VILNIUS UNIVERSITY

NATURE RESEARCH CENTRE
INSTITUTE OF GEOLOGY AND GEOGRAPHY

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PROSPECTS OF CO_2 GEOLOGICAL STORAGE IN THE BALTIC SEDIMENTARY BASIN

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GAMTOS TYRIMŲ CENTRAS
GEOLOGIJOS IR GEOGRAFIJOS INSTITUTAS

RASA ŠLIAUPIENĖ

ANGLIES DVIDEGINIO DUJŲ GEOLOGINIO SAUGOJIMO PERSPEKTYVOS BALTIJOS SEDIMENTACINIAME BASEINE

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INTRODUCTION

Importance of study. Increasing CO_2 concentration in atmosphere and related global climate change is one of the most important concerns of the society. Geological storage of CO_2 is considered as one of the most effective near-future solutions. The Baltic basin contains sediments that were deposited throughout the Phanerozoic thus representing a multilayered system comprising different geological formations that might be prospective for CO_2 geological storage. Furthermore, the basin encompasses a number of countries with high-developed industry. The present study is focused on the basin scale assessment of the CO_2 storage potential with emphasis to Lithuanian CO_2 emissions problem solutions.

Target and tasks. The main target is complex evaluation of CCS potential in the Baltic region. Main tasks are as following: (1) identification of geological formations potential for CO_2 storage, (2) overview of CO_2 emissions in the Baltic Sea region, (3) assessment of storage capacity of saline aquifers of the Baltic basin (and Lithuania in particular), (4) assessment of risk factors, (5) economic evaluation of CCS chain, (6) assessment of potential of alternative storage technologies.

Methods. Most of data applied in the present study were collected from industrial reports stored in Lithuanian and Latvian (LEGMC) geological surveys (drill core description, reservoir properties, hydrogeology parameters, etc.). Some information is available in published sources (papers, open reports). Laboratory studies were carried out to characterise lithology and petrography of major aquifers of Latvia and Lithuania (drill core inspection, optical microscopy, SEM, EDS, CL), grain size (laser grain size equipment), petrophysical properties (porosity, irreducable water content). DSS (*Decision Support System*) programme was applied for economic evaluation. Some specific programs were applied to model particular parameters (CO_2 solubility). Some other parameters (CO_2 density, CO_2 plume migration) were calculated using algorithms provided in published papers.

Novelty of study. CO_2 geological storage is a new technology, though separate chains of this system are proved and commercially available. For the first time, the study was performed for the whole basin and concerns different potential storage technologies.

Defended statements:

- Geological conditions of the Baltic sedimentary basin are favourable for CO_2 storage in the deep saline aquifers.
- Alternative technologies provide largest CO_2 storage volumes – in monoclinal structures and serpentinite carbonation.

Theoretical and practical significance. Potential of different CO_2 storage technologies was evaluated within the common basin comprising different countries. It provides the basic information required in planning CCS strategies in the region.

Personal contribution. Thesis incorporates results of studies performed by author within the frames of CO_2 storage targeted projects in 2005–2014 (national CO_2 storage project financed by Lithuanian Science and Study Foundation in 2005; FP6 GeoCapacity project (2006–2008), FP7 CGS Europe project (2011–2013); abundant information was also collected while participating in in-house projects on oil field issues of Lithuania.

Dissemination of study results. Results were discussed in 14 international conferences.

Publications. Results were published in 12 papers: 2 papers in Thomson Web of Science journals, 4 papers in ISI Master List journals, 3 papers in peer reviewed journals referred in other data bases journals, 2 papers in other journals. Study results on PhD topic were presented in 14 international conferences.

Thesis structure. Thesis consists of introduction, 3 chapters, conclusions, reference list (159 entries) and 2 annexes. It contains 170 pages, 100 figures, 13 tables. There are 159 references in the list.

1. CHALLENGE AND RESEARCH HISTORY

Geological storage of CO_2 as a measure of mitigation of climate change gained close attention in nineties of the previous century. This idea was backed up by the first successful implementation of several large-scale industrial CCS (Carbon Capture and Storage) objects (Sleipner 1994, Weyburn 2000, In Salah 2004). EU countries took a leadership in developing and promoting this technology by initiating a number of EU-scale and national projects (CASTOR, RECOPOL, GeoCapacity, etc.). The situation is changing though, due to accelerating activities in other regions (USA, China, Australia) and decreasing attention to this technology in Europe. Yet, there is a number of research and demo projects running in European countries so far (CARBFIX , CARBOLAB, CGS EUROPE, CO2CARE, CO2-MATE, CO2PIPEHAZ, CO2SHALESTORE, CO2TRAP, COCATE, COMET, ECCSEL, ECO2, MUIGECCOS, MUSTANG, PANACEA, RISCS, SITECHAR). Two full-scale projects are in operation in Norway (Sleipner, Snøhvit).

The Circum-Baltic countries are characterised by considerable differences of the geological and socio-economic conditions that influence differences in CCS strategies in each country. CCS research activities were/are related to international initiatives (CASTOR, GeoCapacity, CGS Europe, CO2Stop, MUSATANG). A number of national projects were initiated during the previous decade, such as pioneering Lithuanian project financed by Lithuanian Science and Study Foundation (2005–2006), CO_2 geological storage opportunity research by Latvian Geological Survey (2007) and Lithuanian Geological Survey (2011–2014). Main national research projects of Estonia are focused on development of carbonation processes and CO_2 transportation scenarios. In Finland, a national research project titled "Application of carbon capture and storage in Finland (CCS Finland, 2008–2010)" (VTT) should be noted. It was preceded by "ECOSERP" project (GTK) as a part of the cross-border collaborative research project "CO2 Nordic Plus". Presently, large national project CLEEN focusing on CO_2 capture, storage and transportation is run (5 years period) in Finland. There was a number of other CCS projects funded by the Finnish industry, the Finnish Funding Agency for Technology and Innovation, and GTK. SwedSTORE^{CO2} project should be mentioned in Sweden. CO_2 capture from pressurized flue gas has been demonstrated at a pilot plant with authentic flue gas from Värtan Combined heat and power plant in Stockholm (2007–2008). Ulcos (Ultra–Low Carbon dioxide Steelmaking) research & development initiative was designed to enable drastic reduction in CO_2 emissions from steel production. Bastor network was initiated in Sweden in 2010 that was later joined by Finish partners. There are ambitions to expand the network to other Baltic Sea region countries. Belchatow (second largest CO_2 emitter in Europe, 4.44 GW_e) and Kedzierzyn demo projects are the largest initiatives in Poland. RECOPOL pilot field test was designed to study ECBM technology in Silesia (2003–2006).

On the other hand we should note some important discontinuation of CCS research and implementation activities, such as withdrawal of Vattenfall in Sweden in 2014, intending instead to make the company's coal power plants greener. Belchatow demo project was stopped in Poland. Meri-Pori CCS project (capture and transportation by ship) has been abandoned in Finland. It seems to mark some important changes in CO_2 emission reduction strategy in the region.

2. DATA AND METHODS

Studies are based on abundant archive data (industrial reports), published information regarding different parameters incorporated into the study, additional laboratory study targeted at obtaining additional information on important parameters in evaluating CO_2 storage potential, specialised computer programs. Verified methodologies were applied in calculating CO_2 storage potential in geological formations.

Stratigraphic data base. Data base of 610 deep wells drilled in different parts of the Baltic basin was compiled that incorporates well coordinates, depths and thickness of main geological layers. It is based mainly on archive data, some information was obtained from published data (papers, reports).

Logging data. Logging data base was compiled for reference wells. The main methods applied were gamma ray log (definition of layers of different stratigraphy and composition, computing clay content) and velocity well log (for calculation of the porosity of concerned reservoirs).

Hydrostatic pressure and temperatures. Those are the most important parameters in defining the prospective geological formations as they control the phase composition of CO_2 (carbon dioxide can be sequestered in supercritical and liquid phases only). Data base of deep wells was compiled bases on archive and published data (260 wells).

Hydrochemical data. Chemical composition of a formation water is an essential parameter for defining the prospective areas (salinity >20–30 g/l) and prognosis of the chemical perturbations in the formation when CO_2 is injected. Also, it is indicatory of the hydrodynamic conditions in the different parts of the basin (active infiltration, stagnant regime). Data base incorporates measurements of the chemical composition of the formation water of Lithuania of Parnu-Kemery aquifer (72 measurements) and Cambrian aquifer (205) and of Latvia (20 measurements of Cambrian formation water). The rest of information on the chemical composition of the aforementioned aquifers was collected from published reports and publications.

Petrophysical parameters. They are essential in calculating the storage capacity of the prospective (Cambrian and Pärnu-Kemeri) aquifers of the Baltic basin. Abundant information on the porosity, permeability (vertical and horizontal), and density is provided in industrial reports. Most of data were collected from Lithuanian deep wells (4668 Cambrian samples and 260 Pärnu-Kemeri samples) and Latvia (260 Cambrian samples and 930 Pärnu-Kemeri samples). Data from other regions were collected from scientific reports and publications. Also, additional petrophysical measurements (porosity and irreducible water content) of Latvian structures were measured in Belorusneft laboratory (15 samples).

Grain size composition. It has crucial effect on the petrophysical properties of sandstones, essentially permeability. 719 measurements of Cambrian sandstones were collected from Lithuanian well reports. Furthermore, 31 sample was collected from Latvian Cambrian structures and measured on laser measurement equipment (*Fritsch Analysette 22 MicroTec plus*). All data were interpreted using GRADISTAT computer program that allows defining different statistical parameters of grain size (sorting, skewness, etc.).

Petrographic analysis. 31 polished thin sections of Latvian Middle Cambrian and Lower Devonian sandstones of Latvia (onshore and offshore) were produced. They were analysed on polarised light microscope, cathodoluminescence microscope, SEM microscope equipped with BSE and EDS tools.

CO_2 parameters at the formation conditions. Salinity, temperature and hydrostatic pressure are essential parameters that control physical parameters of CO_2 at the geological formation conditions, which, in turn, are essential in calculating the storage potential of the geological traps. Physical properties were calculating using equations proposed in different papers (density, migration distance of CO_2 plume before complete dissolution) and computer programs (solubility).

Map compilation. *Surfer 8* program was applied for automatic compilation of maps of different parameters of prospective formations. It was also used for calculation of volumetric of potential traps.

Economic modelling. DSS (*Decision Support System*) tool developed by Ecofys within the frames GeoCapacity international project was used to calculate economic parameters of CO_2 storage in Lithuanian structures. Two scenarios were modelled. Also, far field transportation to North Sea region was analysed.

Calculation of storage capacity. Calculation of storage capacity was based on verified methodologies as proposed by international groups and experts (GeoCapacity, CGS Europe).

3.1. PORTFOLIO OF REDUCTION OF CO_2 EMISSIONS & BASICS OF CO_2 GEOLOGICAL STORAGE

Major avenues of CO_2 emissions reduction list the following activities:

- Decreasing energy consumption.
- Increased effectiveness of application of fossil fuel.
- Renewable energy.
- Application of CO_2 sources with lower CO_2 emissions.
- Increasing natural sinks (biosequestration, etc.).
- Application of CO_2 in technological chain.
- CCS (*carbon capture and storage*).

The latter measure is considered as the most effective option in near-future, while effective implementation of other measures require considerable time frame.

Besides to geological and landscape sinks the ocean is the largest CO_2 natural sink controlling its concentration in atmosphere. The on-surface storage can be applied along with geological storage. It is however considered as having very high risk and strong public opposition therefore is not listed as the up-to-date issue. By contrast, the landscape natural sink is effective in keeping CO_2 concentration low in atmosphere. It however conflicts to industrial activities that lead to systematic reduction of capacity of this sink (paper industry, biomass, etc.).

The CO_2 geological storage represents a technological chain *capture-transportation-storage*. The major capture methods are pre-combustion, post-combustion, and oxifuel. The post-combustion is the most developed technique, while oxifuel is considered as the most effective, though most expensive approach. The capture composes about 90% of total CCS chain costs. The massive research on this issue was postponed until geological storage volumes were asserted globally that explains some delay in development of this economically most crucial part of CCS. National projects on this issue were initiated in Sweden and Finland, and are planned in Poland (Belchatow, Kedzierzyn). Transportation coasts comprise about 5% or total CCS chain costs. This technology is proved at the industrial scale, mainly relating to EOR in USA. These issues, as the far-transportation scenario, were evaluated in Finland and Estonia. Different formations can be applied for CO_2 storage. Saline aquifers have the greatest potential, while EOR is a proved technology at industrial scale. No demo projects were initiated to store CO_2 in saline aquifers of the Baltic sedimentary basin so far, while first field-experiment to increase oil recovery was initiated in west Lithuania in 2013. Carbonation laboratory experiments gained importance in Finland, Estonia, and Lithuania during the last decade. ECBM (enhanced coal bed methane) field experiment and acid gas storage in natural gas structure were carried out in Poland outside the Baltic basin (Silesia and Mid-Polish basin).

It is concluded that different parts of CCS chain are studied in Baltic Sea countries, with different focus, however.

3.2. INDUSTRIAL SOURCES OF CO_2 EMISSIONS

CO_2 emissions amount should be evaluated to match the geological storage potential that primarily affects CCS strategy of any particular country. The total annual CO_2 emissions of sources listed in ETS amount 5.61 Mt in Lithuania. >50% of emissions are produced by energy sector. 10 sources larger than 100 kt CO_2 (viable for capture) produce 4.51 Mt annually. There was no considerable impact of closure of Ignalina NPP on CO_2

emissions in the country as most of the electricity deficiency was compensated by import instead.

Latvia is the smallest CO_2 emitter in the region. Sources exceeding 100 kt/y CO_2 produce only 1.9 Mt/y, while Estonian objects with smaller population emits 11.5 Mt/y owing to extensive application of oil shale in energy sector. Swedish and Finish large sources produce 48 and 62 Mt/y CO_2, respectively. Biomass becomes increasingly important emission source along with fossil fuel in Baltic Sea countries. Most of CO_2 emission sources of Poland (total emissions about 400 Mt CO_2) are located beyond the Baltic sedimentary basin and are not considered in detailed.

The total annual emission rate of large sources of the Baltic Sea countries (Lithuania, Latvia, Estonia, Finland, and Sweden) is as large as 128 Mt CO_2. Assuming 50% of emitters are equipped with CO_2 capture instillations it requires 1.4 Gt storage capacity in 25 years. This number is considered as the strategic volume in assessing CCS prospects of the Baltic basin.

3.3. IDENTIFICATION OF PROSPECTIVE AQUIFERS

The Baltic sedimentary basin is composed of Vendian-Quaternary sedimentary rocks overlying the Proterozoic crystalline basement of the eastern part of the East European Craton. The thickness of sediments increases to southwest to more than 4 km in westernmost part of the basin in Poland. The basin represents the alternation of different-scale aquifers and aquitards. The basin comprises territories of a number of countries that are characterised by different geological conditions owing to location in different parts of the common basin.

The saline aquifers are considered as globally most voluminous geological sinks for storing CO_2. The main criteria (CO2STORE recommendations) for screening saline aquifers are as following:

- Pressure-temperature conditions – storage can be implemented efficiently in only supercritical and liquid state of CO_2, as otherwise injection in gas phase requires excessively large storage volumes and cause injection problems. The potential depths of aquifers are in the range of 800–2500 m.

- Water salinity – should be >30 g/l that excludes utilisation of formation water on larges volumes for potable and agricultural water supply.
- Volumetric of aquifer – it should potentially accommodate large volumes of CO_2, the thickness of formation >20–30 m.
- Reservoir properties – porosity >10% (preferred >20%), permeability >50–100 mD.
- Sealing – aquitard thickness >50 m.

There are only two large scale aquifers that match the basic requirements listed above, i.e. Cambrian sandstones and Pärnu-Kemeri sandstones of Lower-Middle Devonian age. Only these two major reservoirs occur at depths exceeding 800 m in central and western parts of the basin, while other saline reservoirs are distributed at shallower depths.

Cambrian reservoir is represented by triple alternation of marine quartz sandstones, siltstones, and shales. The age of the major Cambrian reservoir is different is different parts of the basin. It is represented by Lower Cambrian sandstones distributed in the shallow periphery of the basin reaching 80–100 m thickness in Middle Lithuania and north Poland. They grade to siltstones and shales to southwest in deeper parts of the basin. These deeper marine Lower Cambrian and about 10 m thick lowermost Middle Cambrian shales and siltstones are overlain by up to 80 m thick Middle Cambrian sandstones of Deimena Series (*A.oelandicus* zone) that represent the major reservoir in west Latvia, west Lithuania, west Kaliningad District, Swedish offshore, and part of the Baltic Sea. Sandstones grade to shales in the southwestern part of the Baltic Sea and are covered by younger Dębki Formation sandstones of upper Middle Cambrian age (*P.paradosissimus* zone) of up to 80 m thick. Zarnowiec (Nexo) continental sandstones and conglomerates represent the basal part of the Cambrian section in southwesternmost part of the basin. The thickness exceeds 100 m.

Data base of several hundred wells was compiled for the whole Baltic basin. It enabled compilation of maps of major parameters of the Cambrian and Lower Devonian aquifers and cap rocks (Ordovician-Silurian shales/marlstones and Middle Devonian marlstones). Based on P-T data 200,000 km^2 large prospective area of Cambrian aquifer was defined (Fig.1). Most of the area is characterised by supercritical state of CO_2 except the northern part comprising liquid carbon dioxide.

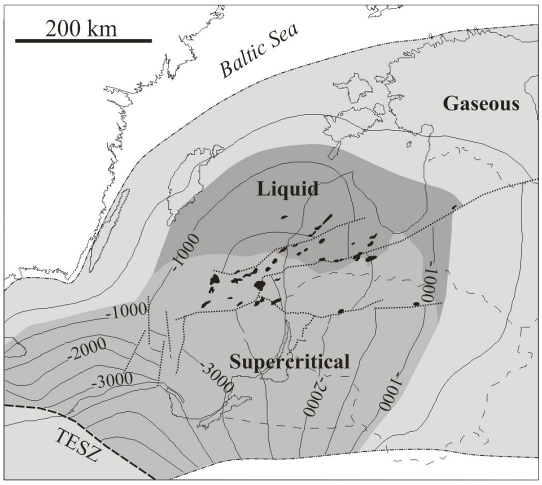

Fig.1. Distribution of Cambrian silicilcastics. Grey scale polygons define areas of different CO_2 phases. Black polygons show identified prospective structures for CO_2 storage

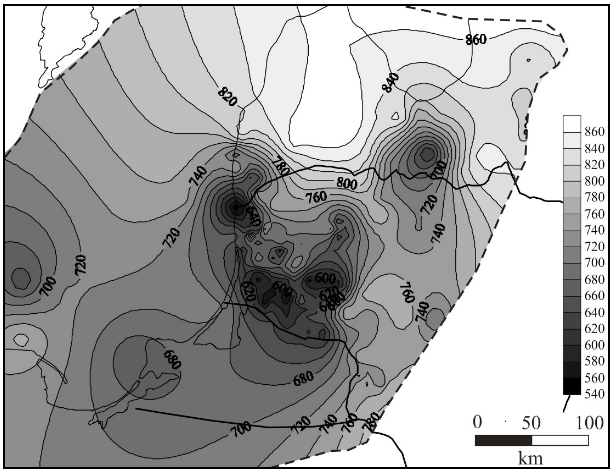

Fig.2. Modelled CO_2 density (kg/m^3) in Cambrian aquifer

CO_2 density was modelled based on equations provided by (Ouyang, 2011) (Fig.2). The largest density exceeding 800 kg/m^3 is defined in west Latvia (liquid), while lowest density 550–700 kg/m^3 of supercritical CO_2 is modelled in west Lithuania owing mainly to high heat flow in West Lithuanian geothermal anomaly.

The total thickness of Cambrian sandstones (that are of different age in different parts of the Baltic basin) is variable across the basin (Fig.3). It ranges from 30 m in the east and north to 260 m in westernmost part of the basin.

Reservoir properties (data base contain about 5000 sample measurements) directly correlate with burial depth of sandstones. Shallow sandstones are characterised by high porosity (20–25%) and permeability (>1000 mD), while decreasing to average 5% and 10 mD in central and western parts of the basin (Fig.4). The main cementing material is represented by calcite and dolomite in shallow setting, while severe late diagenetic quartz cementation is accounted for dramatic decrease of the reservoir quality of deep Cambrian sandstones. *Net-to-gross* ratio varies from 0.35–0.8 in the eastern part to <0.3 in the west of the basin. The architecture of the reservoir varies from simple (sandstones with subordinate shale-siltstone layers subdividing reservoir into several compartments traced within large territory in onshore and offshore Latvia, east and southeast Lithuania, north Poland) to complex (intricate intercalation of sandstones with siltstone and shale interlayers in Middle Lithuania, Poland) and very complex (severe quartz cementation in west Lithuania, southern Baltic Sea).

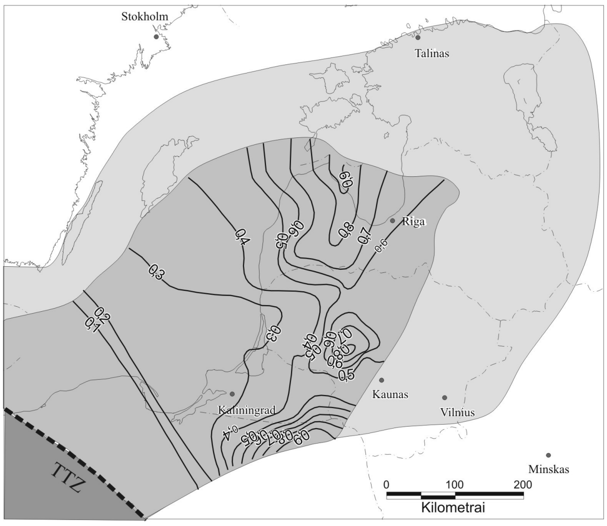

Fig.3. Thickness of Cambrian reservoir (m). Dark grey polygon shows prospective area of Cambrian reservoir for CO_2 storage, while light grey area indicates unfavourable conditions for storage

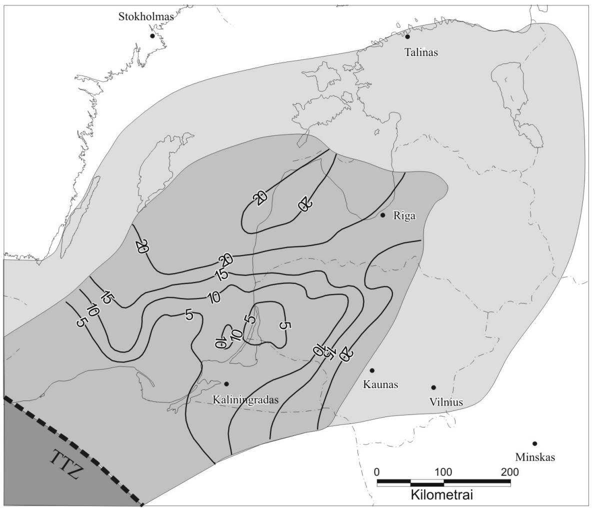

Fig.4. Average porosity of Cambrian sandstones of the prospective area

Grain size is an important parameter controlling reservoir quality (primarily permeability) of sandstones. 829 measurements of grain size measurements were collected from Lithuanian industrial reports. 40 measurements of Latvian sandstones were carried out using laser measuring equipment. GRADISTAT programme was applied to analyse the grain seize composition. Geometric method of moments was used as a most consistent. 0.15–0.22 mm fraction predominates in Cambrian sandstones. Most of sandstones are classified as fine grained (mode 0.18 mm), some part of sandstones is attributed to very fine grained. They are characterised by negative skewness (unimodal distribution with a mode -1.7), leptokurtic and very leptokurtic, mostly poorly sorted (unimodal distribution).

Salinity of formation water is in the range of 100–200 g/l, mainly of Na-Ca-Cl type in the prospective area. In a basin scale, three water salinity zones are defined related, respectively, to ~650 m and 1800 m depths (in Lithuania and Latvia). The shallow zone is affected by infiltration of meteoric waters, while stagnant regime is characteristic for deep basin. The heat flow anomaly imprints the chemical composition of Cambrian aquifer in west Lithuania.

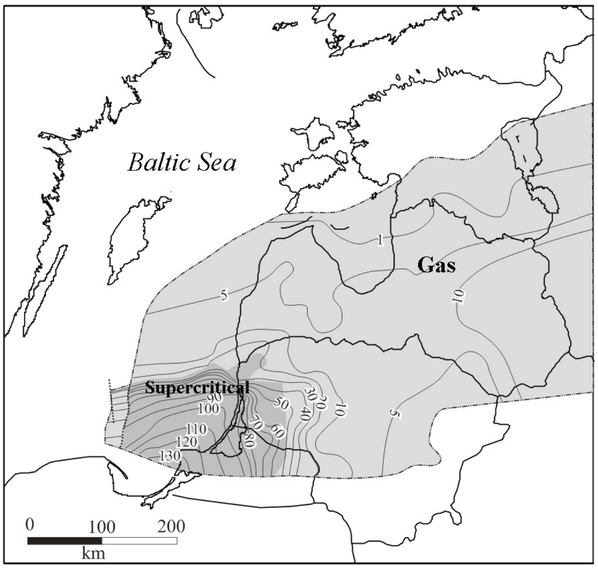

Fig.5. Salinity of formation water of Pärnu-Kemeri aquifer (g/l) (after Юодказис, 1989). Grey scale polygons define areas of different CO_2 phases

The Pärnu-Kemeri aquifer is the second largest reservoir body in the Baltic sedimentary basin. It is dominated by sandstones (quartz, quartz with feldspar) comprising 60–70% of section with subordinate siltstone and shale layers. The reservoir is characterised by complex architecture, individual layers are traced for only limited distance. 36,000 km^2 large central part of the Baltic basin is defined as prospective area for CO_2 storage, the depth of top of the reservoir ranging from 800 m in west Lithuania to 1150 m in eastern Baltic Sea. The thickness of the reservoir attains 160 m in prospective area. The average porosity of sandstones is about 26%, permeability 2000–4000 mD. Salinity ranges from 50 g/l to 130 g/l (Fig.5), pH 6-7, of Na-Cl type. The atmospheric water infiltration zone is close to the limits of the perspective area at the depth of about 800 m.

3.4. ASSESSMENT OF CO_2 STORAGE CAPACITY OF CAMBRIAN SALINE AQUIFER

3.4.1. . HYDRODYNAMIC TRAPS

Onshore traps

Storage capacity of hydrodynamic traps (structures) was calculated:

$$M_{CO2} = A \times h \times \varphi \times \rho_{CO2} \times S_{eff} ,$$

M_{CO2} – kg of CO_2, A – trap area (m^2), h – effective thickness of reservoir within structure closure, φ – porosity (fraction), ρ_{CO2} - CO_2 density at aquifer conditions (kg/m^3), Seff – storage efficiency (fraction). The latter was estimated using approached developed by GeoCapacity project (reservoir quality and fault controlled).

Lithuanian territory is well studied in terms of seismic and deep drilling coverage. 76 local uplifts were identified in Cambrian reservoir (Fig. 6). The total capacity of those structures reaches as much as 102 Mt CO_2. However, capacity of individual structures is bellow 1 Mt CO_2 except the largest Syderiai and Vaškai uplifts located northern part of Lithuania. 21.5 Mt CO_2 can be stored in Syderiai uplift, while 8.7 Mt CO_2 capacity was calculated in Vaškai structure. Small volumes of defined Cambrian structures are accounted to very week structuring of the sedimentary cover of Lithuania (craton setting) that was most intense during latest Silurian-earliest Devonian (Late Caledonian stage).

Alternative scenario of storing CO_2 in Gargždai elevation was considered in west Lithuania (Fig.7). It can accommodate 100 Mt CO_2. On the other hand it has important negative parameters (1) control of eastern flank by Gargždai fault the tightness of which is difficult to prove and monitor, (2) very low reservoir properties of Cambrian sandstones (4–6% average porosity).

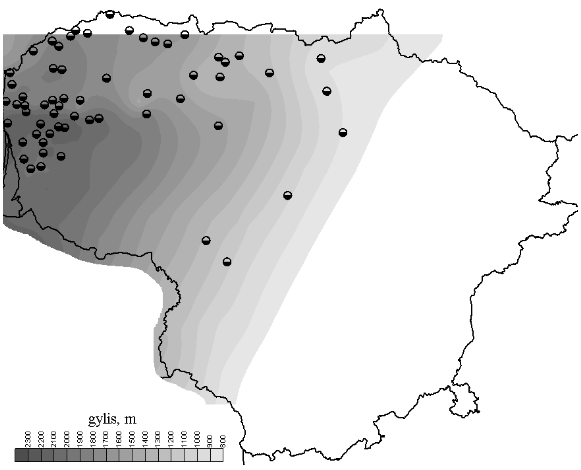

Fig.6. Location of studied Cambrian local uplifts. Depth of top of Cambrian reservoir are shown within the prospective area

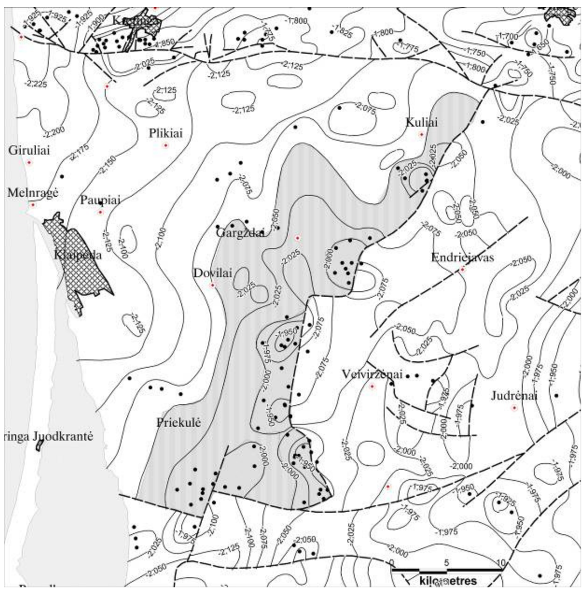

Fig.7. Fig.7. Structural map of top of Cambrian. Shaded area shows Gargždai elevation (compiled by V.Markšaitienė, published Šliaupienė, Šliaupa, 2011)

By contrast to Lithuania, the Latvian territory was subject to more intense faulting and structuring during Phanerozoic. It resulted in establishment of numerous local uplifts characterised by larger size (Fig. 8.). The depths of structures are in the range of 1–1.2 km. Accordingly, they have good reservoir properties (porosity about 20%, permeability about 500 mD). The architecture of the reservoir that is represented by Deimena Series is rather simple within the prospective area, showing three major compartments divided by shaly base of Ablinga Fm. and Giruliai Fm.

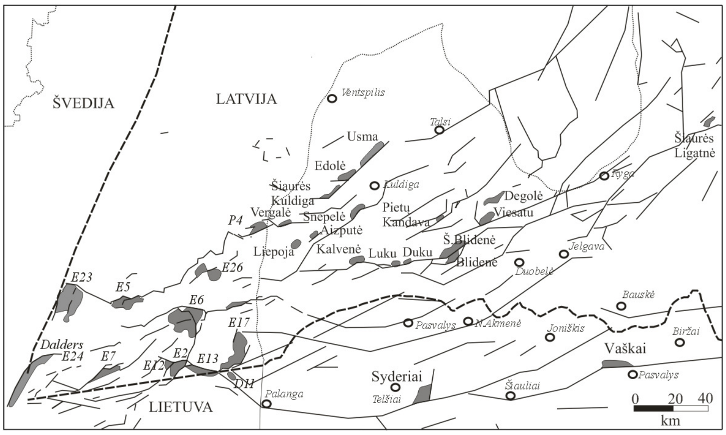

Fig.8. Cambrian structures of storage capacity >1 Mt CO_2. Faults and structures are shown (after Latvian tectonic map (Brangulis, Kanevs, 2002), Lithuanian tectonic atlas)

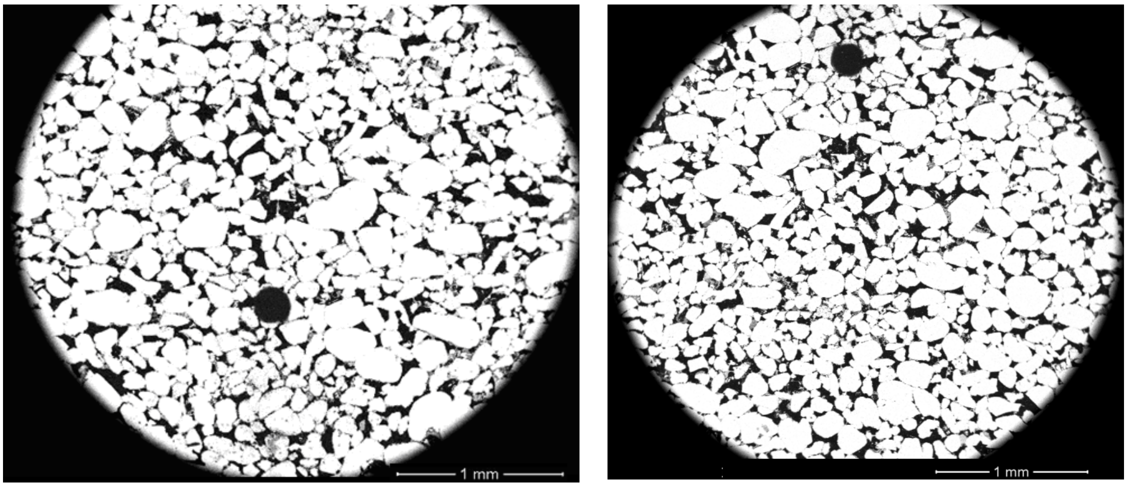

Fig.9. SEM BSE microphotograph of Cambrian quartz sandstones (left – well Vergale-50, depth 1003 m, Giruliai Fm., open porosity 23,7%; right – well Edole-67, depth 1109 m, Ablinga Fm., open porosity 18,6%)

15 onshore structures were studied in detail based on seismic and drilling data presented in industrial reports (Fig.10 shows the largest onshore structure). Besides,

additional studies of petrophysical properties (porosity, irreducible water content), grain size (laser sizing technique) and petrographical composition (CL, SEM, EDX) were carried out (Fig. 9).

CO_2 storage capacity of individual structures varies from 1.8 to 117.5 Mt CO_2. The total storage capacity was estimated as large as 518 Mt CO_2. Ranking of structures was carried out based on 8 major parameters (data quality, trap geometry, conflict of interests, etc.). The average porosity of Cambrian sandstones is close, ranging from 18 to 22% (permeability about 500 mD). Geometry of structures varies considerably from low-amplitude box-type uplifts to high-amplitude brachioanteclines, depending on degree of tectonic strain accumulated mainly along controlling high-angle reverse faults. The well correlation implies that some faults originated as early as the latter part of Cambrian, while most activity took place during late Caledonian phase (Late Silurian–Early Devonian). Sandstones range from very fine grained to fine grained, poorly sorted. Grain size composition and petrographic studies indicate that most drill cores are affected by infiltrated drilling mud. Sandstones are poorly cemented by late diagenetic quartz, in some parts by carbonate cement. The content of irreducible water is in the range of 3–10%. It is, however, much influenced by drilling mud infiltrate which is systematically more abundant in sandstones showing increased late diagenetic quartz cementation that leads in increasing turtuosity and reduced porosity.

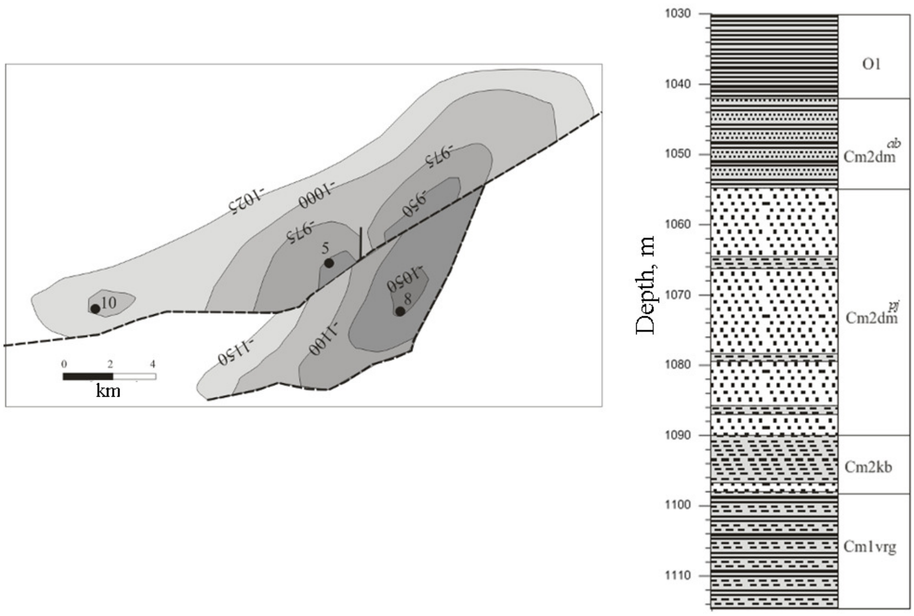

Fig.10. Structural map of top Cambrian, Blidene & N.Blidene structures (largest onshore storage site in Baltic basin). Cambrian geological section of well Blidene-5 is shown on the right (after LEGMC reports)

The onshore potential of Kaliningrad area is related to oil field prospects and therefore is considered in HC field storage chapter. No storage capacity is identified in Estonia due to shallow setting in the basin periphery. Furthermore, onshore territories of Finland and Sweden are located outside the basin within the Fernnoscandian shield with only thin remnants of the sedimentary cover. No traps were identified in Skåne comprising deep fault-controlled sediments either.

Offshore traps

Offshore area is covered by a dense network of seismic profiles. Several dozens of HC exploration and exploitation wells were drilled in the Baltic Sea area. A number of prospective local uplifts have been defined.

CO_2 storage capacity of Lithuanian offshore was evaluated. They are characterised by low capacity values due to small size of local uplifts (area 5–20 km^2, amplitude 20–40 m) and very low reservoir properties (predominating porosity of Cambrian sandstones is <8%). The largest D11 local uplift located close to coast line can accommodate 10 Mt of CO_2 which is considered negligible for offshore trap.

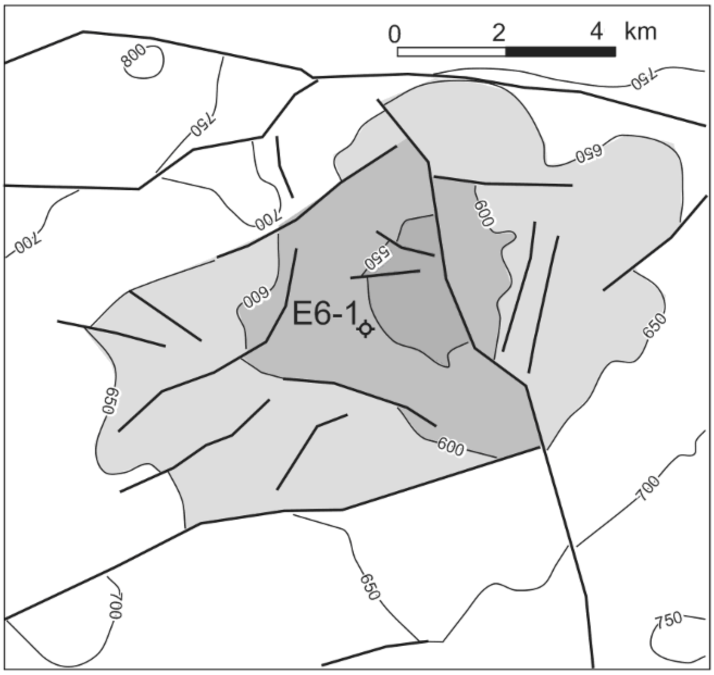

Fig.11. Structural map of top of Cambrian, E6 structure (largest offshore structure in the Baltic basin) (after Odin Energy, 2010). Pleas note fault controlling the structure and the cutting faults

Similarly to onshore area, the Latvian offshore is intensely dissected by faults controlling abundant associating local uplifts. 12 prospective structures were identified for CO_2 storage. The largest E6 uplift can accommodate up to 612 Mt CO_2. Other structures are of smaller size. Capacity of E7 structural trap is evaluated 43 Mt CO_2. Dalders structure extending to Swedish territory can store 130 Mt CO_2. The total storage potential of Latvian offshore structures can be suggested as high as around 1 Gt CO_2.
Local uplifts defined in Kaliningrad District and Polish offshore areas are considered as potential hydrocarbon reservoirs and are discussed in chapter bellow.

No local uplifts were defined in Swedish offshore despite of detailed seismic survey and a number deep wells. The main prospect is related to stratigraphical trap in Faludden sandstones that are correlated to Deimena Series in Lithuania and Latvia. This scenario is rather doubtful taking into consideration the general trends of the basin development that controlled the lithofacies distribution.

3.4.2. STORAGE IN UNCONFINED AQUIFERS IN MONOCLINAL SETTING

Large unconfined monoclinal structures represent alternative storage sites in saline aquifers. The main principle is based on gradual dissolution of carbon dioxide in formation water as it migrates in aquifer. As it dissolves, the brine increases in density that is 2–3% larger than the non-carbonated water. It inevitably leads to reversal of the CO_2 plume migration from up-dip to down-dip, i.e. towards the deeper parts of the sedimentary basin. The essential parameter is therefore the distance of migration of CO_2 before it completely dissolves in the water. The migration distance was calculated using equations accounting to dissolution and migration rates, reservoir properties of sandstones and physical parameters of formation water and CO_2. The CO_2 plume migration distance was estimated only 3.2 km (assuming extreme reservoir anisotropy – 25 km) in the Cambrian reservoir of west Lithuania that proves safe approach of such storage technique in the large Baltic basin. The total storage potential is estimated as large as 27 Gt CO_2.

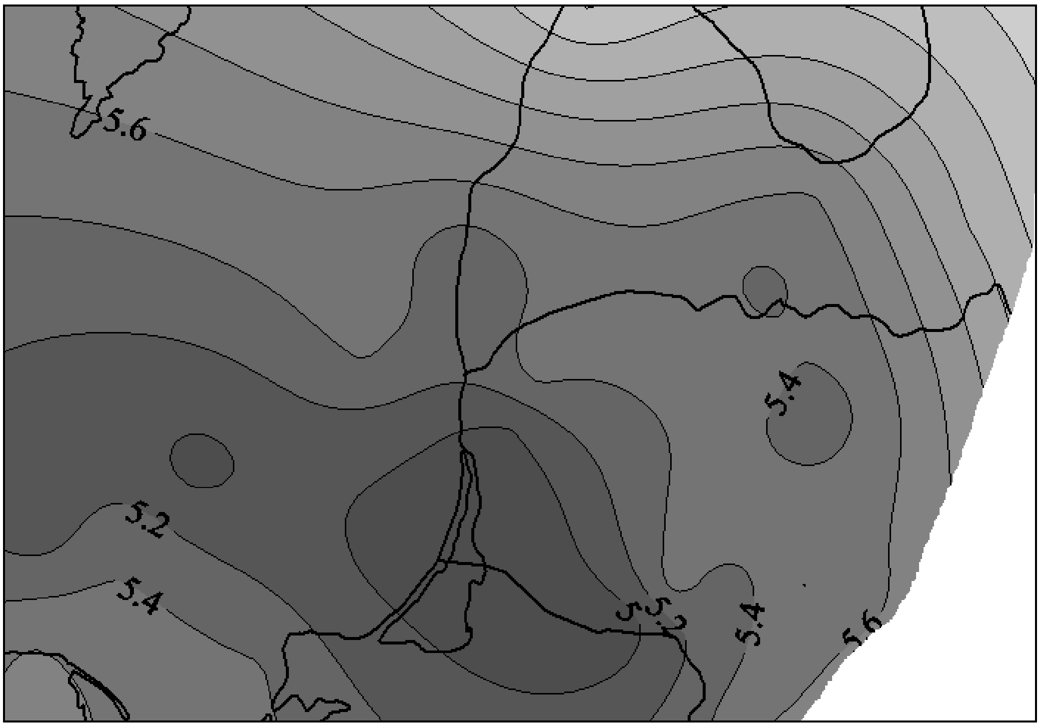

Fig.12. Modelled solubility of CO_2 in Cambrian formation water (%)

3.5. CO_2 STORAGE CAPACITY OF KEMERY SALINE AQUIFER OF LOWER DEVONIAN

Kemeri Regional Stage represents the major part of the Pärnu-Kemeri aquifer distinguished in the Baltic artesian basin. The Pärnu RSt is of very low reservoir quality within the potential area, therefore it is not considered as the potential formation for CO_2 storage. The thickness of the Kemeri aquifer reaches up to 160 m within the prospective area. Lower Devonian sandstones have high porosity and permeability (average 26% and 2000–4000 mD, respectively), average net-to-gross value is 0.65.

Still, the storage potential is defined as negligible due to absence of large structural (or stratigaphic) traps. The amplitudes of identified local uplifts reach up to dozen of meters owing to very low tectonic activity of the basin during the Late Palaeozoic and Mesozoic-Cenozoic.

The alternative storage in unconfined monoclinal setting is evaluated as large as 33 Gt. Yet, this technique is considered as a far-future option that can be implemented only after extensive industrial implementation of CO_2 storage in hydrodynamic traps elsewhere.

3.6. RISK FACTORS

Different risk factors are considered as regards storage of CO_2 in geological formations. At this stage of the study, three major parameters are discussed, i.e. cap rock quality, potential faulted path-ways, and old boreholes.

Cambrian aquifer is characterised by essentially large shaly cap rock package composed of shales with rare limestone layers of Ordovician-Silurian age, while marlstones predominate in the shallower part of the prospective area. The thickness of this seal is in the range of 460–2500 m within the prospective area, increasing in thickness to the southwest.

Ordovician-Silurian cap rocks are dissected by rather scarce fault system that originated during the Late Caledonian (latest Silurian–earliest Devonian) tectonic phase. Three major types of faults were defined. Faults trending NE-SW are predominantly reverse faults of simple geometry that is related to formation of the Caledonian faults be NW-SE compression induced by Baltica-Laurentia collision along the Norwegian Caledonides. W-E oriented faults are mostly characterised as flower structures indicating significant horizontal component of the fault shifting. Large faults are often complicated by small scale reverse (rarely normal) faults of simple geometry. The first type of faults is considered as low-risk zones, while flower structures of complex geometry may provide path-ways for CO_2 leakage from the Cambrian reservoir. Small-scale cutting faults are also viewed as potential leaking structures due to low amplitudes that tentatively are cored by a thin fault-gouge zone.

Structural setting of prospective local uplifts were analysed within the potential area. It is indicated that only a few large local uplifts are devoid of any association with faults, while most of structures are controlled by one or several faults. Some large size uplifts are dissected by complicating faults that considerably increase the storage risk (e.g. the largest E6 local uplift in the Baltic basin).

The onshore part of the potential storage area (Latvia, Lithuania, Kaliningrad District) is extensively drilled owing to oil exploration activities carried out since late fifties. Prospective structures are cut by 1–4 deep wells, some are proved by more wells (e.g. Duobele uplift). The technical state of those wells is highly uncertain due to possible aging (e.g. corrosion), technical inconsistencies during well construction and operation, etc. So far, no leakage of saline water along the wells was noticed within the prospective area, though alarming notes of the saline water surface spill have been reported from other parts of the basin (e.g. southeast Lithuania).

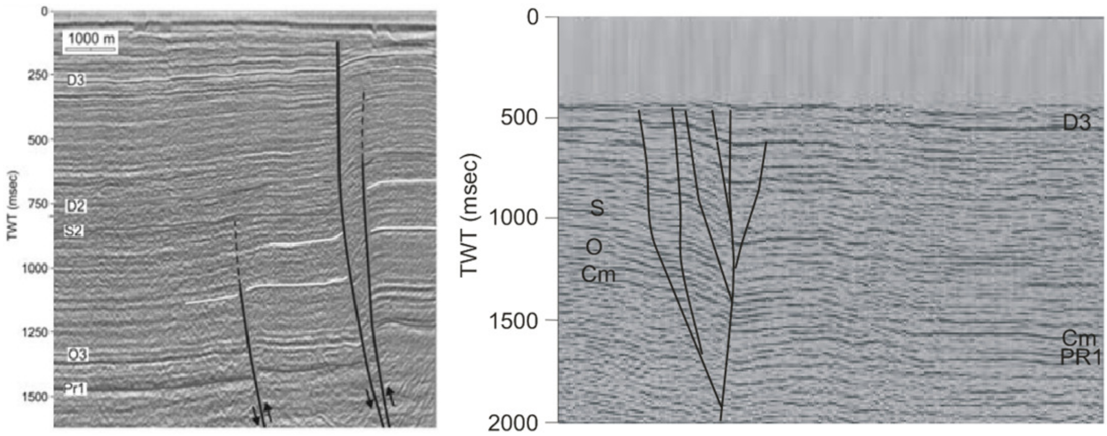

Fig.13. Left – offshore seismic profile crossing southern border of Liepaja-Saldus ridge (reverse faults). Right – Telšiai fault showing complex flower structure, west Lithuania (Šliaupienė, Šliaupa, 2012)

3.7. ECONOMIC EVALUATION OF CO_2 STORAGE

The main risk of industrial implementation of CCS technology is related to economic efficiency as implementation of this technology inevitably increases energy costs (and consumption of fuel by 30%).

Two scenarios were modeled using DSS (Decision Support System, TNO) program. They assume CO_2 capture in Akmenė cement plant and Mazeikiai oil refinery located close to Syderiai and Vaškai structures. DSS tool allows incorporation of a number of essential parameters that affect the CCS costs, e.g. CO_2 emission rate, concentration, type of capture system (pre-combustion, post-combustion, oxyfuel), type of fuel, loading hours, transportation distance and availably of gas or oil pipelines, reservoir properties, storage site characteristics, etc.). The average cost of the near-distance storage scenarios is estimated 21 €/t CO_2 (Table 1.). It is also applicable to near-distance cross-border storage scenario (i.e. in Latvian structures).

Far-distance transportation by interregional pipeline to North Sea was evaluated as a part of the whole-Baltic initiative (Lithuania, Latvia, Estonia, Finland, Sweden, Norway). It has only little effect on the total CCS expenses (1–2%) for Lithuanian industry. By contrast, costs considerably increase (by about 30%) if transportation by ships is considered.

Table 1. Main economic results of Case study 2 (CO_2 capture in "Akmenės cementas", transportation to and storage in Vaškai site)

NPV	259.02	M€
NPV capture	105.44	M€
NPV compression	137.35	M€
NPV transport	8.42	M€
NPV storage	7.81	M€
NPV normalised	21.26	€/tCO_2 avoided
NPV capture normalised	8.62	€/tO_2 avoided
NPV compression normalised	11.23	€/tCO_2 avoided
NPV transport normalised	0.72	€/tCO_2 avoided
NPV storage normalised	0.68	€/tCO_2 avoided

3.8. ENHANCED HYDROCARBON RECOVERY USING CO_2

There is a number of oil (and few gas) fields discovered and operated in the Baltic sedimentary basin, mostly in Middle Cambrian sandstones. Most of fields are in mature and tail operation stages that urge application of the additional techniques to stimulate the oil (and gas) recovery. Therefore, HC fields are considered as potential CO_2 storage sites that might be combined to economic benefit (EOR).

Storage potential of 16 oil fields of Lithuania was evaluated. It was assessed in the range of 0.06–1.22 Mt CO_2. These are very low values owing to small size of structures and very low reservoir properties of Cambrian sandstones. The total storage amount is only 6.45 Mt CO_2. It therefore has no discernable effect on the storage strategy in Lithuania.

This technology might lead to some economic benefit. CO_2 is successfully used for enhanced oil recovery since seventies. The total incremental oil volume gained by application of CO_2 EOR approach is assessed as high as 2.35 Mt in Lithuanian oil fields. Rule-of-thumb approach was applied to calculate volumes of additional oil extracted.

Positive results were reported from two oil fields of west Lithuania by "Minijos nafta" that injected CO_2 into Cambrian reservoir in 2013. It encourages expansion of this technology to other Lithuanian and adjacent oil fields in the Baltic sedimentary basin.

The storage potential of Kaliningrad oil fields was assessed as large as 54 Mt CO_2 onshore and 34 Mt CO_2 offshore. The offshore Polish oil fields can accommodate 6.4 Mt CO_2, while 19,8 Mt CO_2 in gas fields.

Based on study results different parts of the Baltic sedimentary basin were defined according to most prospective CO_2 storage technology (Fig. 14).

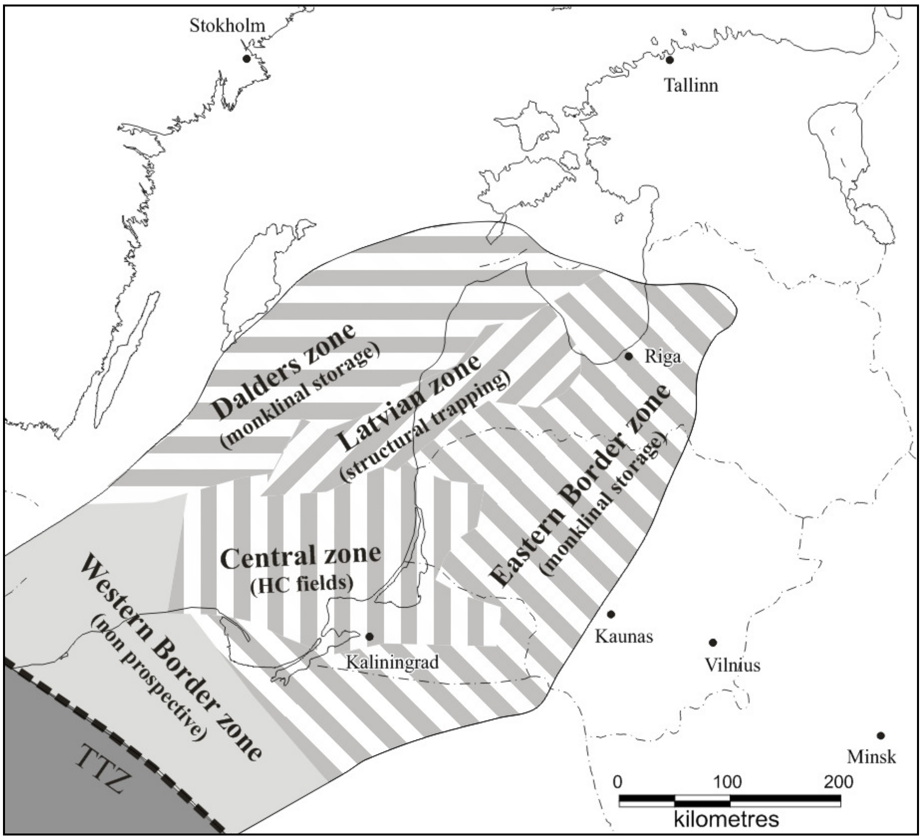

Fig.14. Zonation of the Baltic basin according to prospective CO_2 storage technologies in Cambrian reservoir

3.9. PROSPECTS OF CARBONATION OF SERPENTINITES

As it is shown in previous chapters there is no or miserable storage potential in saline aquifers in Lithuania, Estonia, Sweden, and Finland. It urges consideration of alternative storage technologies.

Application of ultramafic rocks for immobilisation of CO_2 was studied by different research groups in Finland and Lithuania, mainly focusing on improvement of the carbonation reactions that can be applied at an industrial scale. The present study is scoped on calculation of the storage capacity of Lithuanian serpentinites discovered in the crystalline basement (Early Proterozoic) in southeast Lithuania. The largest resources are confined to Varėna magnetite ore deposit. It shows highly complex external and internal geometry that is typical for geological bodies of metasomatic origin. 13 wells were drilled to explore the Varėna iron body. The average total thickness of serpentinties was calculated 41 m. The geometry of the metasomatic body, based on drilling data and modelling of potential fields, represents a large synclinal fold. Assuming 2.6:1 carbonation ratio of serpentinite and CO_2, the total storage capacity of Varėna serpentinites was evaluated 413 Mt CO_2.

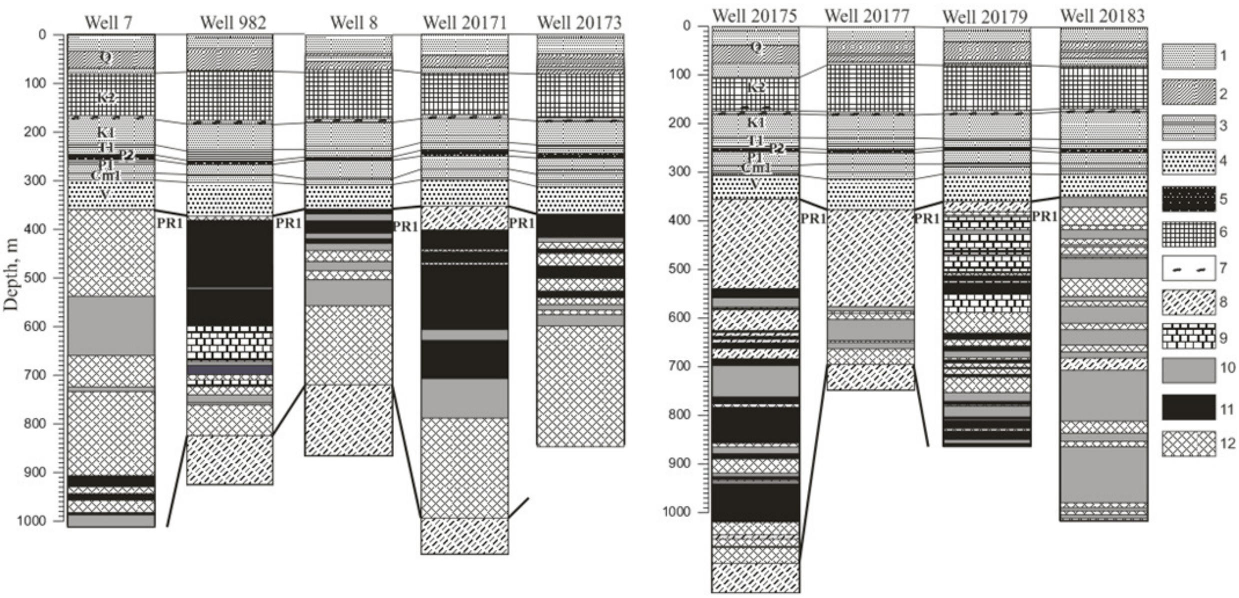

Fig.15. Geological sections of wells dissecting Varėna iron ore deposit. 1 – sandy deposits, 2 – sandy and clayey loam, 3 – sandy sediments with shale interlayers, 4 – conglomerate, sandstone 5 – limestone, dolomite, 6 – chalk, 7 – phosphorite, 8 – gneiss, 9 – marble, 10 – serpentinite, 11 – magnetite ore, 12 – metasomatic skarns of different composition (Varėna Complex)

This technology is considered as excessively costly compared to CO_2 storage in sedimentary formations. In this particular case concerning Varėna iron ore deposit, a better economic effect is expected combining exploitation of serpentinites and magnetite ore.

A similar approach is feasible in Finland, while alkaline ash (by-product of application of oil shales in energy sector) is considered as potential CCS approach in Estonia.

CONCLUSIONS

- CO_2 emissions are very different in Baltic Sea region countries depending on industrial specialisation and require large storage capacities (annual rate 128 Mt CO_2 from large stationary sources).
- Two saline aquifers are defined as prospective formations in the Baltic sedimentary basin, i.e. Cambrian and Lower Devonian. CO_2 can be stored in supercritical and liquid phases depending on P-T conditions.
- Hydrodynamic trapping can be applied in only Cambrian saline aquifer. Most of potential structures are located in Latvia. The total storage capacity of structural traps is calculated as high as 549 Mt onshore. The largest structure E-6 can accommodate 612 Mt of CO_2 offshore.
- The largest storage potential is defined in monoclinal structures in unconfined Cambrian saline aquifer (27 Gt CO_2) and Lower Devonian saline aquifer (33 Gt CO_2). This approach is considered, however, as far-future technology.
- The main risk factor is related to faulted pathways, as almost all potential structures are controlled by faults. Their tightness is suggested different owing to specific kinematic features (bounding compressional and transpressonal faults, cutting faults). Potential leakage of some faults is evidenced by hydrochemical anomalies, also traces of hydrocarbon escape defined in some fields.
- CO_2 storage costs considerably exceed market prices that inevitably increase the energy costs when applied CCS technology. The near- and far-transportation and storage scenarios were considered. It requires the coordinated CCS strategy of the Baltic Sea countries.
- The storage potential of hydrocarbon fields is rather negligible in the Baltic region. It is calculated as high as 6.5 Mt CO_2 in Lithuania, 88 Mt in Kaliningrad District, 26.2 Mt in Poland.
- Carbonation as a CO_2 storage technology potential is high. The storage capacity of serpentinite bodies discovered in SE Lithuania is estimated 413 Mt CO_2.The geological conditions of the Baltic sedimentary basin are favourable for application of different geological storage technologies. Different parts of the Baltic basin were classified according to preferred storage technology.

Anglies dvideginio dujų geologinio saugojimo perspektyvos Baltijos sedimentaciniame baseine

SANTRAUKA

Geologinis CO_2 saugojimas yra viena iš perspektyvių technologijų, kurią galima pradėti taikyti artimiausioje ateityje, mažinant CO_2 emisijas. Keliose pasaulio vietose šis metodas jau dalinai taikomas.

Disertacijoje įvertintos CO_2 geologinio saugojimo potencialas Baltijos sedimentaciniame baseine. Pagrindiniai darbe nagrinėjami uždaviniai: (1) išskirti ir apibūdinti Baltijos sedimentacinio baseino, ypatingai Lietuvoje, pagrindinius vandeningus sluoksnius, tinkamus CO_2 geologiniam saugojimui; (2) apžvelgti CO_2 emisijų Baltijos regiono šalyse mastus ir pobūdį; (3) įvertinti Baltijos sedimentacinio baseino sūrių vandeningų sluoksnių CO_2 saugojimo potencialą; (4) įvertinti saugojimo rizikos elementus; (5) įvertinti CCS (*Carbon Capture & Storage*) ekonominius aspektus; (6) nustatyti alternatyvių CO_2 saugojimo technologijų potencialą.

Didžioji tyrimams naudotos geologinės medžiagos dalis buvo surinkta iš gamybinių ataskaitų, saugomų Lietuvos ir Latvijos (LEGMC) geologijos tarnybų fonduose (uolienų aprašymas, kolektorinės savybės, seisminių tyrimų medžiaga, hidrocheminė ir geoterminė informacija, granuliometrinė sudėtis ir kt.). Taip pat didelę informacijos dalį suteikė publikuoti darbai (ataskaitos, moksliniai straipsniai). Analizuotos potencialių sluoksnių kolektorinės savybės, termobarinės ir struktūrinės bei hidrogeologinės sąlygos, dengiančių sluoksnių litologiniai ypatumai. Skaičiuojant formacijų saugojimo apimtis, buvo taikoma verifikuota metodika. Papildomai atlikti laboratoriniai tyrimai, nustatant kambro uolienų petrografinę sudėtį (naudota poliarizuota mikroskopija, SEM (papildyta EDS), katodoliuminescencinis mikroskopas), smiltainių grūdelių dydis (lazerinis matuoklis), poringumas ir liekaninis porinis vanduo smiltainiuose. Kadangi kolektorinės savybės gręžiniuose buvo tiriamos ribotai, poringumo nustatymui atraminiuose gręžiniuose papildomai panaudotas geofizinių tyrimų gręžiniuose kompleksas. CO_2 parametrų skaičiavimui naudotos specializuotos programos (CO_2_solubility.exe), taip pat atlikti skaičiavimai naudojant algoritmus, skelbtus mokslinėse publikacijose (pvz., CO_2 tirpumas poriniame vandenyje, CO_2 pliumo migracija). Ekonominiam modeliavimui

panaudota DSS (Decision Support System) kompiuterinė programa. Žemėlapių automatiniam braižymui naudota *Surfer 8* programa.

Vieno sedimentacinio baseino ribose įvertintos alternatyvios CO_2 saugojimo technologijos, atsižvelgiant į jo teritoriją patenkančių valstybių pramonės ir geologinių sąlygų specifiką. Gauti rezultatai suteikia bazinę informaciją, planuojant praktinio CCS technologijos įgyvendinimo strategiją regione.

Darbe apibendrinta multidisciplininių tyrimų medžiaga, surinkta ir analizuota pačios autorės arba jai dalyvaujant kompleksiniuose tyrimuose. Pirminė medžiaga surinkta Valstybinio mokslo ir studijų fondo finansuoto 2005 m. projekto, skirto CO_2 geologinio saugojimo galimybių vertinimui Lietuvoje, metu. Autorė dalyvavo tarptautiniuose CCS projektuose: GeoCapacity (2006–2008 m.), CGS Europe (2011–2013 m.).

Baltijos regionas pasižymi labai skirtingomis geologinėmis sąlygomis – Skandinavijos šalys (Švedija, Suomija) daugiausia yra Fenoskandijos skydo teritorijoje, kurioje beveik nėra gilių nuosėdinių uolienų sluoksnių, išskyrus atskirus nedidelius plotus (Skonė, Botnijos įlanka), tuo tarpu Estija, Latvija, Lietuva, Kaliningrado sritis, Lenkijos šiaurinė dalis išsitenka Baltijos sedimentacinio baseino, kuriame yra pakankamai didelė nuosėdinių formacijų storymė, ribose. Atitinkamai labai skiriasi ir vykdomi tyrimai, sprendžiant CO_2 emisijų problemą.

Baltijos šalių CO_2 emisijų pobūdis skiriasi dėl skirtingos industrijos specializacijos. Didžiausiomis emisijomis (vienam gyventojui) pasižymi Estija ir Suomija (viršija 10 tonų). Lietuvos ir Švedijos apimtys yra panašios ir apibūdinamos kaip vidutinės (4–6 tonos vienam gyventojui). Stacionarūs šaltiniai, kurių emisijos viršija 100 tūkst. tonų per metus, išmeta bendrai: Lietuvoje – 4,6 mln. t, Latvijoje – 1,9 mln. t, Estijoje – 11,5 mln. t, Suomijoje – 62 mln. t, Švedijoje – 48 mln. t. Bendra šių šalių emisijų apimtis sudaro 128 mln. t. Vertinant geologinio saugojimo galimybes regione, būtina atsižvelgti į emisijų apimtis.

Atlikti tyrimai parodė, kad Baltijos sedimentaciniame baseine gali būti išskiriamos dvi geologinės formacijos, pagal temperatūros ir hidrostatinio slėgio sąlygas ir sluoksnio apimtis tinkamos CO_2 geologiniams saugojimui, – kambro ir apatinio devono. Pirmojo kolektoriaus plotas siekia 200 tūkst. km^2, antrojo – 36 tūkst. km^2. Vandens mineralizacija perspektyviame plote viršija 50 g/l, tad vanduo nėra tinkamas plačiam naudojimui (geriamo vandens tiekimui, žemės ūkiui ir t.t.). Kambro sluoksniui būdinga labai žymi kolektorinių savybių kaita baseine, tai apsprendžia skirtingas sluoksnio panaudojimo CO_2 saugojimui galimybes skirtinguose rajonuose; apatinio devono vandeningas sluoksnis turi išimtinai geras kolektorines savybes, jos mažai kaičios perspektyvaus ploto ribose.

CO_2 geologinio saugojimo potencialas skirtingose Baltijos sedimentacinio baseino dalyse yra kaitus. Pagrindinės perspektyvos (pagal technologijos brandumą) siejamos su CO_2 saugojimu kambro vandeningo sluoksnio lokaliose pakilumose (struktūrinėse talpyklose). Sausuminėje baseino dalyje Lietuvos teritorijoje nustatytos tik dvi lokalios pakilumos kambro sluoksnyje, kurių saugojimo potencialas viršija 1 mln.t CO_2, – Syderių ir Vaškų. Jų bendra talpa paskaičiuota 30,2 mln.t. Tačiau perspektyvos jose saugoti CO_2 praktiškai yra nulinės. Syderių struktūroje planuojama ateityje įrengti gamtinių dujų saugyklą, Vaškų struktūros uždarumas lieka abejotinas. Alternatyvus sprendimas – saugojimas Gargždų pakilumų zonoje, jos saugojimo apimtis siektų 100 mln.t. Tačiau šis variantas reikalauja didžiulių investicijų, susijusių su saugumo užtikrinimu (CO_2 pliumo kambro vandeningame sluoksnyje kontrolė). Didžiausiu potencialu sausuminėje dalyje pasižymi Latvijos teritorija, kurioje išskirta 15 struktūrų, kurių talpa viršija 1 mln.t (didžiausia Šiaurės Blidenės pakiluma – 117 mln.t CO_2). Bendra pakilumų saugojimo apimtis – 549 mln.t CO_2. Estijos, Suomijos ir Švedijos sausuminėje dalyje nėra gilių nuosėdinių gilių vandeningų sluoksnių, tinkamų CO_2 saugojimui (Pietų Švedijos nuosėdinėje storymėje nerasta perspektyvių pakilumų). Šiaurės Lenkijos ir Kaliningrado teritorijų saugojimo potencialas siejamas su naftos telkiniais (ši technologija aptariama atskirame skyriuje).

Baltijos jūroje, kaip ir sausumoje, didžiausias saugojimo potencialas sutelktas Latvijos ekonominėje zonoje. Išskirta 12 perspektyvių pakilumų. Didžiausios E6 pakilumos potencialas viršija 600 mln.t CO_2. Kitos struktūros smulkesnės. Bendra struktūrinių saugyklų apimtis vertinama apie 1 mlrd.t CO_2. Lietuvos, Kaliningrado ir Lenkijos šelfo potencialas susijęs su naftos telkiniais. Švedijos akvatorijoje galimas saugojimas vidurinio kambro stratigrafinėje talpykloje, tačiau jos patvirtinimui būtini papildomi tyrimai, todėl kol kas jos potencialas nėra vertinamas.

Didžiausia CO_2 saugojimo apimtimi pasižymi monoklininės (atviros) struktūros. Tai sietina su anglies dvideginio tirpumu vandeningame sluoksnyje. Bendra saugojimo apimtis vertinama keliasdešimt mlrd.t. Tačiau ši technologija praktikoje gali būti įgyvendinama tik pramoniniu mastu adaptavus saugojimo struktūrinėse (ar stratigrafinėse) talpyklose technologiją Baltijos ir kituose regionuose.

Apatinio devono vandeningas sluoksnis pasižymi ženkliai geresnėmis kolektorinėmis savybėmis ir talpumo charakteristikomis. Nepaisant to, kad dalis vandeningo sluoksnio tenkina pagrindines P-T sąlygas, CO_2 saugojimo uždarose lokaliose struktūrose galimybė yra praktiškai nulinė, nes dėl gerokai mažesnio tektoninių procesų intensyvumo (hercininis struktūrinis kompleksas) sluoksnis yra mažai deformuotas, lokalios pakilumos yra mažos amplitudės (iki keliolikos metrų). Didelis potencialas siejamas su monoklininiu saugojimu atvirame vandeningame sluoksnyje, jo apimtis vertinama 33 mlrd.t.

CO_2 geologinis saugojimas susijęs su tam tikra rizika, kurią galima minimizuoti detaliais tyrimais ir griežtu technologinių reikalavimų laikymusi. Pagrindiniai rizikos faktoriai ir pavojai: vandeningo sluoksnio dangos integralumo pažeidimas eksploatacijos metu viršijus jos mechaninį atsparumą, dujų pertekėjimais lūžiais ir senais gręžiniais. Kambro sluoksnis pasižymi išimtinai gera danga – nuo geriamo vandens sluoksnių, esančių vidutiniškai iki 200–300 m gylyje, jį skiria 500 m, o vakaruose daugiau kaip 1000 m storio molinga ordoviko–silūro danga. Didžiausią pavojų kelia lūžiai. Beveik visos struktūrinės gaudyklės yra kontroliuojamos vieno arba kelių lūžių, kurių tipas skirtingas – transpresinis, kompresinis. Jie pasižymi nevienodomis pralaidumo charakteristikomis. Didžiausias pavojus siejamas su struktūromis, kurias lūžiai ne tik kontroliuoja, bet ir kerta. Preliminarią informaciją apie vieno ar kito lūžio uždarumą galima gauti iš hidrocheminių duomenų – Lietuvos teritorijoje nustatyta nemažai hidrocheminių anomalijų, rodančių vertikalų požeminio vandens pertekėjimą išilgai lūžių. Kitas rizikos faktorius siejamas su senais gręžiniais. Per ilgą laikotarpį jų konstrukcija gali būti pažeista (pvz., korozija), kai kurie gręžiniai galėjo būti netinkamai likviduojami.

Atliktas CO_2 saugojimo ekonominis modeliavimas. Saugojimo kaštai žymiai viršija ATL (apyvartinių taršos leidimų) kainas, CCS technologijos taikymas neišvengiami didina energijos kainas. Išnagrinėti artimojo ir tolimojo transportavimo scenarijai. Artimo bei tolimo (Šiaurės jūros regionas) kaštai skiriasi nedaug, išskyrus transportavimo laivais scenarijų, kuris žymiai padidina CCS išlaidas.

CO_2 gali būti saugojamas angliavandenilių telkiniuose. Baltijos sedimentaciniame baseine naftos telkiniai atrasti Lietuvoje, Kaliningrado srityje, Lenkijoje, Švedijoje (Gotlando sala). Pagrindinis talpinantis sluoksnis – vidurinis kambras. Lietuvoje naftos gavyba krenta nuo 2002 metų, tad gavybos apimčių palaikymui labai svarbi telkinių stimuliacija. Ji gali būti siejama su CO_2 geologiniu saugojimu kaip brandžiausia technologija. Saugojimo apimtys Lietuvos telkiniuose įvertintos 6,5 mln.t CO_2. Tai įgalintų apie 2,3 mln.t. papildomos naftos išgavimą. Kaliningrado srities potencialas yra gerokai didesnis dėl gausesnių ir stambesnių telkinių. Bendra apimtis sudaro 88 mln.t. CO_2, iš jų – 54 mln.t sausumoje ir 34 mln.t šelfe. Lenkijos šelfe pagal išžvalgytus naftos ir dujų telkinius saugojimo apimtys siekia 26,2 mln.t CO_2 (6,4 mln.t naftos telkiniuose ir 19,8 mln.t dujų telkiniuose). Šie skaičiai gali būti gerokai didesni, atsižvelgiant į seisminės žvalgybos duomenimis identifikuotas gausias lokalias pakilumas Lenkijos šelfe. Švedijos potencialas dėl labai smulkių naftos telkinių (ordoviko organogeniniai kūnai) nebuvo vertintas. Bendras saugojimo potencialas Baltijos sedimentacinio baseino angliavandenilių telkiniuose siekia 120,7 mln.t.

Svarbios ir kitos alternatyvios CO_2 geologinio saugojimo perspektyvos. Baltijos sedimentaciniame baseine karbonizacijos perspektyvos konstatuotos Lietuvoje, Estijoje ir Suomijoje. Lietuvos pietryčiuose kristaliniame pamate paplitusių ultrabazinių uolienų (serpentinitų) saugojimo potencialas įvertintas daugiau kaip 413 mln.t CO_2. Jų panaudojimas sietinas su naudingų iškasenų (geležies rūdos) eksploatacija, kuri gerokai sumažintų mineralizacijos technologijos savikainą. Panašios perspektyvos yra nustatytos Suomijos teritorijoje, kurioje yra gausūs serpentinitų klodai bei su jais susijusios naudingų mineralų sankaupos; kai kurie telkiniai yra eksploatuojami. CO_2 saugojimo potencialas Suomijoje kol kas nebuvo vertinamas. Estijoje karbonizacijos galimybės susijusios su šarminių pelenų, liekančių po degiųjų skalūnų deginimo, panaudojimu. Vidutinė metinė saugojimo apimtis vertinama apie 1 mln.t CO_2.

Disertacinį darbą (170 psl.) sudaro sekantys skyriai: įvadas, problematika ir ankstesnių tyrimų apžvalga, tyrimų metodai, tyrimų rezultatai, išvados ir literatūros sąrašas (159 pozicijų) bei 2 priedai. Jis iliustruotas 100 paveikslų ir 13 lentelių.

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