative evaluation of clayey rock suitability for the DGR.

The specific surface area of particles may be determined only as an indicator of suitability evaluation for the DGR because of very few samples tested. The values of this parameter are larger in Lower Triassic samples, and this formation could be evaluated as relatively more suitable for the DGR according to this indicator.

Calculations according to the created formation selection methodology (Kanopienė, Gadeikis 2022) showed a higher suitability of the Lower Triassic formation compared to the Lower Cambrian formation. Analysis of the laboratory test results also shows that Lower Triassic clay is relatively more suitable for the DGR installation than Lower Cambrian clay is. This illustrates the benefit of the use of the created formation selection methodology prior to detailed direct investigations and drilling.

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Conflict of interests. The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The author declares that AI technologies have not been used for the preparation of the article.

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