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Prospects for CO_2 geological storage in deep saline aquifers of Lithuania and adjacent territories

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Carbon dioxide emission to the atmosphere is one of the most urgent global-scale ecological problems. A large amount of gas emitted since the nineteenth century has led to a 0.5 °C climate warming which seems to progress. Different possibilities of eliminating CO_2 have been considered over the past decades, but no effective method has been developed so far.

The geological storage of CO_2 is regarded as one of the most mature technologies. Depending on geological conditions, several types of geological formations, such as deep saline aquifers, depleted oil / gas fields and coal seems, are considered as potential geological formations for CO_2 storage.

The Baltic sedimentary basin contains several large deep saline reservoirs. Our study shows that only the Cambrian aquifer representing the basal part of the sedimentary cover can be used for the geological storage of carbon dioxide. The practical storage capacity of Lithuania is evaluated as low. On the other hand, a higher-risk scenario implies a rather large storage potential in West Lithuania.

Key words: CO_2 emissions, the Baltic, geological storage, saline aquifer, structural trap

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INTRODUCTION

Most energy used to meet human needs is derived from the combustion of fossil fuels (natural gas, oil, coal, oil shale), which release carbon to the atmosphere, primarily as carbon dioxide (CO_2). Every year, about 7 Gt of carbon dioxide is emitted globally (IPCC, 2007). The atmospheric concentration of CO_2, the greenhouse gas, is increasing, raising concerns that solar heat will be trapped and the average surface temperature will rise in response.

According to the Kyoto protocol, the emissions should be decreased by 8% during 2008–2012 (reference year 1990). Lithuania has joined the protocol along with other countries.

Geological storage of carbon dioxide is one of the major options of the CO_2 emission reduction portfolio (IPCC, 2005; Lackner Ziock, 2000). This approach can be applied to storing CO_2 emitted from large industrial sources such as coal-based power plants, steel plants, cement plants, refineries, etc. In Lithuania, CO_2 emissions are rather low: the CO_2 emission rate is 4.51 tons per capita (http://earthtrends.wri.org). Annual CO_2 emissions amount to 15.1 Mt (year 2008). The stationary sources, the annual rate of which exceeds 100,000 tons of CO_2, produce in total about 4.5 Mt of CO_2 annually. The emission rate was declining since 1993 and reached the minimum in 2001 (about 12 Mt). Yet the emission rate shows a gradual increase since 2001 (National Greenhouse…, 2007); 101 instillations are provided with the allowances that produced 6.4 Mt of CO_2 (year 2010) (http://www.laaif.lt).

For comparison, large sources emit 1.9 Mt of CO_2 in Latvia. Nine large (>100,000 t/a CO_2) sources are located in Estonia. They are concentrated in the north and northeast of the country, producing altogether 11.5 Mt CO_2 (2005), i. e.

91% of all emissions produced in Estonia by 42 enterprises registered in the ETS and 55% of the total Estonian CO_2 emissions (20.9 Mt). Large emissions were produced mainly by two big power plants (10 Mt CO_2) using oil-shales (Shogenova et al., 2009).

CO_2 is already being captured and injected in the geological formations in the oil and gas and chemical industries. Since early 1970s, it has been applied for enhanced oil recovery (Kane, 1979; Jessen et al., 2005), when Chevron first developed a plan for the first miscible CO_2 flood in the Permian Basin, at the SACROC Unit. The Chevron company is recovering CO_2 from produced gas at four gas plants since 1972. While only about 10–30% of oil is typically extracted by conventional oil production processes, EOR (enhanced oil recovery) methods can enhance these recovery rates by an additional 5% to 20% on a conservative average. Since 2005, when it totalled $3.1 billion barrels of crude oil, it has been showing a rapid growth. EOR application provides a valuable experience for large-scale CO_2 geological storage planning. Recently, CO_2-EGR (enhanced gas recovery) studies have been initiated as another prospective technique (Polanck, Grimstad, 2009).

CO_2-EOR is considered as most mature technology for storing carbon dioxide in geological formations. However, the volumes available for CO_2 sequestration are rather limited and can not cover the needs of industry for CO_2 capturing and storaging. Deep saline aquifers are considered as the most prospective formations for CO_2 sequestration (Bruant et al., 2002; Lokhorst, Wildenborg, 2005). Only aquifers unsuitable for potable water supply and agricultural purposes are considered as the target formations.

There is an immense volume of deep saline aquifers. However, the storage capacity of a particular aquifer is limited to the volume of the hydrodynamic traps. The concept of CO_2 storage requires the confinement of gas within stratigraphic or structural traps (Fig. 1), like the underground natural gas storage, in order to ensure a safe entrapment and no escape of gas into the overlying potable water aquifers or atmosphere.

CO_2 injection in a gas phase is a challenging reservoir engineering problem. By contrast, the storage of CO_2 in a supercritical state is a more efficient approach. Therefore, the potential of deep saline aquifers is limited to >800 m in depth and a temperature of 31 °C (e. g., Ennis-King et al., 2003). At greater depths, carbon dioxide is stored in a supercritical state.

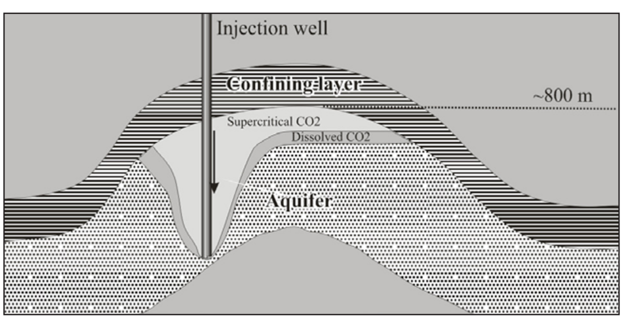

Fig. 1. Concept of CO_2 storage in deep saline aquifer
1 pav. CO_2 geologinio saugojimo koncepcija

There are other alternative technologies for CO_2 storage in geological formations, such as storage in unminable coal seams (Stevens, Spector, 1998) and salt caverns (Dusseault, Bachu, Davidson, 2001). However, these technologies are immature and are not considered as the near-future storage options.

STORAGE CAPACITY ASSESSMENT

An assessment of the storage potential of structural traps in deep saline aquifers of Lithuania was performed. Data on reservoir properties, depth, formation water composition and pressure, temperatures were collected from industrial reports.

In a saline aquifer, the pore volume available for CO_2 storage (the effective storage capacity) depends on the geometric volume of the structural or stratigraphic trap down to the spill point, as well as on its porosity, sweep efficiency and the irreducible water saturation (Bachu et al., 2007):

$$M_{CO2} = A \times h \times \varphi \times \rho_{CO2} \times S_{eff} \times (1 - S_{Wirr}),$$

here

M_{CO2} = effective storage capacity,
A = area of trap,
h = average thickness of trap multiplied by the net-to-gross ratio,
φ = average aquifer porosity,
ρ_{CO2} = CO_2 density at saline aquifer conditions,
S_{eff} = sweep efficiency,
S_{Wirr} = irreducible water saturation.

The storage capacity of individual structures was assessed using this approach.

BASIC REQUIREMENTS TO DEEP SALINE AQUIFERS FOR CO_2 STORAGE

There are certain requirements to a deep saline aquifer. As stressed above, the major condition is unsuitability of an aquifer for water exploitation. Also, the storage site must ensure a safe entrapment of carbon dioxide to prevent it from gas leakage to other geological formations and atmosphere. The formation should be well sealed by overlying impermeable lithlogies (e. g., shales) thick enough to resist the pressure induced by CO_2 injection into the reservoir. Furthermore, as far as very large quantities of CO_2 are considered to be stored in geological formations, the aquifer should be characterised by large storage volumes and good reservoir properties.

All these requirements considerably reduce the potential of saline aquifers. Therefore, an integrated study has to be performed to screen the geological formations in the region. Such assessment, using a common approach, was performed in the Baltic States.

PROSPECTIVE AQUIFERS OF THE BALTIC REGION

Lithuania is situated in the eastern part of the Baltic sedimentary basin (Paškevičius, 1997). All geological systems are present in the geological section of the sedimentary basin. Due to protracted sedimentation processes, a number of aquifers separated by impermeable lithologies have accumulated in the basin. Only the largest aquifers were inspected for CO_2 storage purposes.

The Cambrian saline aquifer

The deep saline Cambrian aquifer matches the basic requirements to a reservoir for CO_2 sequestration (Shogenova et al., 2007, 2008, 2009; Šliaupa et al., 2009). It represents the basal part of the sedimentary cover and is the most tectonised (though to a minor degree) layer in the region (Stirpeika, 1997). Accordingly, a number of structural traps have been identified. The reservoir is well studied owing to petroleum prospects in West Lithuania. The reservoir is sealed by 400–800 m thick carbonaceous-shaly cap rocks; this is important for a safe storage of CO_2. The depth of the Cambrian sediments ranges from 0.3 km in Southeast Lithuania to more than 2 km in West Lithuania (Fig. 2). The prospective area, in terms of P-T conditions, encompasses the western part of Lithuania and extends to West Latvia, Kaliningrad District and offshore (Fig. 2).

The reservoir is composed of quartz sandstones with rare shale and siltstone layers. The thickness of the reservoir is about 40–60 m. The formation water is of Na–Cl type, and salinity is in the range 100–200 g/l within the prospective area. The reservoir properties are decreasing westward mainly due to an increase in quartz cementation. The average porosity is about 22% in Central Lithuania and less than 10% in West Lithuania (Šliaupa et al., 2003).

Middle–Lower Devonian saline aquifer

The Pärnu–Kemeri (Middle–Lower Devonian) aquifer is distributed in Central and West Lithuania. The depths exceeding 800 m and a temperature higher than 31 °C have been reported from only westernmost Lithuania and the adjacent Baltic Sea.

The aquifer is composed of quartz and feldspar-quartz fine-grained sandstones with siltstone and shaly layers composing 30–40% of the succession. The average porosity of sandstones is 26%, and the permeability is in the range 0.5–4 D.

The total thickness varies from 100 m. in the east to 160 m in the west of Lithuania and in the adjacent offshore. The aquifer is covered by 80–120 m thick marlstones with subordinate dolomites and strongly cemented sandstones attributed to the Narva Formation of the Middle Devonian. It is a basin-scale aquitard which separates the

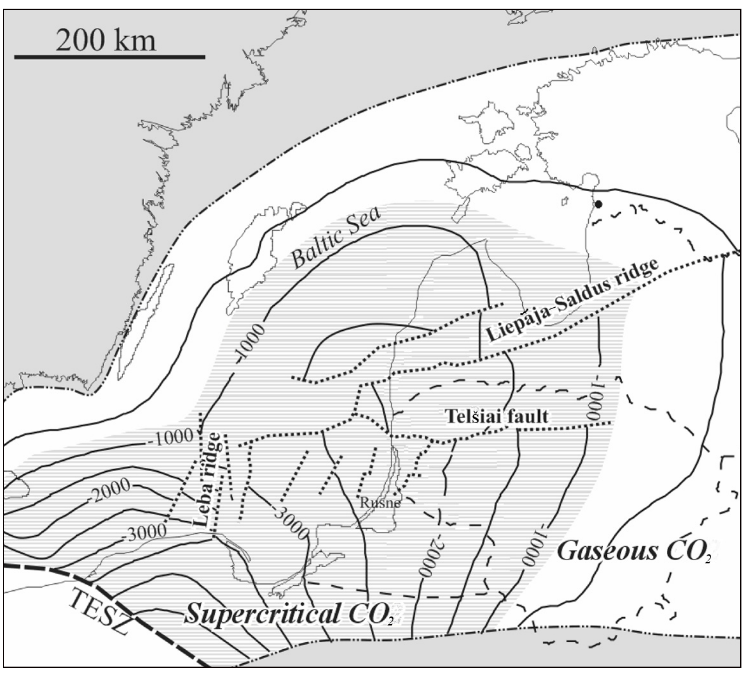

Fig. 2. Depths of the top of the Cambrian aquifer. Contour lines indicate the depths of the Cambrian top. Hatched lines show major faults. P-T fields of gaseous (white) and supercritical (dotted) state of CO_2 are indicated

2 pav. Kambro vandeningojo sluoksnio kraigo gyliai. Izolinijos žymi gylius, brūkšninės linijos – lūžius. Pažymėti CO_2 superkritinės ir dujinės būklės laukai

Pärnu–Kemeri aquifer from the overlying Šventoji–Upninkai aquifer extensively used for drinking water supply. The salinity of the Pärnu–Kemeri formation water in West Lithuania is 40–90 g/l.

Despite the high quality of the reservoir, the Pärnu–Kemeri aquifer is not considered as prospective for CO_2 storage. The hydrodynamic traps (structures) are required to store CO_2. Based on seismic and drilling data, only small-scale uplifts were identified; their amplitude did not exceed 15 m. Typical examples of Lower Devonian structures are shown in Fig. 3.

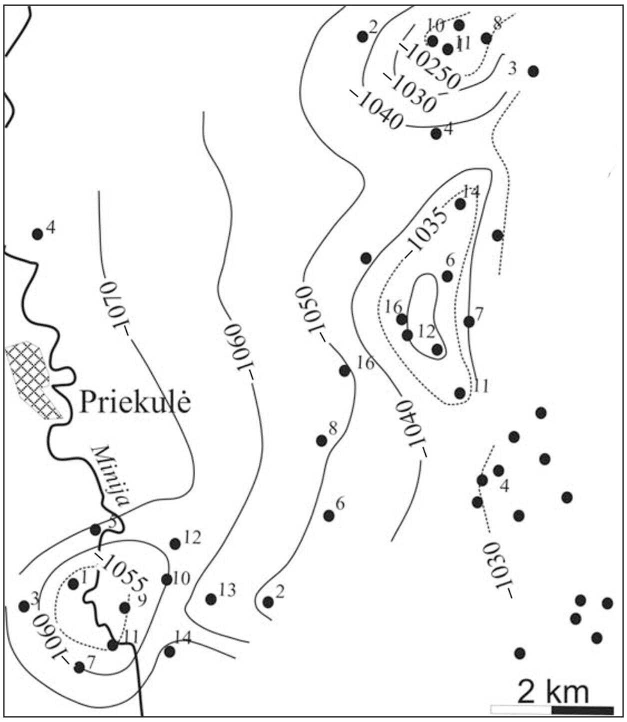

Fig. 3. Structural map of Lower Devonian reservoir top. Several uplifts are defined in Gargždai area, West Lithuania. The amplitude of local uplifts is 8–16 m
3 pav. Apatinio devono struktūrinis žemėlapis. Gargždų zonoje išskiriamos kelios struktūros, kurių amplitudės yra 8–16 m

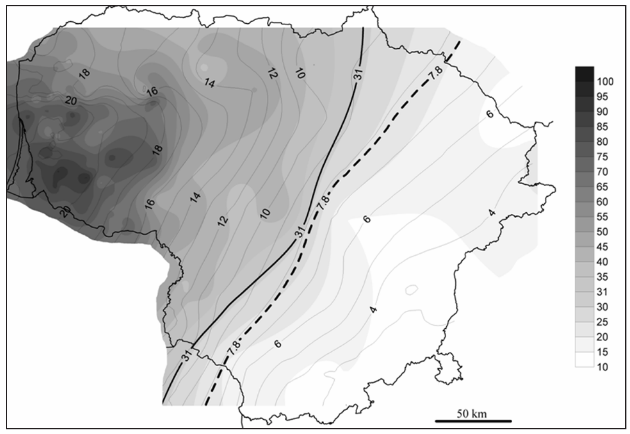

Fig. 4. Hydrostatic pressure (contour lines, MPa) and temperature (grey colour scale, °C) of Cambrian aquifer, Lithuania
4 pav. Kambro vandeningojo sluoksnio hidrostatinis slėgis (izolinijos, MPa) ir temperatūra (pilka skalė, °C)

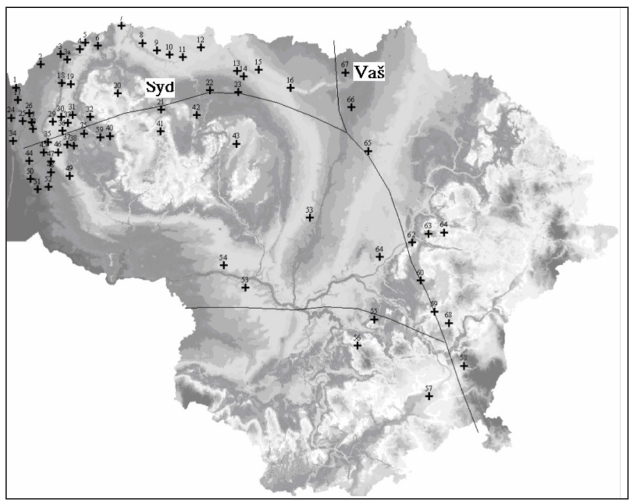

Fig. 5. Local uplifts (crosses) of Cambrian reservoir assessed for CO_2 storage in Lithuania (topography shown as a background). Syderiai (Syd) and Vaškai (Vaš) structures are marked. Major gas pipelines are shown
5 pav. Kambro kolektoriaus lokalių pakilumų (žvaigždutės) įvertinimas CO_2 saugojimo atžvilgiu. Pažymėti topografijos elementai, Syderių ir Vaškų struktūros

CO_2 STORAGE POTENTIAL OF CAMBRIAN DEEP SALINE AQUIFER

The parameters of the Cambrian reservoir vary considerably across the basin. The porosity ranges from 20–25% in the shallow periphery of the basin to 5–10% in West Lithuania. The temperature changes from 10–15 °C in the north and east to 70–90 °C in West Lithuania. The hydrostatic pressure changes from 10 bar in the shallow setting to 230 bar in West Lithuania (Fig. 4).

The storage potential of 76 uplifts defined in the Cambrian layer was assessed (Fig. 5). The total storage capacity is 102 Mt of CO_2. Furthermore, 52 structures were assessed offshore (Fig. 12). The offshore potential is 35 Mt of CO_2. However, these structures are small-scale and not suitable for storing CO_2. Only two uplifts onshore (Syderiai and Vaškai) and one uplift offshore (D11) are large enough to be considered prospective for CO_2 storage.

The onshore structures with the capacity of 0.1–0.2 Mt of CO_2 comprise 13% of the assessed uplifts; structures of 0.2–0.4 Mt capacity comprise 14%, 0.4–0.7 Mt 24%, 0.7–1 Mt 13%, 1–2 Mt 20% and 2–5 Mt 12% (Fig. 6).

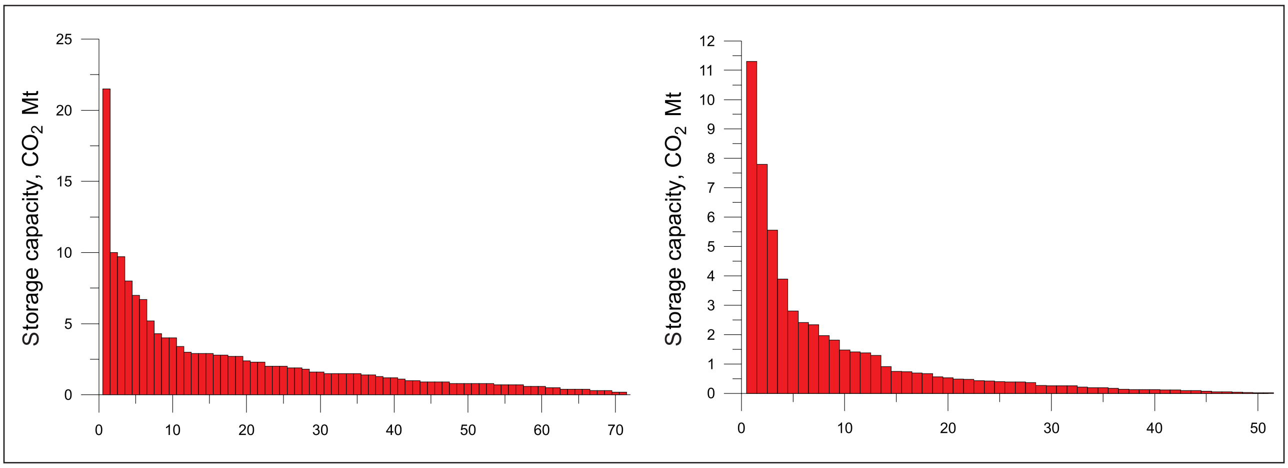

Fig. 6. Storage capacity of Cambrian structures of Lithuanian onshore (76 structures, left) and offshore (52 structures, right)
6 pav. Lietuvos kambro struktūrų saugojimo potencialas sausumoje (kairėje) ir jūroje (dešinėje)

The Syderiai structure

The Syderiai structure is situated in a favourable geographic position. It is located 40–50 km away of the Mažeikiai refinery and Akmenė Cementas, two largest CO_2 emitters in Lithuania. The Syderiai structure was investigated in detail by seismics and one deep well (Syderiai-1) as the prospective structure for oil exploration in the eighties. It represents the local uplift bounded by the large-scale Telšiai fault in the south (Fig. 7). In the east, the structure is bordered by a small-scale fault trending NE–SW; its amplitude reaches 100 m. The structure is of oval shape, its amplitude is 80 m. It is 12 km long and 8 km wide (Fig. 7). The formation of the Syderiai uplift was related to the tectonic compression induced by a collision of the Baltica and the Laurentia continents in the latest Silurian – earliest Devonian (Šliaupa et al., 1998). It led to the formation of a number of faults and associated uplifts in the Baltic basin.

The Cambrian top occurs at a depth of 1458 m (Fig. 8). It is sealed by a 560 m thick shaly package of the Ordovician–

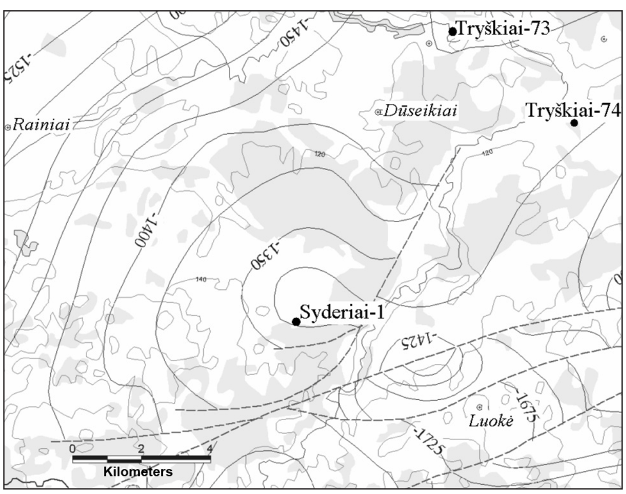

Fig. 7. Structural map of top of Cambrian reservoir, Syderiai uplift, West Lithuania (after Baliukevičius, Čyžienė, Šliaupa – unpublished report, 2006). Contour lines indicate the depths of Cambrian top, hatched lines show faults. Deep wells are indicated. Landscape features are shown

7 pav. Kambro kraigo struktūrinis žemėlapis, Syderių pakiluma (pagal Baliukevičių, Čyžienę, Šliaupą – nepublikuota ataskaita, 2006), Vakarų Lietuva. Izolinijos žymi gylius, brūkšninės linijos – lūžius. Pažymėti giluminiai gręžiniai, kraštovaizdžio elementai

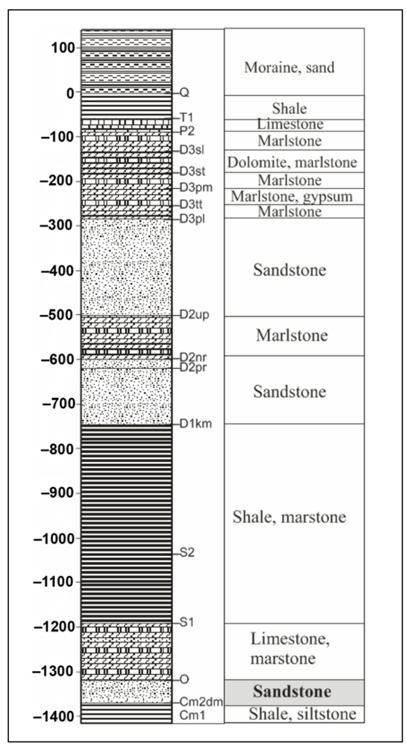

Fig. 8. Geological section of Syderiai area. Prospective Cambrian aquifer is marked by grey shadowing
8 pav. Syderių ploto geologinis pjūvis. Paryškintas kambro kolektorius

Silurian age. It is an important parameter for considering the safety of CO_2 storage. Above the sealing package, there are several large-scale aquifers, but they are not used for water supply due to the high salinity. Potable water is supplied from the Upper Permian carbonaceous aquifer and younger aquifers at a depth less than 90 m (Fig. 8).

The prospective reservoir is comprised by Middle Cambrian (Deimena Regional Stage) sandstones 48 m thick, the net-to-gross being as high as 0.75 (Fig. 9, Table 1). Two compartments are defined in the section (Fig. 9). Sandstone 1 and Sandstone 2 are attributed respectively to the Ablinga and the Pajūris formations separated by a 9 m thick shaly basal part of the Ablinga Formation. Sandstones are well sorted, fine-grained, cemented by late diagenetic quartz. Quartz comprises about 97–98% of rock volume with a scarce potassium feldspar, pyrite, clay admixture.

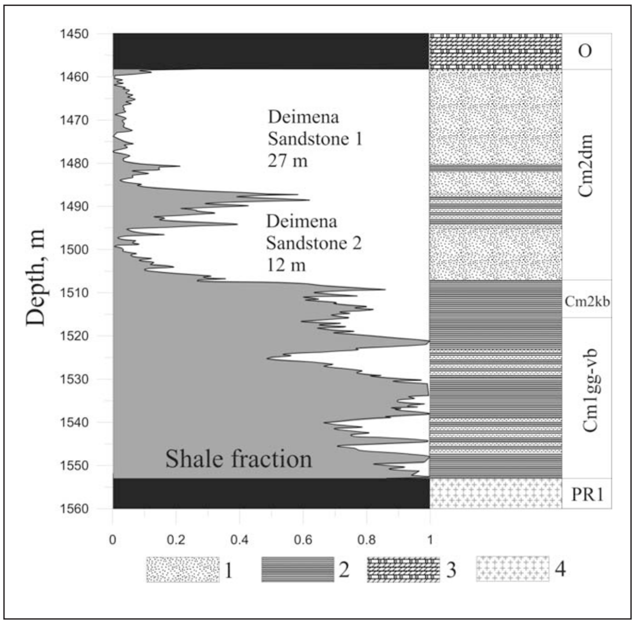

Fig. 9. Lithological section of Cambrian succession, Syderiai-1 well. Symbols: *1* – sandstone, *2* – shale, *3* – marlstone and limestone, *4* – crystalline basement

9 pav. Syderių ploto kambro geologinis pjūvis, Syderių-1 gręžinys: *1* – smiltainis, *2* – molis, *3* – mergelis ir klintis, *4* – kristalinis pamatas

Only the upper part of the Middle Cambrian reservoir has been sampled for assessing its properties (Fig. 10). Neutron Gamma Ray (NGR) logging data were used to calculate the porosity distribution (Fig. 10). The average porosity of sandstones is 16%. The reservoir properties are increasing downward in the Ablinga Formation (Sandstone 1) from about 10% at the top to 24% at the base (Fig. 10); this is related to a decrease in quartz content. The Pajūris Formation (Sandstone 2) is rather uniform, its average porosity being 16%.

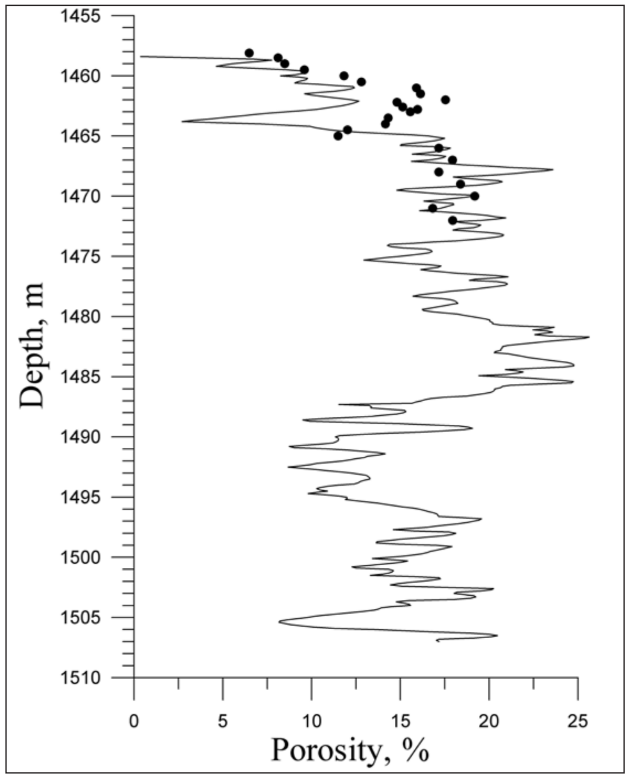

Fig. 10. Porosity of Cambrian sandstones (points show measured porosities, line shows porosities calculated from NGR logging)

10 pav. Vidurinio kambro kolektoriaus poringumas (taškai rodo išmatuotas reikšmes, kreivė – poringumą, nustatytą pagal neutron-gama diagrafiją)

The permeability correlates with porosity (Fig. 11). It ranges from 4 mD in shaly sandstone to 850 mD in massive sandstone. The correlation is described by the equation Permeability = 0.3*Porosity + 0.97. The average permability of Middle Cambrian sandstones is 400 mD. Sandstones are rather anisotropic. The ratio of the vertical to horizontal permeability is 0.56.

The density of supercritical CO_2 is an important parameter in assessing the storage capacity of a particular structure. The density depends basically on temperature, pressure and pore water salinity (e. g., Duan et al., 2008). The temperature of the Cambrian reservoir is 50 °C in the Syderiai-1 well and the pressure is 153 bars. Pore water salinity was defined to the 122 g/l,

Table 1. **Summary information on individual aquifers**

1 lentelė. **Atskirų vandeningųjų horizontų charakteristikos**

Structure	Stratigraphic unit	Formation	Lithology	Top depth, m	Permeability, mD
Syderiai	Middle Cambrian	Deimena	Sandstone	1458	400
Vaškai	Lower-Middle Cambrian	Gėgė-Deimena	Sandstone	896	280
D11	Middle Cambrian	Deimena	Sandstone	1700	300

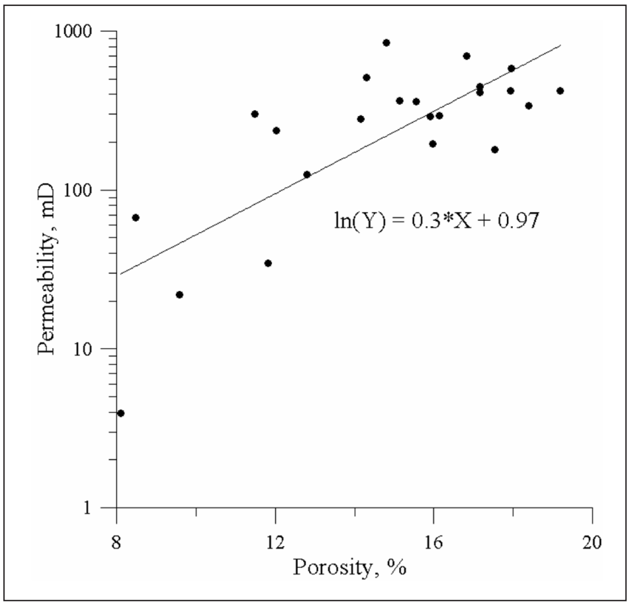

Fig. 11. Porosity vs permeability of Middle Cambrian sandstones Syderiai-1, well
11 pav. Vidurinio kambro poringumo ir skvarbumo palyginimas, Syderių-1 gręžinys

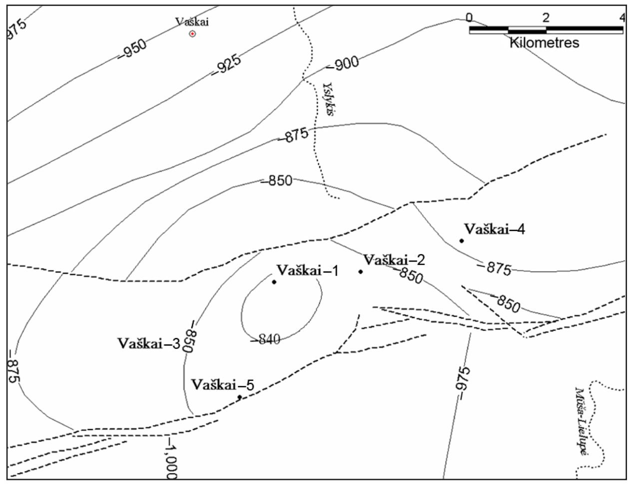

Fig. 12. Structural map of top of Cambrian reservoir, Vaškai uplift, North Lithuania. Contour lines indicate Cambrian top depths, hatched lines show faults, dotted lines mark rivers. Deep wells are indicated
12 pav. Kambro kolektoriaus kraigo struktūrinis žemėlapis, Vaškų pakiluma, Šiaurės Lietuva. Izolinijos žymi gylius, brūkšninės linijos – lūžius, taškinės linijos – upes. Pažymėti giluminiai gręžiniai

the water is of Na–Cl type. The density of CO_2 was estimated using the MIDCARB calculator (http://www.kgs.ku.edu/Midcarb/). In these conditions, CO_2 density is 710 kg/m^3.

Taking into consideration the volumetrics of the structure, reservoir properties and CO_2 density, the storage capacity of the Syderiai structure is assessed to be as large as 21 Mt of CO_2 (Table 1).

The Vaškai structure

The Vaškai uplift is located 10 km from the Pasvalys region centre; 168 km of seismic lines were determined in 1992–1999, and five wells were drilled in the area to evaluate the suitability the Vaškai structure for underground gas storage. The structure was abandoned due to uncertain tightness of the bounding faults as the Vaškai structure is limited by two faults trending West–East. The length of the structure is 12 km. The Telšiai fault zone is of complex geometry and is 500 m to 1 000 m wide; the Cambrian reservoir is 250 m away (Fig. 12). The area of the Vaškai uplift is 11 × 3.2 km, it has a pop-up geometry. The closure amplitude is 36 m. It is, however, not clear whether the closure is controlled by faults on the either side of the uplift or the Cambrian layer is flexed at the faults.

The aquifer is composed of Lower–Middle Cambrian sandstones with subordinate shales and siltstones. Sandstones are fine-grained, silty, cemented by dolomite and quartz, their content being 2–4%; quartz grains comprise about 94%, clay admixture averages to 2%, and the pyrite content is about 2%.

The top of the Cambrian reservoir occurs at the depth of 896–932 m. It is overlain by 360 m thick Ordovician–Silurian shales and carbonates (Fig. 13). They provide a reliable seal for storing CO_2. The tightness of the Ordovician caprock was

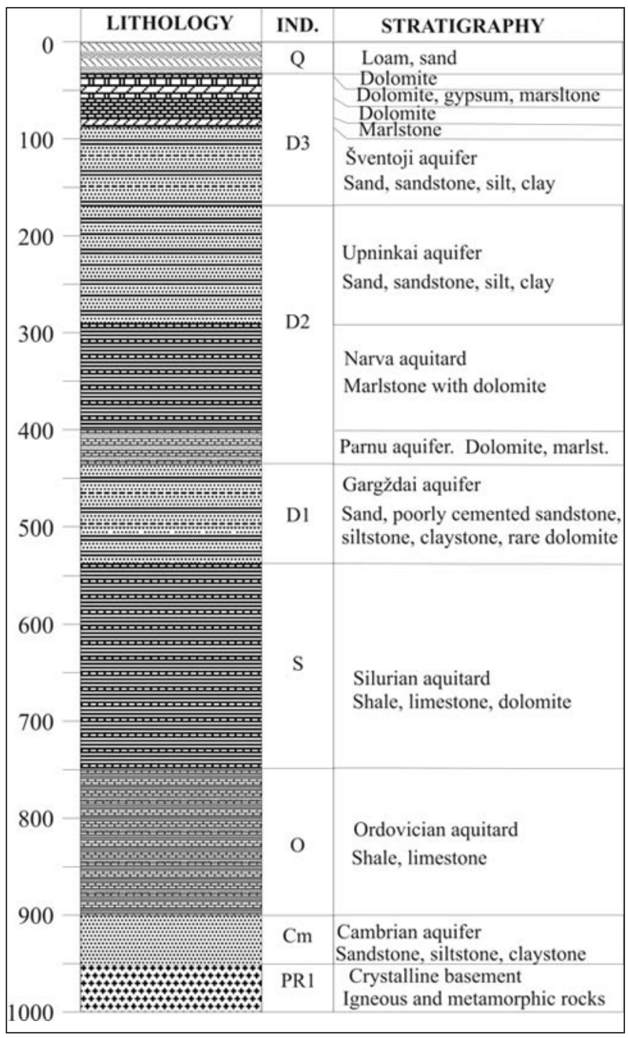

Fig. 13. Geological section of Vaškai area
13 pav. Vaškų ploto geologinis pjūvis

proven by a drill stem test, logs in the wells and threshold pressure measurements on cores. The Cambrian reservoir overlies the crystalline basement.

There are three compartments defined in the Cambrian aquifer (Fig. 14). The upper compartment (Sandstone 1) represents the basal part of the Deimena Regional Stage. It is separated from the Lower Cambrian by Kybartai Formation shales 8 m thick with rare sandstones. The middle and the lower compartments (Sandstone 1 and Sandstone 2) represent the upper and the lower parts of the Virbalis Formation (Lower Cambrian). They are separated by 10 m thick shales with sandstone interlayers. The lower part of the Cambrian succession is comprised by siltstones and shales of the Gėgė Formation.

The porosity of Cambrian sandstones is 17–26.5%; 150 samples were taken for laboratory analysis (unpublished industrial reports). Furthermore, the porosity distribution was also calculated using sonic logging data (Fig. 15). The average porosity of sandstones is 23%. The net-to-gross ratio is 0.5. The permeability ranges from 90 to 1628 mD (Fig. 16). However, the average permeability is rather low (280 mD) mainly because of the presence of some clay admixture in sandstones. The vertical permeability of sandstones is half as low.

The hydrostatic pressure is 90 bar. The temperature was not measured in this area. Based on regional estimates, the temperature of Cambrian water is 33 °C. The pore water salinity is as high as 127 g/l, similarly to that in the Syderiai structure. The water is of Na–Cl type. In these conditions, the density of CO_2 was evaluated to be 580 kg/m^3, which is lower than in the Syderiai area due to pressure difference.

Based on the above data, the storage capacity of the Vaškai structure was assessed to be 8.7 Mt of CO_2.

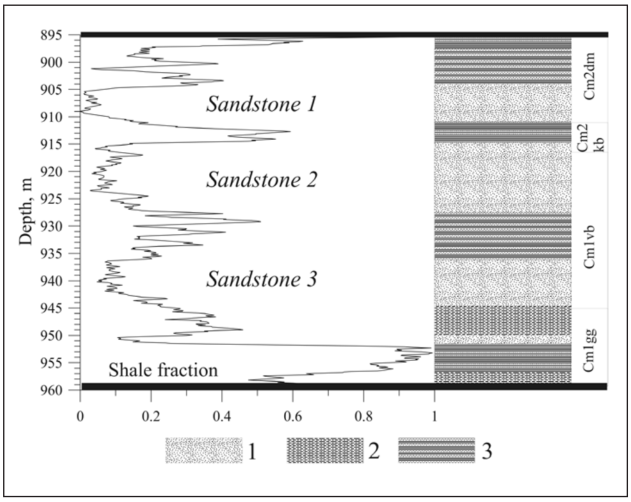

Fig. 14. Lithological section of Cambrian succession, Vaškai-1 well. Symbols: *1* – sandstone, *2* – siltstone, *3* – shale with sandstone

14 pav. Kambro geologinis pjūvis, Vaškų-1 gręžinys: *1* – smiltainis, *2* – aleurolitas, *3* – molis su smiltainio tarpsluoksniais

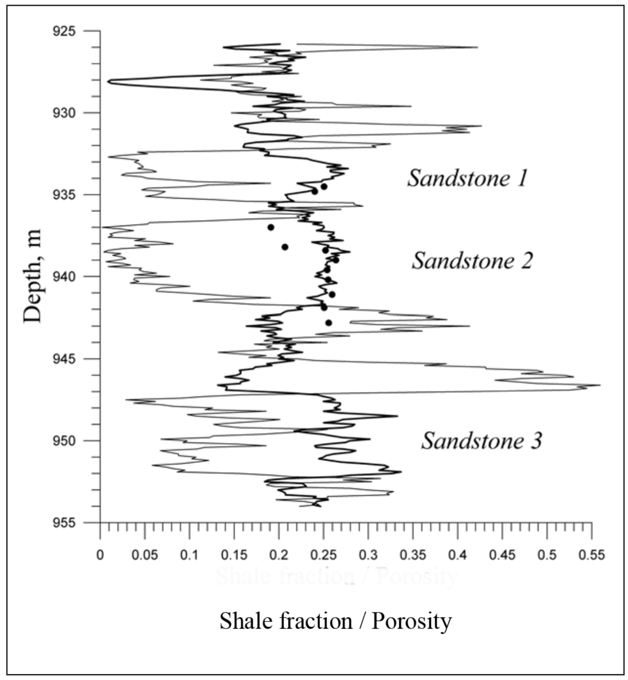

Fig. 15. Shale fraction (thin line) and open porosity (calculated from sonic and GR logs, bold line, and measured porosity, dots) of Cambrian sandstones, Vaškai-4 well

15 pav. Kambro kolektoriaus molio kiekis (plona linija) ir atviras poringumas (stora linija žymi poringumą, apskaičiuotą pagal akustinę ir gama diagrafiją, taškai – išmatuotą poringumą), Vaškų-4 gręžinys

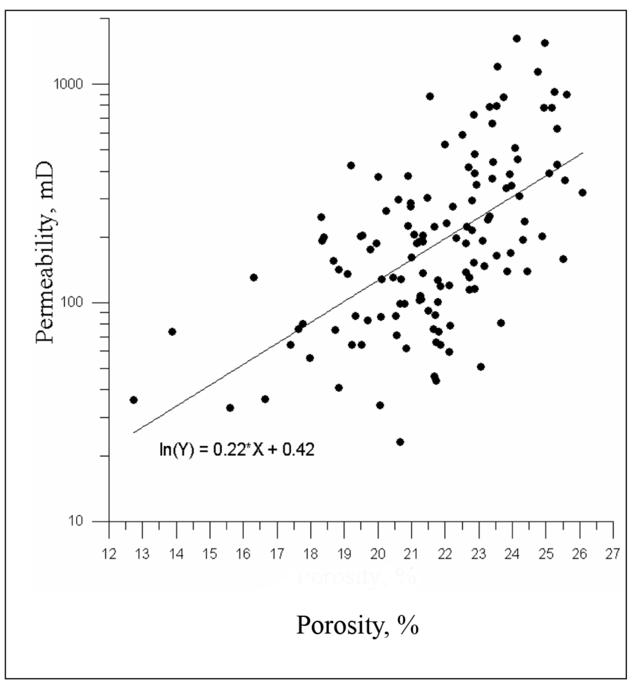

Fig. 16. Porosity vs permeability of Lower-Middle Cambrian sandstones and siltstones, Vaškai area

16 pav. Vidurinio–apatinio kambro smiltainių ir aleurolitų poringumo ir skvarbumo palyginimas, Vaškų plotas

ALTERNATIVE SCENARIO OF CO_2 STORAGE IN DEEP SALINE AQUIFERS IN LITHUANIA

The CO_2 storage capacities discussed above are regarded as practical storage values. Apart from these options, there is some alternative scenarios to be discussed. The analysed structures represent simple tectonic forms that can be used for a safe storage of CO_2. The other prospective structure for CO_2 storage is related to the Gargždai zone of uplifts (Fig. 17). It is defined in West Lithuania and hosts a number of oil fields, e. g., Vilkyčiai, Pociai, Degliai, etc. (Zdanavičiūtė, Sakalauskas, 2001). The zone is bounded in the east by the Gargždai fault zone trending NNE–SSW. This system was formed during the latest Silurian – earliest Devonian due to the Caledonian tectonic activation (Šliaupa, 1998). The amplitude of the fault zone is 50–100 m. The zone is encompassed by the depth contour line of 2050 m. The prospective storage area is limited by the depth contour line of 2025 m, and the total amplitude of the storage trap is 80 m. The total potential storage area is 217 km². The thickness of the Middle Cambrian reservoir is about 60 m, and the net-to-gross ratio is about 0.35. Sandstones are characterized by highly variable porosity and permeability values. This is primarily related to the uneven quartz cementation (Vosylius, 1998; Molenaar et al., 2008). The upper part of the aquifer shows generally lower reservoir properties (Fig. 18). The average

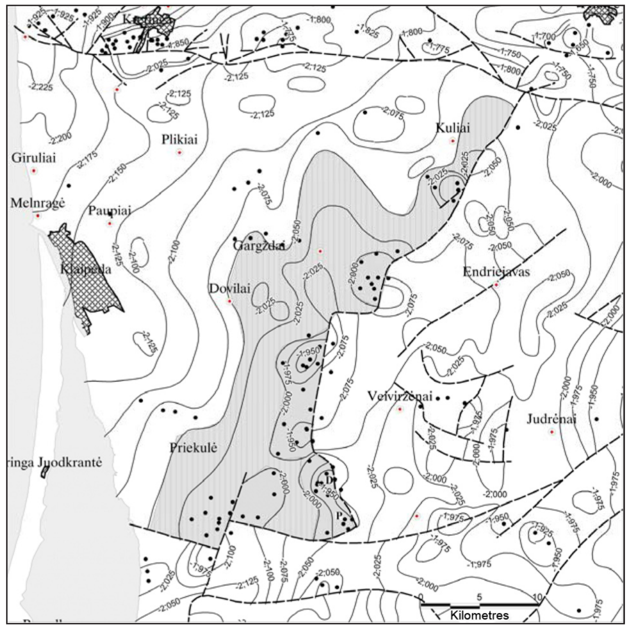

Fig. 17. Structural map of Cambrian aquifer top. Shaded area indicates the area of Gargždai uplifts. Faults are shown as hatched lines. P and D mark Pociai and Degliai structures, respectively (discussed in the text)

17 pav. Kambro kolektoriaus kraigo struktūrinis žemėlapis. Pilkas plotas žymi Gargždų pakilumų zoną, izolinijos – gylius, brūkšninės linijos – lūžius. Pažymėti giluminiai gręžiniai. P ir D žymi Pocių ir Deglių struktūras minimas tekste

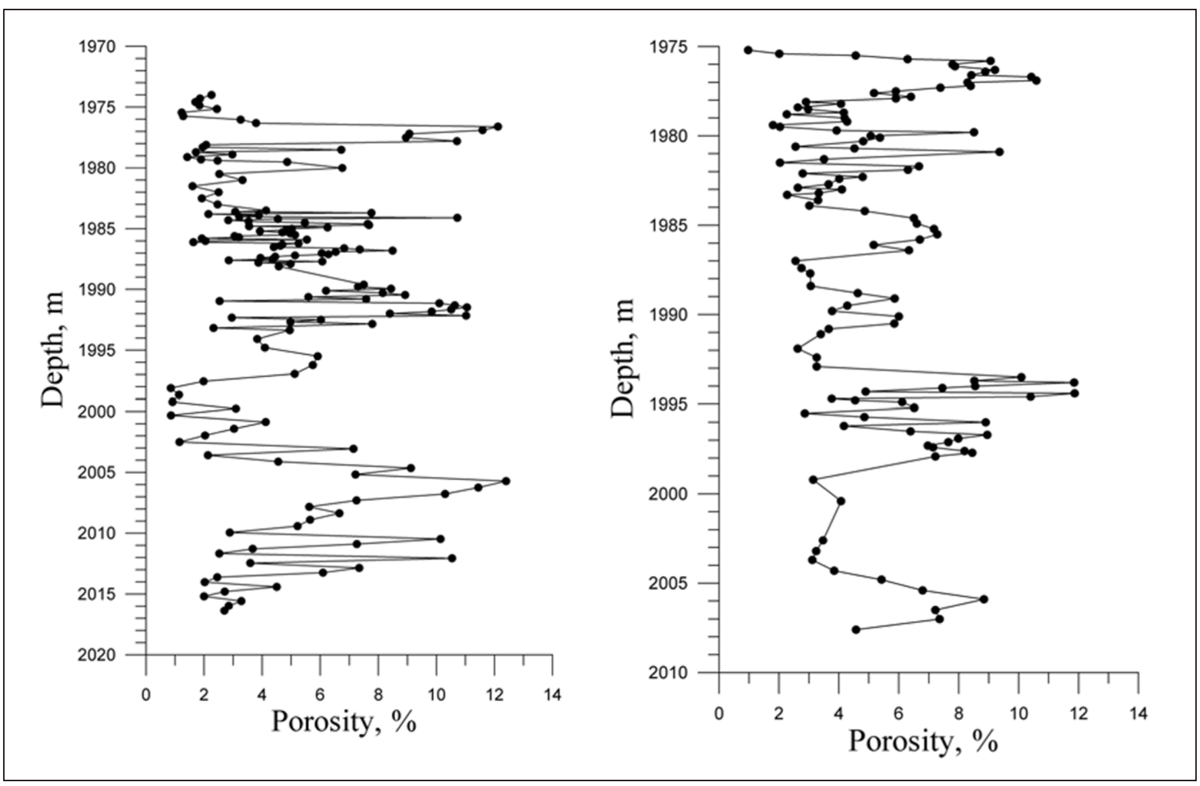

Fig. 18. Examples of measured porosity distributions in Middle Cambrian reservoir of Gargždai uplift zone, wells Pociai-4 (left) and Degliai-2 (right)

18 pav. Vidurinio kambro smiltainių ir aleurolitų išmatuoto poringumo pavyzdžiai, Pocių-4 ir Deglių-2 gręžiniai porosity of the upper part (Giruliai and Ablinga formations) is 4–5%, while the average porosity of sandstones in the lower part of the reservoir is 6–8%. The aquifer is classified as a dual-porosity reservoir.

The temperature of the reservoir is about 80 °C and pressure about 200 bar. CO_2 density in these conditions is about 600 kg/m^3.

The assessed storage capacity of this uplift zone exceeds 100 Mt of CO_2.

SHORT OVERVIEW OF CO_2 STORAGE PROSPECTS FOR DEEP SALINE AQUIFERS IN ADJACENT AREAS

Latvia

In the Baltic basin, Latvia is characterised by the largest CO_2 storage potential (Geological structures…, 2007). Fifteen large structures, their estimated storage capacity ranging from 2 to 80 Mt CO_2, have been identified in West Latvia (Vangkilde-Pedersen et al, 2009) (Fig. 19, Table 2). Such a high storage potential is related to two major factors: (1) intense structuring of Latvian Earth's crust and (2) high reservoir properties of Cambrian sandstones. The tectonic fabric of Latvia is cored by the Liepaja–Saldus ridge extending WSW–ENE (Brangulis, Kanevs, 2002). It is dissected by a number of faults and associating local uplifts that formed during the latest Silurian – earliest Devonian when the Scandinavian Caledonian orogeny induced a strong tectonic compression in the adjacent platform areas (Šliaupa, 1998). The good reservoir properties are related to the shallower depth (about 1 km) of Cambrian sandstones as compared with West Lithuania. The average porosity is about 20–22% and permeability is about 1000 mD. The total storage capacity is assessed to be 400 Mt of CO_2. All prospective structures are located in the west of the country.

No suitable aquifers are present in the Estonian territory. The Cambrian aquifer and other reservoirs are too shallow for CO_2 injection in a supercritical state. Furthermore, no large structural traps are mapped in the country. Therefore, alternative CO_2 geological storage options are considered, such as carbonation of carbon dioxide by alkaline ash, a product of utilisation of oil shales in the energy sector (Shogenova et al., 2009).

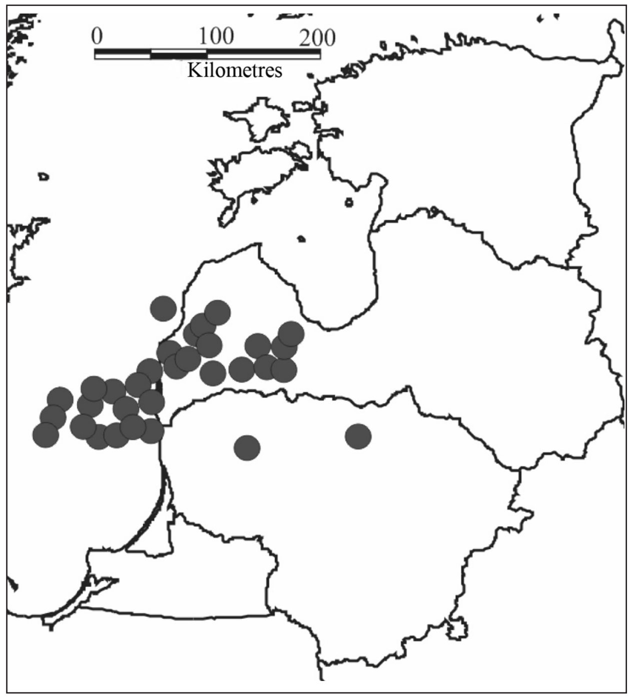

Fig. 19. Prospective deep saline Cambrian aquifer structures for CO_2 geological storage in the Baltic region

19 pav. Sūraus vandeningojo sluoksnio (kambras) CO_2 saugojimui perspektyvios struktūros Baltijos regione

Kaliningrad District

In Kaliningrad District, the potential structures are related to oil fields which are abundant in the western and central parts of the district. Therefore, the CO_2 storage potential is related to the EOR technology.

The largest oil field has been discovered in the Baltic Sea. The Kravtsovskoye (D-6) offshore oil field is on commercial production since 2004. The field is 22.5 km off the Kaliningrad Region coast. It contains an estimated 21.5 million tons of C1 + C2 geological oil reserves and 9.1 million tons of recoverable oil. It is planned to drill 27 wells to bring the output to 600,000–650,000 tons per year. The field is expected to be at its productive peak for 12 years out of its 30–35-year useful life.

Table 2. **Aquifer CO_2 storage capacity estimation**
2 lentelė. **Vandeningųjų sluoksnių CO_2 saugojimo potencialas**

Structure	Area	Thickness	Net / gross ratio	Porosity	CO_2 density, t/m^3	Storage efficiency factor	Total estimated CO_2 storage capacity, Mt
Syderiai	26.0 km^2	57	0.75	0.16	710	0.3	21.5
Vaškai	12.3 m^2	57	0.5	0.23	580	0.3	8.7
D11	25 km^2	65	0.35	0.10	750	0.3	11.3
Total estimated CO_2 storage capacity in deep saline aquifers, Mt							41.5

Offshore

The storage potential was preliminarily assessed for the offshore territories of Lithuania and Latvia (the eastern Baltic Sea). A dense 2 × 2 km network of the industrial seismic profiles covers the offshore territory. One well (D5-1) was drilled through the sedimentary cover to the crystalline basement, the drill cores were collected from the upper part of the Middle Cambrian succession. Several wells penetrated the whole sedimentary cover in the Latvian economic zone (E7-1 and E6-1 wells).

In the Lithuanian economic zone, the amplitudes of the uplifts reach 20–40 m, the area of the largest structures being 5–20 km^2. In the Lithuanian economic zone, only one rather large structure D11 has been identified. The amplitude of the D11 structure is 35 m, and the area is 80 km^2. The storage capacity was evaluated to be 11 Mt CO_2. The uplift is located 5 km west of the shoreline.

Fifteen prospective structures were defined in the Cambrian reservoir in the economic zone of Latvia (Fig. 20). The total offshore storage capacity is preliminarily estimated to be 300–400 Mt.

Similarly, a large storage potential is suggested in the western part of the Baltic Sea in the Swedish offshore economic zone (Bergman, Juhojuntti, 2010).

DISCUSSION

Only several structures suitable for CO_2 storage have been defined in Lithuania. The Syderiai structure is in a favorable location situated close to the Mažeikiai refinery and Akmenės Cementas which are the largest CO_2 emitters in Lithuania. The Vaškai structure is located at a distance of 120 km from the Akmenė cement plant. These structures can cover the sequestration needs for 10–20 years. There are, however, the safety issues that should be addressed. Both structures associate with the large-scale Telšiai fault and smaller-scale faulted structures. The tightness of these faults remains not clear. On the other hand, both structures are overlain by a thick shaly package of the Ordovician–Silurian age, which ensures the safe storage of CO_2. However, the storage capacities are far too low to cover the needs of Lithuania in reducing considerably CO_2 emissions.

An optimistic scenario regards the utilization of the Gargždai uplift zone. It potentially provides for a large storage capacity. The main concern is related to the risk assessment of this zone. The uplift zone is bounded by a system of Gargždai faults in the east. The tightness of this faulted structure should be proven.

In parallel to the development of Lithuanian structures, the cross-border CO_2 sequestration strategy should be considered. The afore-mentioned Mažeikiai refinery and Akmenės Cementas are located only 30–40 km away of prospective structures in adjacent Latvia. The close distance minimizes CO_2 transportation costs.

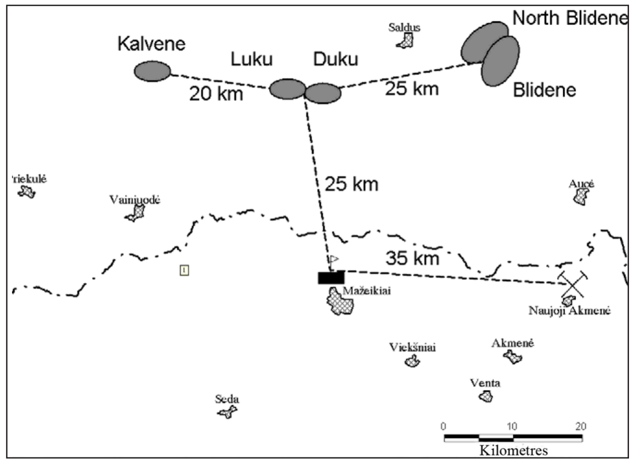

Fig. 20. Cross-border North Lithuania – South Latvia CO_2 storage scenario. Dark grey polygons indicate major Cambrian structures. Dotted line shows proposed transportation pipe-lines

20 pav. Galimas CO_2 saugojimo variantas – Šiaurės Lietuva–Pietų Latvija. Tamsiai pilki plotai žymi perspektyvias kambro struktūras, taškinė linija – numatomus dujotiekius

One of the possible cross-border CO_2 storage scenarios is shown in Fig. 20. The two largest CO_2 emission sources – Mažeikiai Refinery and Akmenės Cementas – are located close (25 km) to several large Cambrian structures in South Latvia (Kalvene, Luku, Duku, North Blidene, Blidene) which can fully cover the needs of those industrial objects for several decades, along with the storage of CO_2 emitted from West Latvian large CO_2 sources.

CONCLUSIONS

The geological storage of CO_2 is one of the most developed technologies in reducing CO_2 emissions. The Lithuanian territory contains large-scale deep saline aquifers. Based on the evaluation of the parameters relevant to CO_2 storage, only one Cambrian aquifer has been defined as a prospective formation. There is a number of local structures defined in Lithuania. They are well isolated from the overlying aquifers by a thick shaly package of the Ordovician–Silurian age. Furthermore, most of faults are tipped at the base of the Lower Devonian aquifer and do not show any penetration into the younger sediments, thus ensuring no escape of gas along the faulted pathways.

Lithuania has a rather limited storage potential. Two prospective structural traps, Vaškai and Syderiai, have been defined. They can cover emissions of a few decades of the major industrial CO_2 sources, such as the Mažeikiai refinery or Akmenės Cementas. The prospects of the large-scale Gargždai uplift zone should be considered; it may provide large volumes for storing CO_2 in the Cambrian reservoir.

The conflict of interests may be an important reason to hamper the CO_2 storage initiative. The Syderiai structure is in parallel considered as one of the most prospective objects for establishing an underground gas storage. Similarly, the Vaškai uplift is also considered for similar purposes.

A large potential has been estimated in Latvia; it can accommodate large quantities of CO_2 emissions from large sources. The high potential is related to the presence of large structural traps and good reservoir properties of the Cambrian aquifer.

The offshore area also comprises a number of large structural Cambrian traps which can be utilised for CO_2 sequestration. The storage capacity is compatible with that estimated for onshore structures.

ACKNOWLEDGMENT

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GEOLOGINIO CO_2 SAUGOJIMO GILIUOSE IR SŪRIUOSE VANDENINGUOSIUOSE SLUOKSNIUOSE PERSPEKTYVOS LIETUVOJE IR GRETIMOSE TERITORIJOSE

Santrauka

Anglies dvideginio išmetimas į atmosferą yra viena aštriausių žmogaus intensyvios gamybinės veiklos ekologinių problemų. Didžiuliai šio cheminio junginio kiekiai atmosferoje gali sukelti katastrofišką klimato atšilimą ir su tuo susijusias skaudžias pasekmes. Per pastaruosius 150 metų daugiausia dėl deginamo kuro anglies dvideginio koncentracija atmosferoje padidėjo beveik trečdaliu. Pagal Kioto protokolą, išsivysčiusios šalys iki 2008–2012 m. turi sumažinti anglies dvideginio emisiją 5,2 % (baziniai metai 1990). Protokolą pasirašė ir Lietuva, įsipareigojusi iki 2008–2012 m. sumažinti išmetimo lygį 8 %. Vis labiau įsigali nuomonė, kad netaršių energijos šaltinių ir aukštų technologijų panaudojimas yra gana tolimos ateities strategija, todėl būtinos alternatyvios priemonės. Geologinis CO_2 saugojimas suteikia tokio pereinamojo laikotarpio galimybę. Pagrindiniai reikalavimai geologiniam anglies dvideginio saugojimui yra šie: ilgalaikiškumas (amžiai iki geologinių periodų), minimalios saugojimo išlaidos, tarp jų ir transporto, minimali aplinkosauginė rizika, saugojimo būdas neturi prieštarauti tarptautiniams ir valstybės įstatymams bei susitarimams.

Anglies dvideginis gali būti saugomas įvairaus tipo geologiniuose kūnuose – išeksploatuotuose dujų ir naftos telkiniuose, sūriuose vandeninguosiuose horizontuose, druskos kupoluose, anglies kloduose keičiant metaną į CO_2. Jų potencialas yra skirtingas. Didžiausiu potencialu pasižymi sūraus požeminio vandens sluoksniai.

Lietuvos vandeningųjų sluoksnių analizė rodo, kad tik kambro kolektorius yra perspektyvus anglies dvideginiui saugoti. Tą lėmė gana geros sluoksnio kolektorinės savybės, gera izoliacija nuo aukščiau esančių kitų vandeningųjų sluoksnių (ordoviko ir silūro molinga storymė), pakankamai didelės lokalios struktūros. Būtent lokaliose pakilumose numatoma saugoti CO_2 (panašiai, kaip požeminėse dujų saugyklose). Kiti stambūs vandeningieji sluoksniai (devonas) nėra perspektyvūs, nepaisant labai gerų kolektorinių savybių. Pagrindinė priežastis – labai silpna jaunesnių sluoksnių tektonizacija. Devono sluoksniuose esančios pakilumos neviršija 10–15 m amplitudės, todėl struktūrų dydžio nepakanka saugykloms įrengti.

Kambro vandeningojo sluoksnio perspektyvus plotas apima Lietuvos vakarinę pusę. Jo rytinė riba eina per Pasvalio, Panevėžio, Jonavos, Kauno, Marijampolės rajonus ir siejama su 31 °C izoterma ir 78 bar hidrostatiniu slėgiu. Šios minimalios reikšmės leidžia CO_2 pereiti iš dujų į superkritinę būklę. Esant superkritinei būklei labai palengvėja CO_2 patekimas į sluoksnį. Įvertintas visų žinomų kambro struktūrų potencialas, tiek sausumoje, tiek ir jūroje (per 100 objektų). Deja, tik kelios struktūros, Syderių ir Vaškų, yra pakankamai didelės ir tinkamos CO_2 saugyklai. Jūroje gana didelė yra tik D11 struktūra. Pagrindinė priežastis, galinti užkirsti kelią šių struktūrų panaudojimui CO_2 saugykloms, yra galimas interesų konfliktas. Syderių ir Vaškų objektai yra traktuojami kaip labai perspektyvūs Lietuvoje steigiamoms požeminių dujų saugykloms. Vertintas ir alternatyvus optimistinis variantas panaudoti Gargždų pakilumų zonos potencialą. Šios talpyklos saugojimo dydžiai yra labai dideli. Pagrindinė galima kliūtis yra rizikos (saugumo) veiksnys. Zoną ribojančios Gargždų lūžių sistemos laidumą / uždarumą būtina nuodugniai ištirti, kad neįvyktų ekologinė katastrofa.

Iš gretimų valstybių Latvija pasižymi didžiausiu CO_2 saugojimo potencialu, kuris vertinamas keliais šimtais milijonų tonų CO_2. Tai siejama su geromis kambro kolektorinėmis savybėmis ir daug intensyvesne sluoksnio tektonizacija, čia gausu stambių struktūrų, tinkamų saugykloms įrengti. Taigi galimybė transportuoti CO_2 iš Lietuvos į Latviją saugojimui kambro struktūrose gali būti analizuojama kaip perspektyvus scenarijus.

Dideliu potencialu pasižymi ir Latvijos Baltijos jūros teritorija. Čia išskirta 15 stambių struktūrų, kurių potencialas panašus į sausumos struktūrų.

Pagrindinės CO_2 geologinio saugojimo perspektyvos siejamos su naftos telkinių intensyvinimu naudojant anglies dvideginį ir kartu jį saugant.

Estijos teritorija nėra tinkama CO_2 saugykloms dėl kelių priežasčių: per mažas kambro sluoksnio gylis, mažos struktūros, kambro sluoksnis naudojamas geriamojo vandens tiekimui šiaurinėje šalies dalyje.

Raktažodžiai: CO_2 emisijos, geologinis saugojimas, sūrus vandeningasis sluoksnis, kambras, struktūrinė saugykla