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Risk factors of CO_2 geological storage in the Baltic sedimentary basin

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The Baltic sedimentary basin is relatively little affected by tectonic structuring owing to cratonic setting of the region. However, the fault network cutting the sedimentary layers is identified. The distribution of faults is highly variable. It is notable that the major local uplifts prospective for CO_2 geological storage are associated mainly with those faulted structures. Therefore the risk of the CO_2 leakage from the potential storage sites should be evaluated.

The main prospects of the CO_2 geological storage are related to the Cambrian siliciclstics that represent the basal part of the Baltic sedimentary basin. In terms of the hydrostatic pressure and temperature conditions, the most part of the Baltic sedimentary basin is favourable for CO_2 storage in the Cambrian saline aquifer. This prospective area is characterised by a rather thick (in access of 0.5 km) shaly package of the Ordovician–Silurian age that provides a reliable seal which is a very important parameter for safe storing CO_2 in Cambrian sandstones.

The main faulting of the sedimentary cover of the Baltic basin took place during the latest Silurian – earliest Devonian referred to as the Caledonian phase of the tectonic activity. Different types of faults are defined that show different geometries which, in turn, may affect the tightness of faults. The compressional reverse faults of predominating NW–SE orientation show rather simple geometries, while flower structures are typical for the transpressional faults striking mainly in sub-latitudinal direction. Accordingly, the former type of faults is considered of lower risk in terms of CO_2 leakage compared to the latter type of faults.

Furthermore, three types of local uplifts prospective for CO_2 storage were defined, i. e. (1) uplifts not associated with any faulted structures, (2) uplifts associated with fault(s), and (3) uplifts dissected by faults. The second type of structures predominates in the Baltic sedimentary basin. It is therefore not surprising that majority of the largest and most prospective local uplifts are located in Latvia that is affected by the largest scale Liepaja–Saldus fault zone. Analysis of fifteen major uplifts of Latvia and two potential storage sites of Lithuania indicates that only two structures (Degole and Liepaja) do not have any evident association with faults. The rest uplifts were formed along the dominating fault or the intersection of several faults of either transperssional (higher risk) or compressional (lower risk) types.

The other important parameter that may affect the isolation of the storage structure relates to drilling. The wells are mainly 30–40 years old therefore some might lose the integrity. The prospective storage structures are drilled to a different degree. The number of wells ranges from 1 to 15 wells; in most cases structures were investigated by 2–4 wells.

Key words: CO_2 geological storage, risk, faults, boreholes, Baltic basin

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INTRODUCTION

Global annual CO_2 emissions have grown from 21 gigatonnes (Gt) in 1970 to 38 Gt in 2004 (IPCC, 2005, 2007). The measures have to be taken urgently for reduction of emissions. The carbon management consists of a broad portfolio of strategies to reduce carbon emissions via carbon capture and storage in the geological formations, enhanced efficiency of power generation and use, application of low carbon fuels and the employment of renewable energy sources (Lokhorst, Wildenborg, 2005).

According to the Kyoto Protocol signed by the Baltic countries in 2002, the level of air-polluting greenhouse gases emissions should be reduced by 8% during the commitment period 2008–2012 compared to the 1990 level. Post Kyoto Targets published in the European Strategic Energy Plan "Towards a low carbon future" aimed to reduce greenhouse gas emissions by 20% to 2020 and to reduce GHG emissions by 60–80% by 2050. Compared to 1990, the greenhouse gas (GHG) emissions decreased in Latvia, Lithuania and Estonia for more than 50%, while systematically increasing in other circum-Baltic countries. Furthermore, the changing energy market (e. g. closure of the Ignalina NPP) and increasing industrial growth urge to evaluate different options of reducing CO_2 emissions, including the assessment of the potential of geological sinks and mineral trapping (Shogenova et al., 2007, 2008; Šliaupa et al., 2009).

Geologic storage of CO_2 can be a vital part of the solution to the problem of global climate change. Methods and technologies are developing rapidly, as are the legal frameworks to regulate them. Geologic storage projects undertaken over the next ten years will be critical for demonstrating CO_2 storage in diverse geologic settings and will establish the basis for its widespread global application as a means of preventing climate change.

In geological storage, CO_2 is injected under high pressure into deep rock formations (Fig. 1). In many areas, these rocks already securely hold fluids such as oil, natural gas or water that is too salty to use. Several natural trapping mechanisms keep these natural fluids in place, often for millions of years. These trapping mechanisms can do the same for CO_2.

A key factor affecting the implementation of carbon capture and storage (CCS) technology is the risks associated with CO_2 storage in geological formations. The understanding and assessment of these risks are required to ensure the safety standards during the injection and site closure stages. The risks associated with underground CO_2 storage have been discussed extensively in an EU study on underground disposal of CO_2 (Holloway, 1996). Furthermore, new insights have been obtained into the risks of CCS.

Risks associated with CCS can be caused by operation of surface and injection installations and by storage of CO_2 in a geological reservoir (Fig. 2).

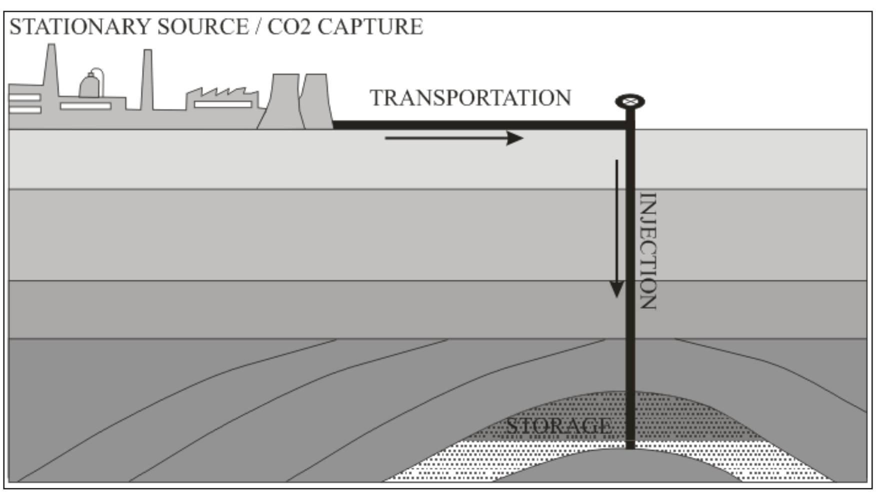

Fig. 1. CO_2 geological storage chain "capture–transportation–injection"
1 pav. CO_2 geologinio saugojimo grandinė „sugavimas–transportavimas–injekcija"

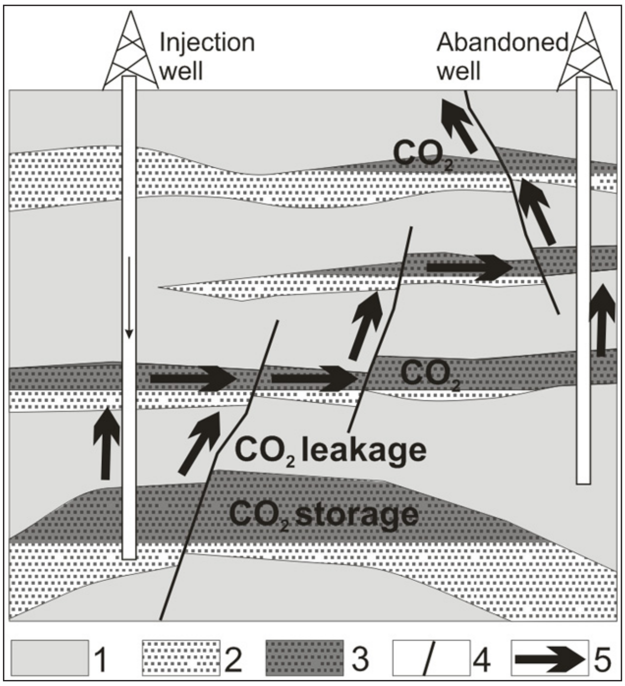

Fig. 2. Major CO_2 leakage pathways. *1* – impermeable rocks, *2* – reservoir rocks, *3* – CO_2 accumulations, *4* – faults, *5* – CO_2 migration

2 pav. Pagrindiniai CO_2 nutekėjimo keliai. *1* – nepralaidžios uolienos, *2* – saugyklos uolienos, *3* – CO_2 sankaupos, *4* – lūžiai, *5* – CO_2 migracija

When CO_2 is injected in geological reservoirs, it might potentially migrate out of the reservoir, migrate laterally in overburden formations and finally leak to the surface. The risk of the leakage relates to well and cap-rock integrity and the trapping mechanism. CO_2 can be retained in reservoirs by different trapping mechanisms (Bachu et al., 1994; Ennis-King, Paterson, 2001; Damen et al., 2006): (1) CO_2, injected in an oil reservoir, rises up due to buoyancy effect. The low-permeable cap-rock prevents CO_2 to migrate further up leading to its accumulation in the upper part of the reservoir; (2) CO_2 injected in deep saline aquifers can take thousands to millions of years to migrate from the injection point to the surface due to low flow rates; (3) CO_2 is partly trapped in pores by capillary forces; (4) CO_2 dissolves in formation water, therefore the solubility trapping is an important mechanism. Modelling indicates (Ennis-King, Paterson, 2003) that complete dissolution is a rather slow mechanism (10,000–100,000 yr); (5) Dissolved CO_2 can react with silicates and carbonates to form bicarbonate or carbonate ions; (6) CO_2 reacts with matrix minerals of the reservoir and becomes a part of the solid matrix. This is the most secure form of trapping. However, it is a very slow mechanism.

The hydrocarbon (HC) fields are considered as safe potential CO_2 traps, as the reliable sealing is proved by presence of oil and gas. Furthermore, each HC field is studied in detail. However, there is a certain risk of CO_2 escape from the reservoir along the wells (well completion problems) or by means of a cap-rock failure due to access overpressure during CO_2 injection. CO_2 might also escape via spill points or dissolve in fluid flows in the reservoir rock beneath the CO_2 accumulation to surrounding formations. These processes are considered of greater risk in a virgin aquifer reservoir that is less studied compared to HC fields.

The well openness can be caused by casing or cementation defects due to improper design or construction, corrosion of the casing and deterioration of cement plugs by CO_2 and brine. Abandoned wells can provide migration path-ways, since depleted oil / gas reservoirs are generally "punctured" by a large number of non-operative wells, some of them in bad condition. Over long time scales, wells may thus serve as preferential leakage pathways and may therefore represent a significant (long-term) risk (Celia, Bachu, 2003). In order to assess potential leakage of a reservoir, detailed information must be available on the number, type and age of wells, completion technique. It is essentially an important problem in the Baltic Region that is rather well studied by extensive drilling.

There are different mechanisms of a cap-rock failure.

The capillary leakage occurs when the pressure difference of the fluid phase and the water phase in the pores adjacent to the cap rock is higher than the capillary entry pressure of the cap rock. Since the capillary entry pressure of the cap rock has generally been sufficient to retain hydrocarbons, such as those in the Baltic Region, capillary leakage of CO_2 is not considered to be a problem (Jimenez, Chalaturnyk, 2003).

The diffusion of CO_2 through the cap rock is expected to be a very slow process, but can be the controlling mechanism for leakage on the long-term (Jimenez, Chalaturnyk, 2003).

CO_2 might leak through hydraulic induced fractures due to over-pressuring of a reservoir. In order to prevent fracturing, the maximum injection pressure should always be kept below the level at which the cap rock may shear (fracture pressure) (Over et al., 1999). The risk of leakage through fracturing is low as long as the storage pressure does not exceed the initial reservoir pressure. This "safety factor" depends on the stress state of the cap rock, which depends on depth, pore pressure, rock properties, and sedimentary and tectonic history (Holloway, 1996).

The permeable zones can also be formed by reaction of CO_2 with the cap-rock, causing its dissolution. CO_2 can dehydrate clay shales increasing its permeability.

CO_2 can leak through open faults. The risk of leakage along faults can be minimised by performing a detailed analysis of the geological setting of the reservoir prior to injection and selecting only those reservoirs with no / minimal faulting.

Of these mechanisms, leakage along or trough wells, faults and fractures are generally considered to be the most important leakage pathways (Fig. 2).

It should be noted that CO_2 capture and compression are already applied technologies at the industrial scale for production of CO_2 applied for enhanced oil recovery, carbonisation of beverages, cooling, drinking water treatment, welding. An extensive knowledge on long-way CO_2 transportation was collected owing to enhanced oil recovery (EOR) activities in USA.

The Baltic sedimentary basin is one of the largest depocentres in Europe. The previous studies unravelled some potential of the basin for CO2 geological storage that mainly relates to the siliciclastic Cambrian reservoir (Shogenova et al., 2007, 2008; Šliaupa et al., 2009).

The paper discusses main risk parameters associated with CO_2 storage in the Cambrian sandstone reservoir that is the main prospective formation of the Baltic basin.

GEOLOGICAL SETTING

The Baltic sedimentary basin overlies the western margin of the East European Craton (Fig. 3). The basin contains Ediacaran (Vendian) and all Phanero-

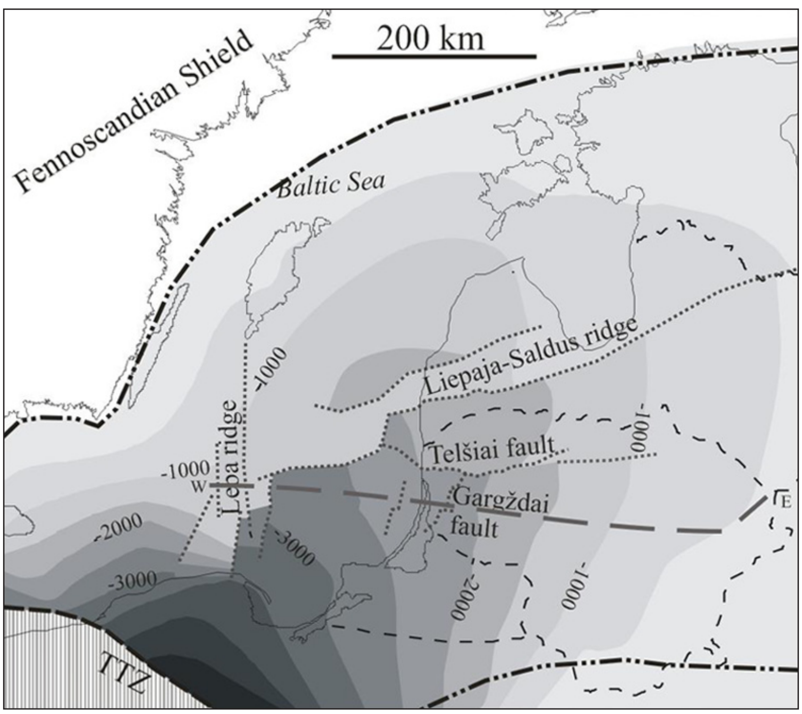

Fig. 3. Depths of the top of the crystalline basement. Border line shows the limits of distribution of the Cambrian aquifer. Line of the geological profile W–E is shown (see Fig. 4)

3 pav. Kristalinio pamato kraigo gyliai. Linija pažymėtos kambro vandeningojo sluoksnio paplitimo ribos. Nubrėžta geologinio profilio vakarai–rytai linija (4 pav.)

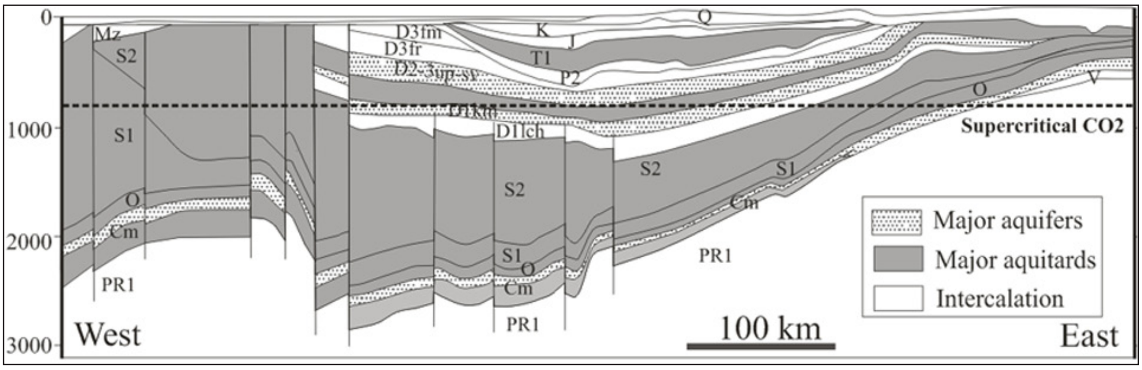

Fig. 4. Geological profile west–east (see Fig. 3 for location)
4 pav. Geologinis profilis vakarai–rytai (jo liniją žr. 3 pav.)

zoic systems that point to the protracted subsidence history of the craton western margin. The basin is relatively weakly tectonized, the sedimentary layers are gently inclined to the southwest. The thickness of the sedimentary pile is less than 100 m in North Estonia, increasing to 1 900 m in Southwest Latvia and 2 300 m in West Lithuania. The depth of the Early Precambrian basement exceeds 4 000 m in the deepest western part of the basin in Poland.

The oldest sediments are represented by Ediacaran arkosic conglomerates, sandstones and clays of up to 200 m thick. They are distributed in the eastern part of the Baltic countries. The Blue Clays of the lowermost Cambrian age of up to 120 m thickness accumulated in the similar setting.

The "trilobite" Cambrian sea invaded the region from the west, resulting in deposition of the quartz sandstones, siltstones, and shales that show different proportions across the basin. The thickness of the Cambrian attains 170 m in West Lithuania. It is overlain by 40–250 m tick Ordovician and up to 800 m thick Silurian shaly-carbonaceous succession which is in most part of the basin a regional aquitard except the eastern and northern periphery of the Baltic basin dominated by limestones and dolomites.

At the end of the Silurian – beginning of the Devonian, the intense faulting took place in the basin. It was succeeded by deposition of a thick Devonian succession composition which is highly variable; the marly and carbonaceous packages alternate with sandy aquifers. The maximum thickness of the Devonian is reported from West Lithuania where it is of up to 1 100 m thick.

The younger sediments of Permian, Mesozoic, and Cenozoic ages are distributed in the southwest of the basin. The total thickness increases to the southwest. The Upper Permian deposits consist of carbonates and evaporates of about 100 m thick. They are overlain by the Lower Triassic red-bed mudstones attaining 250 m in thickness. Jurassic sandstones and clays with limestones are of up to 120 m thick. The Cretaceous is composed of glauconitic sands and chalk, the total thickness is up to 140 m.

CAMBRIAN AQUIFER

The Cambrian siliciclastics compose the basal part of the sedimentary cover. They are considered as the most prospective geological formation for CO_2 storage in the Baltic Region (Shogenova et al., 2008, 2009; Šliaupa et al., 2009).

Cambrian sediments were deposited in two different depocentres. The oldest pretrilobitic Cambrian deposits (Sabellidites–Platysolenites zones) are distributed in the eastern part of the Baltic Region and extend further to the east within the Moscow palaeobasin. The Pretrilobitic Cambrian is dominated by shallow marine clays and shales (often referred to as the Blue Clays) with rare quartz sandstone and siltstone interlayers, which grow in abundance close to the western shore of the palaeobasin. The thickness attains 120 m in north–east Lithuania, increasing further to the east. Cambrial clays compose the regional scale aquitard separating Vendian silicilastics from younger Cambrian sandstones.

The trilobitic Cambrian sediments are most widely distributed in the Baltic sedimentary basin that is accounted to vast transgression of the Baltic

Cambrian marine basin and later denudation that affected the Cambrian layers to a less extent compared to younger sediments. The thickness increases to the west (southwest) and is about 170 m in the central part of the basin, while exceeding 500 m in thickness in the western margin of the Baltic basin along the bounding Teissier–Torquist zone (TTZ).

The trilobitic Cambrian sediments are composed of triple alternation of tidal and shallow marine sandstones, siltstones and claystones, which show different proportions across the basin (Jankauskas, Lendzion, 1992). Sandstones dominate in the basin periphery. Abundance of the shales and siltstones increases gradually towards the basin centre. The Lower Cambrian sediments are more widely distributed than the Middle Cambrian deposits that are largely accounted to basin regression. The basin regression started in the late Early Cambrian and climaxed in the Late Cambrian that is reflected in narrowing of the sedimentation area and shifting of lithofacies zones towards the basin centre.

The trilobitic Lower Cambrian attains 80 m in thickness and consists of fine-grained grey, rarely brown and greenish grey sandstones which grade into the alternation of siltstones and shales in the west. The Middle Cambrian reaches 70–80 m in thickness. It consists of fine- and medium-grained sandstones comprising argillite and siltstone layers. Cambrian sandstones of the Baltic basin are composed of quartz for 95–99% (Šliaupa et al., 2000). Feldspar does not exceed 1–3%. Sandstones are cemented by secondary quartz, dolomite and clay. Quartz cement dominates in the deep central and western parts of the basin reducing the porosity of sandstones to 3–15%, while carbonate (mainly dolomite) cement predominates in the shallow periphery of the basin (Fig. 5). Clay minerals of shales are represented by kaolinite and illite with some content of mixed-layer I-S clays. The chlorite becomes an abundant clay mineral in the deeper central part of the basin.

Two lithologically distinct parts are identified in the Middle Cambrian succession. The lower ~10 m thick layer is composed of siltstones and shales attributed to the Kybartai RSt. They are overlain by a 50–60 m thick succession of quartz sandstones comprising rare siltstone and shale layers. These sandstones represent the main oil reservoir of Lithuania and Kaliningrad district (Vosylius, 1987; Ulmiszek, 1990; Zdanaviciute, Lazauskiene, 2004).

A B

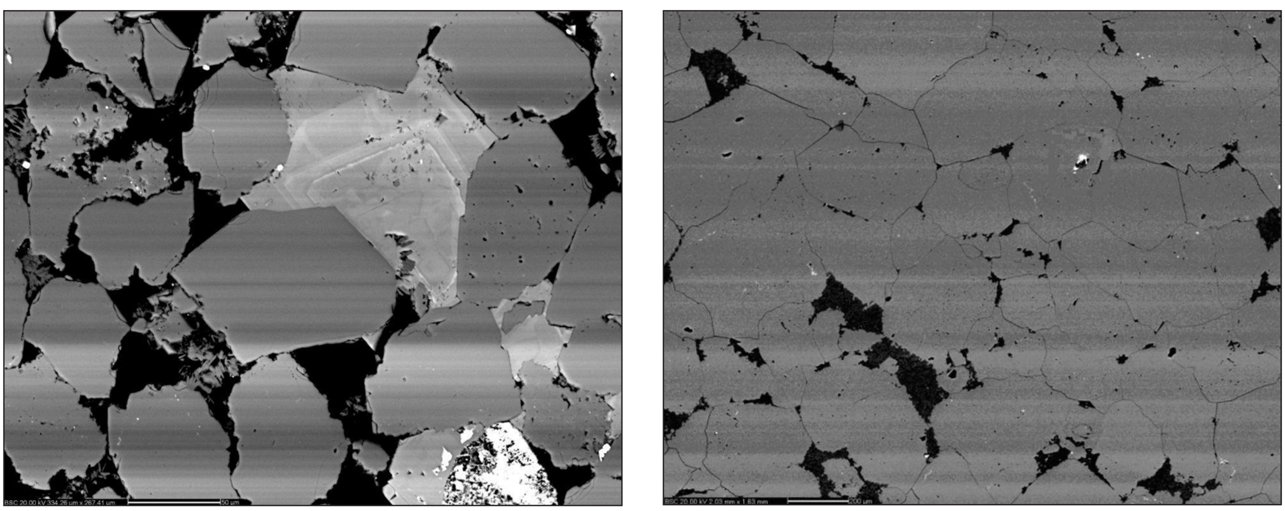

Fig. 5. Microphotographs of Cambrian sandstones. A – high-porosity quartz sandstone cemented by authigenic quartz and dolomite, well Akmenynai-149, depth 1 147.0 m (south Lithuania). B – low-porosity quartz sandstone strongly cemented by authigenic quartz, well Šilgaliai-1, depth 2 059.4 m (west Lithuania)

5 pav. Kambro smiltainių mikrofotografijos. A – didelio poringumo kvarcinis smiltainis, sucementuotas autigeniniu kvarcu ir dolomitu (pavyzdys iš Pietų Lietuvoje esančio Akmenynų-149 gręžinio 1147,0 m gylio). B – mažo poringumo kvarcinis smiltainis, tvirtai sucementuotas autigeniniu kvarcu (Šilgalių-1 gręžinys, 2059,4 m gylis, Vakarų Lietuva)

They are defined as the Deimena Regional Stage subdivided into three sedimentation cycles (Giruliai, Ablinga, and Pajūris formations). The Deimena RSt sandstones grade to shales in the west (Baltic Sea area) where they are overlain by sandy Dębki Fm (Pokorski, 2010). The Dębki sandstones comprise several large gas and light oil accumulations in the Polish Exclusive Economic Zone (Sikorski, Solak, 1991; Karnowski et al., 2010; Kotarba, 2010; Wiecław, 2010). The Dębki sandstones gradually give way to shales in the westernmost part of the Baltic sedimentary basin (Jaworowski et al., 2010).

DEFINING PROSPECTIVE AREAS OF CO_2 GEOLOGICAL STORAGE

In a sedimentary basin, the capability of an aquifer to transmit and store CO_2 is controlled by the depositional environment, structure, stratigraphy, and pressure / temperature conditions. Critical factors are 1) the thickness, lateral extent, and continuity of the aquifer; 2) the tightness of the seal above the aquifer; 3) the regional water flow system; 4) possible leakage along the faults; 5) the capability of overburden layers above the reservoir seal to delay or diffuse leakage.

Some of the injected CO_2 (up to 6%) will dissolve in the water and travel with the velocity of the formation waters (of the order of cm / year). The rest will form a plume that will over-ride at the top of the aquifer driven both by the hydrodynamic flow and by its buoyancy. Therefore, the structural traps are needed to store CO_2 gas.

The P-T conditions are very important when considering the potential of the deep saline aquifers. Depending on in-situ pressure and temperature, CO_2 can be stored either as a compressed gas or in a supercritical state (phase transition P = 73.8 bars, T = 31 °C). Carbon dioxide, injected in a supercritical state, has a much lower density and viscosity than the liquid brine it displaces. In situ, the supercritical CO_2 partitions between an immiscible gas-like phase and dissolution in the aqueous phase. At depths greater than about 800 m the CO_2 will be in a supercritical state, i.e. gas that is the same density as a liquid, which enables an efficient injection method in both pipeline engineering and in filling deep pore space. Therefore, the thermobaric conditions P = 73.8 bars, T = 31 °C are considered as the lower limit for the geological storage of CO_2. Some of the deep aquifers of the Baltic basin meet these basic requirements and therefore have potential for storing CO_2.

The temperature of the Cambrian reservoir systematically increases to the south–west. Cambrian sediments are exposed at the surface along the margin of the Fennsoscandian margin (Estonia, Sweden) and are buried to about 300 m in Southeast Lithuania. Temperatures are accordingly 8–15 °C in the basin margin (Fig. 6). They increase in Middle Lithuania and Central Latvia to 30–50 °C. The highest temperatures of the Cambrian reservoir are measured in West Lithuania and southern part of the Baltic Sea area. The maximum values exceeding 90 °C are registered in Šilutė region and Gdansk region. The critical isotherm 31 °C is traced along Middle Lithuania and in the west of Middle Latvia tending further to the west in the southern part of the Baltic Sea and North Poland. The prospective areas (in terms of temperature distribution) are as large as about 180,000 km^2.

The increase of the temperature to the west and southwest is primarily related to deepening of the Cambrian reservoir. The anomalous temperatures in West Lithuania are explained in terms of the heat flow anomaly. The heat flow in the peripheral part of the Baltic sedimentary basin (East Lithuania, East Latvia and Estonia) is in the range of 30–40 mW/m^2 (Kepežinskas et al., 1994). It increases about twice in West Lithuania, where the heat flow ranges from 70 mW/m^2 to nearly 100 mW/m^2. The very high heat flow values defined in West Lithuania are related to double effect of (1) high heat generation of crystalline basement rocks and (2) deep mantle processes (Šliaupa, Rastenienė, 2000).

The hydrostatic pressure is the second basic parameter controlling the phase state of CO_2. The measurements of the hydrostatic pressure of the oil and gas fields did not unravel any discernible overpressure effect in the Cambrian reservoir of the Baltic basin. Therefore the linear pressure / depth relationship can the assumed in the basin-scale assessment. The critical hydrostatic pressure value 7.8 MPa is traced along Middle Lithuania, Central Latvia, Riga Bay and Baltic Sea across the southernmost Gotland Island (Fig. 7). The highest pressures

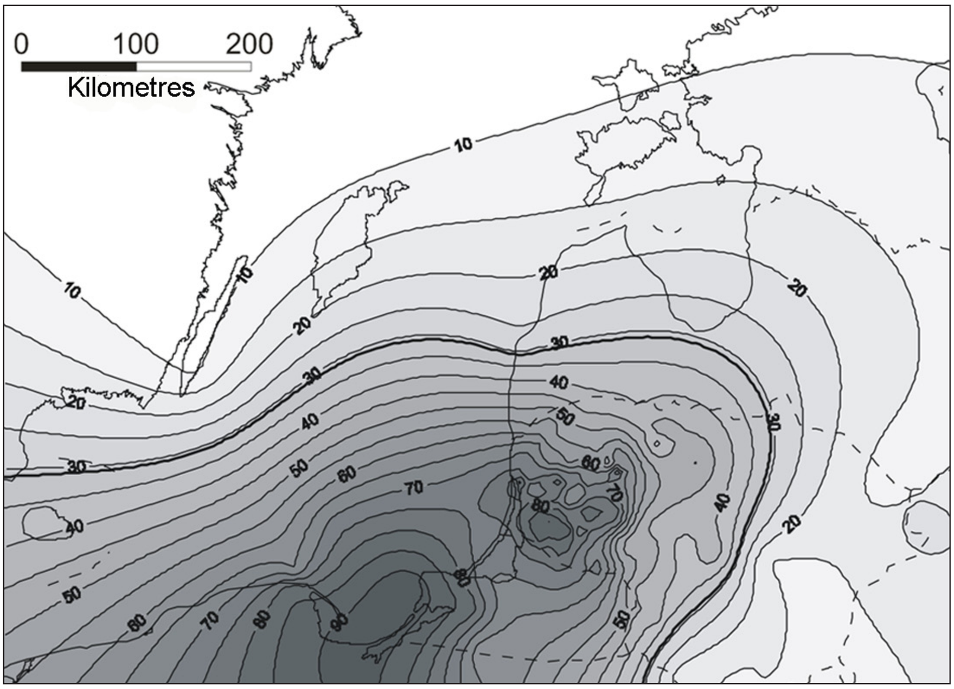

Fig. 6. Temperatures of the Cambrian aquifer (contour lines, °C). Bold line marks isotherm 31 °C
6 pav. Kambro vandeningojo sluoksnio temperatūra (izolinijos, °C). Stora linija rodo 31 °C izotermą

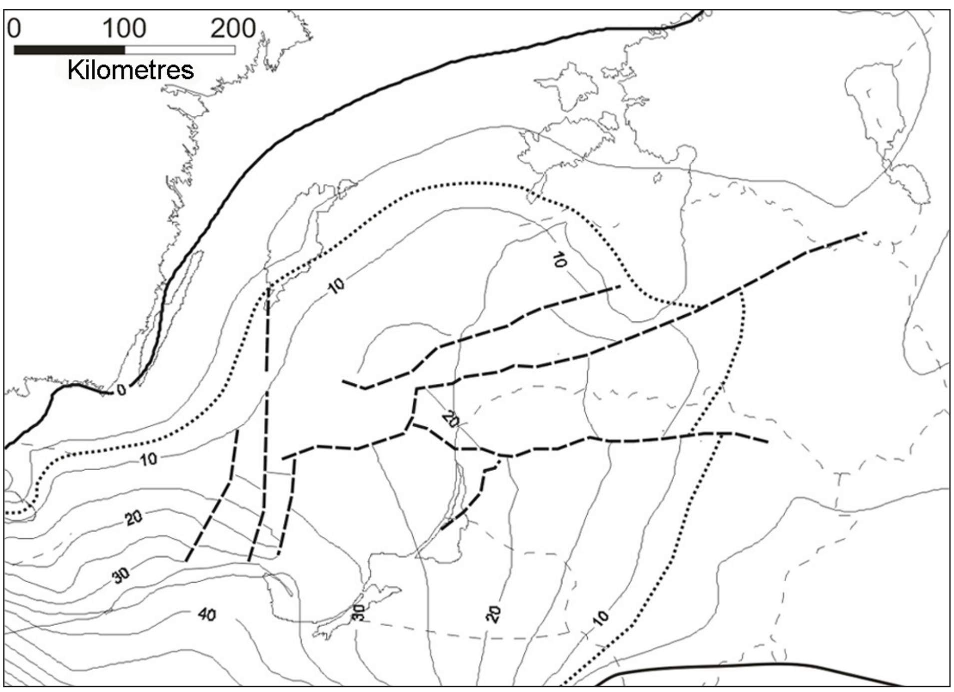

Fig. 7. Hydrostatic pressure of the Cambrian aquifer (contour lines, MPa). Bold hatchet lines show major faults. Dotted line marks hydrostatic pressure contour line 7.8 MPa. Bold line indicates distribution of Cambrian deposits
7 pav. Kambro vandeningojo sluoksnio hidrostatinis slėgis (izobaros, MPa). Stora punktyrinė linija rodo pagrindinius lūžius. Taškine linija pavaizduota 7,8 MPa izobara. Stora linija žymi kambro uolienų paplitimo ribą

are distributed in the westernmost part of the Baltic sedimentary basin.

Based on the temperature and hydrostatic pressure values, the prospective area for CO_2 geological storage was defined as large as 200,000 km^2 (Fig. 8). It covers most of the Baltic basin, covering West Lithuania, West Latvia, offshore Sweden and offshore Poland, North Poland.

CAPROCK CHARACTERISTICS

The Cambrian reservoir is covered by Ordovician shaly-carbonaceous and Silurian carbonaceous-shaly successions that compose the largest basin-scale aquitard separating the Cambrian aquifer from the Lower Devonian saline aquifer. The thickness of the aquitard is increasing to the south and south-west (Fig. 9). It is as thick as 400–500 m along the limit of the prospective area increasing to 800–900 m along the Baltic Sea cost of Lithuania and Latvia and exceeding 2 000 m in the westernmost part of the basin (Fig. 4).

The thickness of the Ordovician succession is an order lower than that of the Silurian succession that is accounted to different geodynamic situation of sedimentation processes. The Ordovician sediments were accumulated in the passive continental margin tectonic setting characterised by a low rate of subsidence, while Silurian deposits formed in the foreland setting related to overriding of the East Avalonian continent onto the western margin of the Baltica leading to increasingly high rate subsidence (Šliaupa et al., 1997; Poprawa et al., 1999; Lazauskiene et al., 2002).

The common depth of the Ordovician sediments ranges from 40 to 250 m. Männil (1966) and Jaanusson (1976) divided the Ordovician of the Baltoscandian Basin into confacies belts characterised by specific sedimentological and palaeontological features (Fig. 10). The North Estonian confacies and Lithuanian confacies are represented by shallow-water carbonate rocks, while the Central Baltoscandian confacies extending in South Estonia and Latvia is of more clayey composition. The graptolitic shales dominate in the westernmost part of the basin.

Subsidence intensity started to accelerate in the Early Silurian and increased drastically during the latest Silurian. This change in subsidence was due to the flexural bending of the western margin of

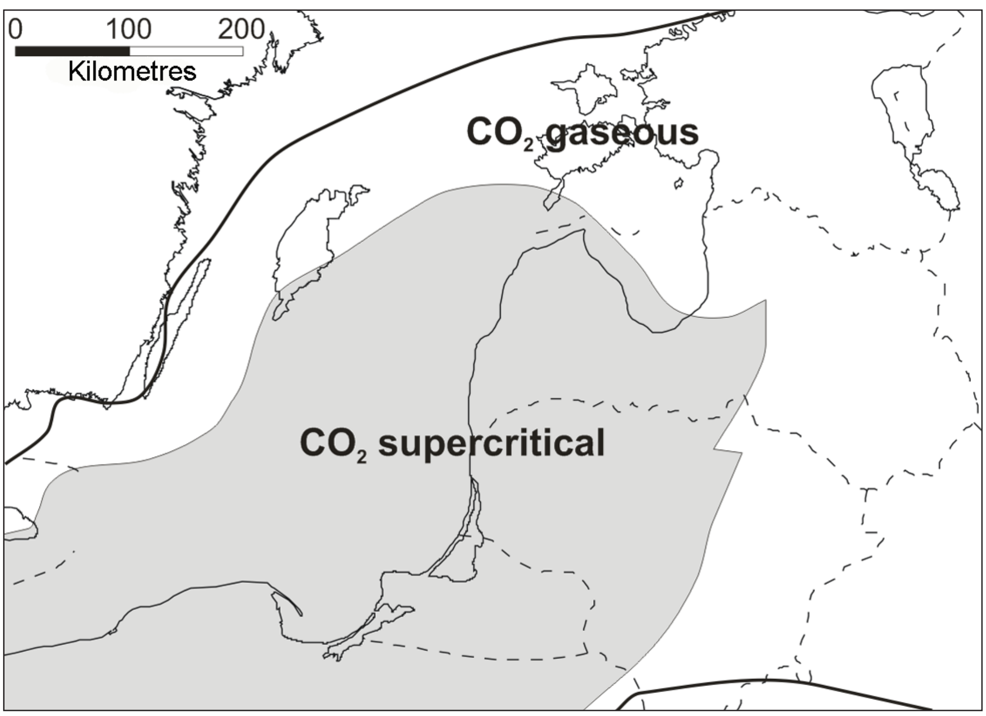

Fig. 8. Phase distribution of CO_2 of the Cambrian aquifer
8 pav. CO_2 fazinės būklės paplitimas kambro vandeningajame horizonte

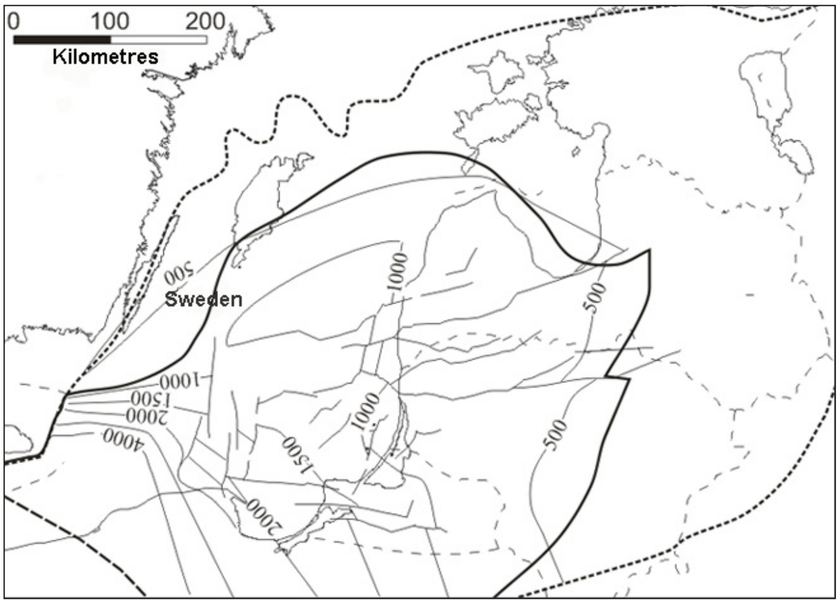

Fig. 9. Isopach map of the Ordovician–Silurian succession. Limit of supercritical CO_2 phase is marked by bold line (bold line). Hatchet line shows the limit of distribution of Ordovician–Silurian deposits

9 pav. Ordoviko–silūro sluoksnių storių žemėlapis. Stora linija rodo superkritinės CO_2 būklės ribą. Punktyrine linija pavaizduotos ordoviko–silūro uolienų paplitimo ribos

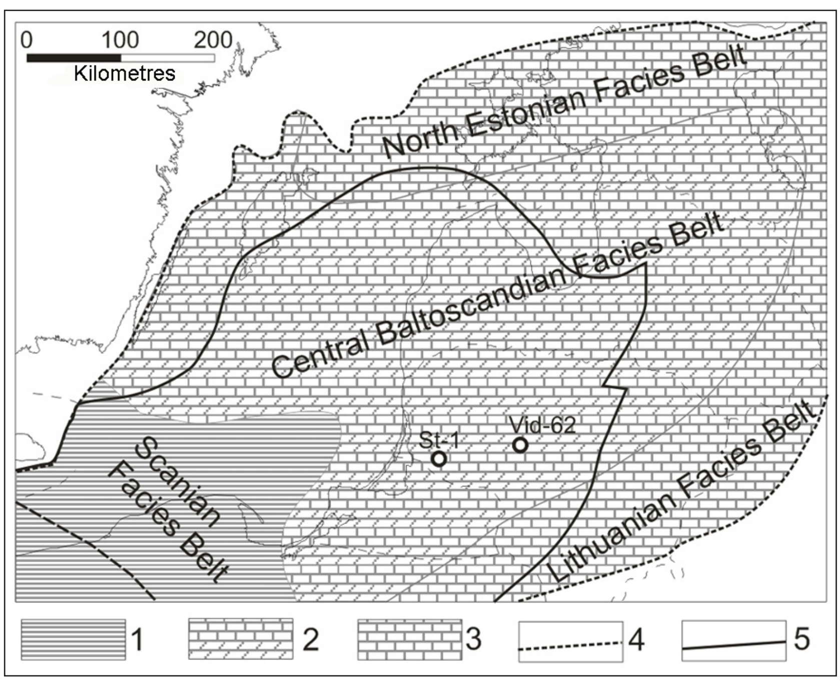

Fig. 10. Ordovician lithofacies of the Baltic sedimentary basin. *1* – shales, *2* – marlstones with limestones, *3* – limestones and dolomites with marlstones, *4* – limit of distribution of Ordovician deposits, *5* – limit of supercritical CO_2 phase. Locations of wells Stoniškiai-1 and Viduklė-62 are indicated

10 pav. Baltijos sedimentacinio baseino ordoviko uolienų facijų žemėlapis. *1* – argilitas, *2* – mergelis su klintimi, *3* – klintis ir dolomitas su mergeliu, *4* – ordoviko uolienų paplitimo ribos, *5* – superkritinės CO_2 būklės riba. Pažymėti Stoniškių-1 ir Viduklės-62 gręžiniai the Baltica plate because of the docking of the East Avalonia plate in the west (Šliaupa et al., 1997; Poprawa et al., 1999). The progressing advancement of the North German–Polish orogenic build-up in the west is reflected by the compensation of the subsidence by the sedimentary load during the Late Silurian time.

The rapid tectono-sedimentary evolution of the basin during the Silurian is recorded in a more than 3 km thick sedimentary succession (Lapinskas, 1973, 1987, 2000). The stratigraphic section is almost complete with no hiatuses recognised in the central part of the basin (Paškevičius, 1997). The thickness of the Silurian succession increases in the south–west direction reaching the maximum close to the Teisseyre–Tornquist Zone (TTZ) (Jaworowski, 2000), while the succession reduces to ca. 50–100 m in the basin margin (Kaljo et al., 1991). Graptolite shales dominate in the sedimentary succession in the western and central parts of the basin grading to marlstones in the transitional zone and to the carbonate platform in the shallow eastern margin of the Baltic basin (Figs. 11, 12).

The thickness of the Llandovery strata varies in a range of a few dozen meters up to 160 m in South Estonia and exceeding 300 m adjacent to the Caledonian Deformation Front. Early Llandovery shallow water packstones accumulated in the eastern marginal zone and pass into greenish and dark claystones in the south-west (Fig. 11). The upper

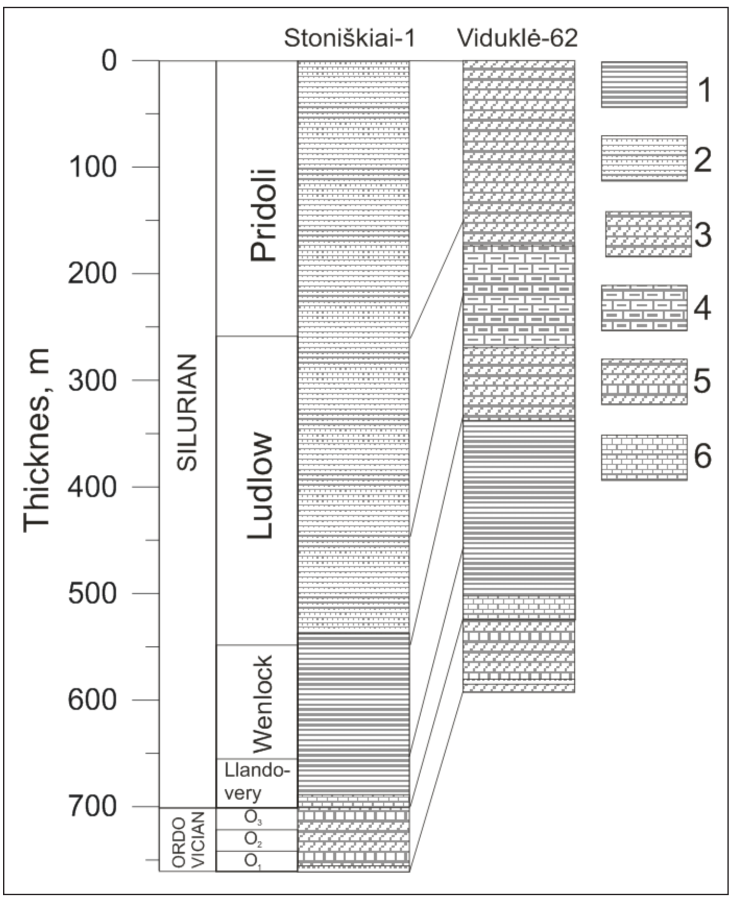

Fig. 11. Geological sections of the Ordovician–Silurian aquitard, wells Stoniškiai-1 (West Lithuania) and Viduklė-62 (Central Lithuania). *1* – shales, *2* – carbonaceous shales, *3* – marlstones, *4* – clayey limestones, *5* – limestones / marlstones, *6* – limestones
11 pav. Ordoviko–silūro vandensparos geologinis pjūvis, Stoniškių-1 (Vakarų Lietuva) ir Viduklės-62 (Vidurio Lietuva) gręžiniai. *1* – argilitas, *2* – karbonatingas argilitas, *3* – mergelis, *4* – molinga klintis, *5* – klintis / mergelis, *6* – klintis

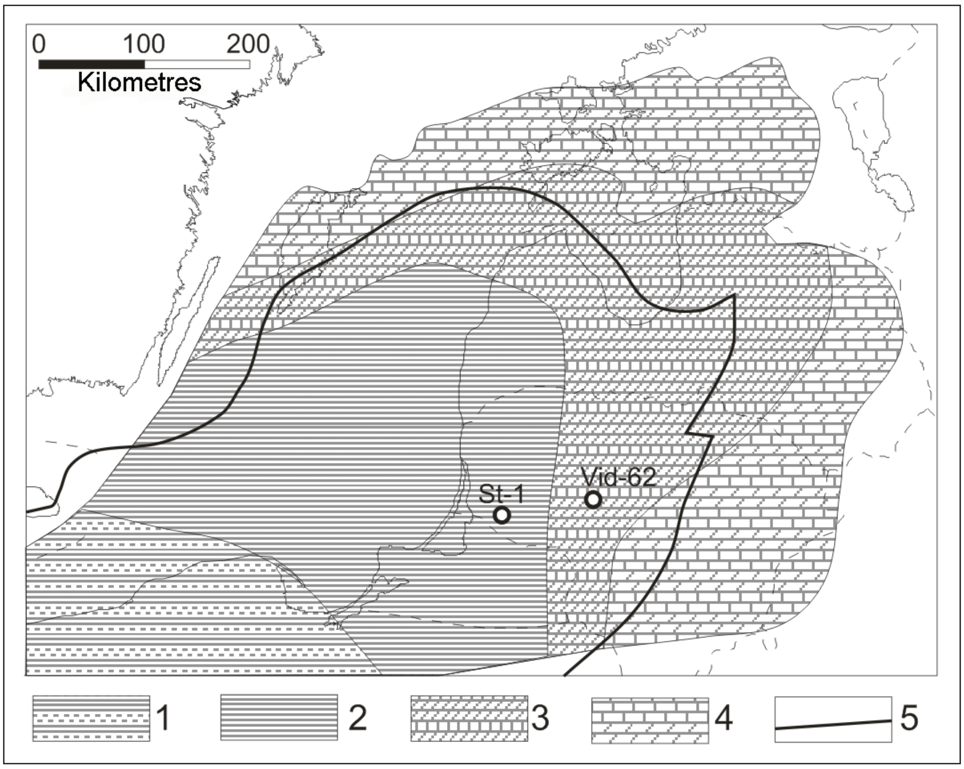

Fig. 12. Silurian lithofacies of the Baltic sedimentary basin. *1* – predominating mudstones, *2* – shales and carbonaceous shales, *3* – marlstones with limestones and dolomites, *4* – limestones and dolomites with marlstones, *5* – limit of supercritical CO_2 phase. Locations of wells Stoniškiai-1 and Viduklė-62 are indicated
12 pav. Baltijos sedimentacinio baseino silūro litofacijų žemėlapis. *1* – dominuojantis smėlingas argilitas, *2* – argilitas ir karbonatingas argilitas, *3* – mergelis su klintimi ir dolomitu, *4* – klintis su dolomitu ir mergeliu, *5* – superkritinės CO_2 fazinės būklės riba. Pažymėti Stoniškių-1 ir Viduklės-62 gręžiniai

parts of Rhudanian, Aeronian and Telychian successions are composed of greenish-grey calcareous shales interbedded with clayey marlstones.

The Wenlock succession ranges from 40 m to 600 m close to Teisseyre–Tornquist Zone pointing to increasing sedimentation rates. Graptolite shales dominate in the westernmost part of the Silurian Baltic basin giving way to greenish-grey marlstones and micritic limestones (Fig. 11), while grainstones (limestones and dolomites) represent the near-shore environment of the easternmost periphery of the basin.

The thickness of Ludlow sediments ranges from 50 m in the east to 2 400 m in the west. They are represented by marlstones, limestones, dolomitic marlstones, and dolomites extended over the eastern shelf and passing to graptolite shales in the west.

A similar trend of sedimentation preserved during the Pridoli time (Fig. 11). The thickness of Pridoli sediments does not exceed 700 m in the west, although the original thickness was much larger (Paškevičius, 1997). The nearshore carbonaceous sediments pass westwards into a deeper water clayey succession. The latter part of the Pridoli shows a shift of the clayey and shallow water carbonaceous facies boundary to the eastern nearshore zone.

It can be stated that the Ordovician–Silurian shaly package represents a reliable cap-rock owing to large thickness and predominance of impermeable lithologies. There is no evident risk associated with the capillary leakage, as the abundant HC fields hosted by Cambrian sandstones overlain by Ordovician carbonates and shales prove that the entry pressure of the cap-rock is sufficient to retain hydrocarbons in the reservoir.

The formation of the permeable zones due to cap-rock reaction to CO_2 is also negligible due to a large Ordovician–Silurian aquitard thickness and a miserable fraction of carbonates compared to clay minerals. Limestones that may react to CO_2 and dissolve are abundant in the lower (and upper) part of the Ordovician succession. The leaching risk is, however, considered as miserable due to (1) very low porosity (3–4%) and low permeability (<1 mD) of limestones and (2) a very large thickness of overlying Silurian shales.

The large thickness and predominance of shales also prevent from any risk of hydraulic induced fracturing. Therefore, the main potential risk should be considered in relation to tectonic fracturing of the seal.

POTENTIAL CO_2 LEAKAGE ALONG FAULTED PATH-WAYS

The Baltic sedimentary basin is relatively little affected by tectonic structuring due to cratonic setting of the depocentre. However, faults of different scale are defined in the sedimentary cover (Fig. 13) and therefore may potentially provide the risk for CO_2 leakage.

Several phases of tectonic activity affecting the sedimentary pile are identified in the Baltic Region. The earliest phase took place before the Vendian–Cambrian sedimentation. A dense cluster of drape structures (basement blocks covered by the Vendian and Lower Cambrian sediments) occurs in the Zura depression in West Latvia and adjacent offshore (Brangulis, Kanevs, 2002). Similar drape structure clusters were identified in West Lithuania (Stirpeika, 1997). Drape structures are also recognized in Estonia, East Lithuania and the western part of Kaliningrad District. Seismic data hint to an extensional kinematic type of those fault-blocks. The vertical displacement of faults reaches 170 m. These structures suggest the tectonic extensional regime related to breaking apart of the Rodinia supercontinent (Šliaupa, Hoth, 2010).

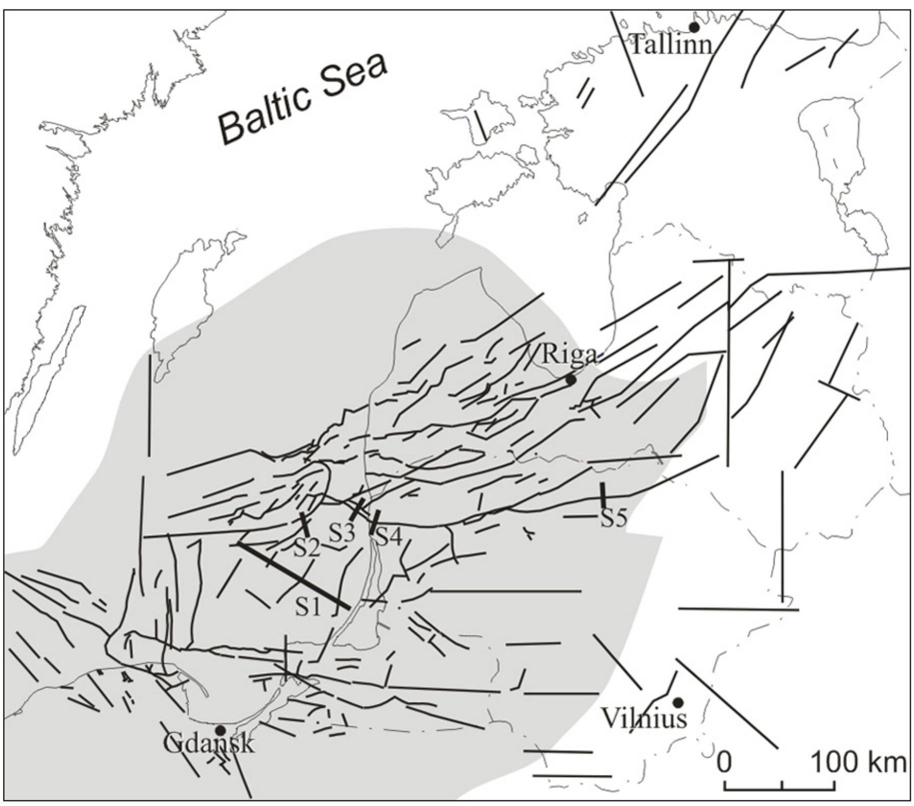

Fig. 13. Faults defined in the sedimentary cover. Locations of seismic profiles referred in the text are marked. Grey polygon shows the limits of the supercritical CO_2 phase
13 pav. Lūžiai sedimentacinėje storymėje. Parodytos straipsnyje minimų seisminių profilių linijos. Pilka spalva pažymėtas superkritinės CO_2 būklės plotas

No evidences of significant faulting are recognized during the Cambrian, Ordovician and Early Silurian times suggesting low tectonic stresses affecting the Baltic basin. In some seismic profiles evidences of Late Ordovician faulting were reported from some Lithuanian and Latvian offshore areas. Although fault amplitudes reach only a few dozen meters, some of them controlled the growth of Ordovician reefs (Kanev et al., 2000). They mainly show reverse kinematic features implying compressional tectonic activity during the Late Ordovician.

The main structuring phase of the Baltic Sea Basin took place during the latest Silurian to the earliest Devonian. The detailed structural analysis revealed that the region was exposed to NW–SE directed horizontal compression in relation to the collision of Laurentia and Baltica (Šliaupa, 1999; Šliaupa et al., 2000). Two dominating groups of E–W (ENE–WSW) and NE–SW (NNE–SSW) striking reverse faults have been formed. Typical for the first group are transpressional geometries, the second fault group is mainly of the compressional type.

The faulting was focussed on specific areas (Fig. 13). Main tectonic strain accumulated in the west–east directed Liepaja–Saldus ridge zone and the Telšiai fault zone in the central part of the Baltic basin. Such a selective faulting can be explained in terms of structural inheritance.

To the south of the Liepaja–Saldus–Telšiai zone the prevailing direction of Caledonian faults is NE–SW. The amplitudes are in the range of 30–500 m. These faults are rather regularly spaced at a distance of about 30 km and show quite simple compressional geometries. They dip to the west at high angles of 70–80°. The Leba ridge faults tending N–S were probably also established during the Caledonian stage, but their main activity happened during the Permocarboniferous. The onset of this large-scale feature during the Late Silurian is supported by the presence of associating gas fields in the Polish offshore area.

The faulting is only of minor intensity north of Liepaja–Saldus ridge. Small-scale faults trending mainly NE–SW are reported from Estonia. The amplitudes are in the range of 10–30 m only. A network of smaller faults striking NW–SE is mapped in northeast Estonia (Sokman et al., 2008). Here, amplitudes reach a few meters. The faults are dipping mainly to the northwest at predominating angles of 60–70° and show the compressional style.

During the Permocarboniferous phase the tectonic processes were reactivated. Most intense tectonic deformation took place in the south-westernmost Baltic Sea area along the Teisseyre–Tornquist Zone (TTZ). In the southern part of the Baltic basin a set of large E–W striking faults were established. This faulting was associated with the intense doming of the lithosphere that also led to the erosion of Devonian and older sediments. The largest fault of this group is the Kaliningrad fault striking across the Gdansk Bay and extending further onshore to the east. The amplitudes of those faults are in the range of 30–50 m.

The Leba ridge is composed of a set of N-S striking faults activity of which led to the truncation of more than 1 km of Devonian and uppermost Silurian sediments in the west (Domżalski et al., 2004). The seismic profiles reveal the compressional nature of the Leba faults. The other Caledonian faults were also reactivated in a compressional regime during the Permocarboniferous. The most intense fault reactivation is reported from the Liepaja–Saldus ridge.

In terms of CO_2 storage, the earliest drape structures are not considered to cause any potential risk. The fault-blocks were not or only little reactivated during later tectonic phases and do not affect the cap-rocks to any significant extent.

The densest network of faults was formed during the Caledonian tectonic phase. The faults affect the Cambrian reservoir and overlying Ordovician–Silurian aquitard. Two major fault families were established striking, respectively, W–E and NE–SW. They show different geometries that imply different risk level associating to CO_2 geological storage.

The NW–SE tending faults show mainly compressional kinematic features. They have relatively simple geometries, comprising a single (or several) fault plain crossing the Lower Palaeozoic strata (Fig. 14, profile S1). Therefore this type of reverse faults can be considered as potentially tight structures.

The faults striking roughly W–E are predominantly transpressional flower structures (Figs. 14S3, 15, 16). Due to highly complex geometry this group of faults is considered as bearing a higher CO_2 leakage risk.

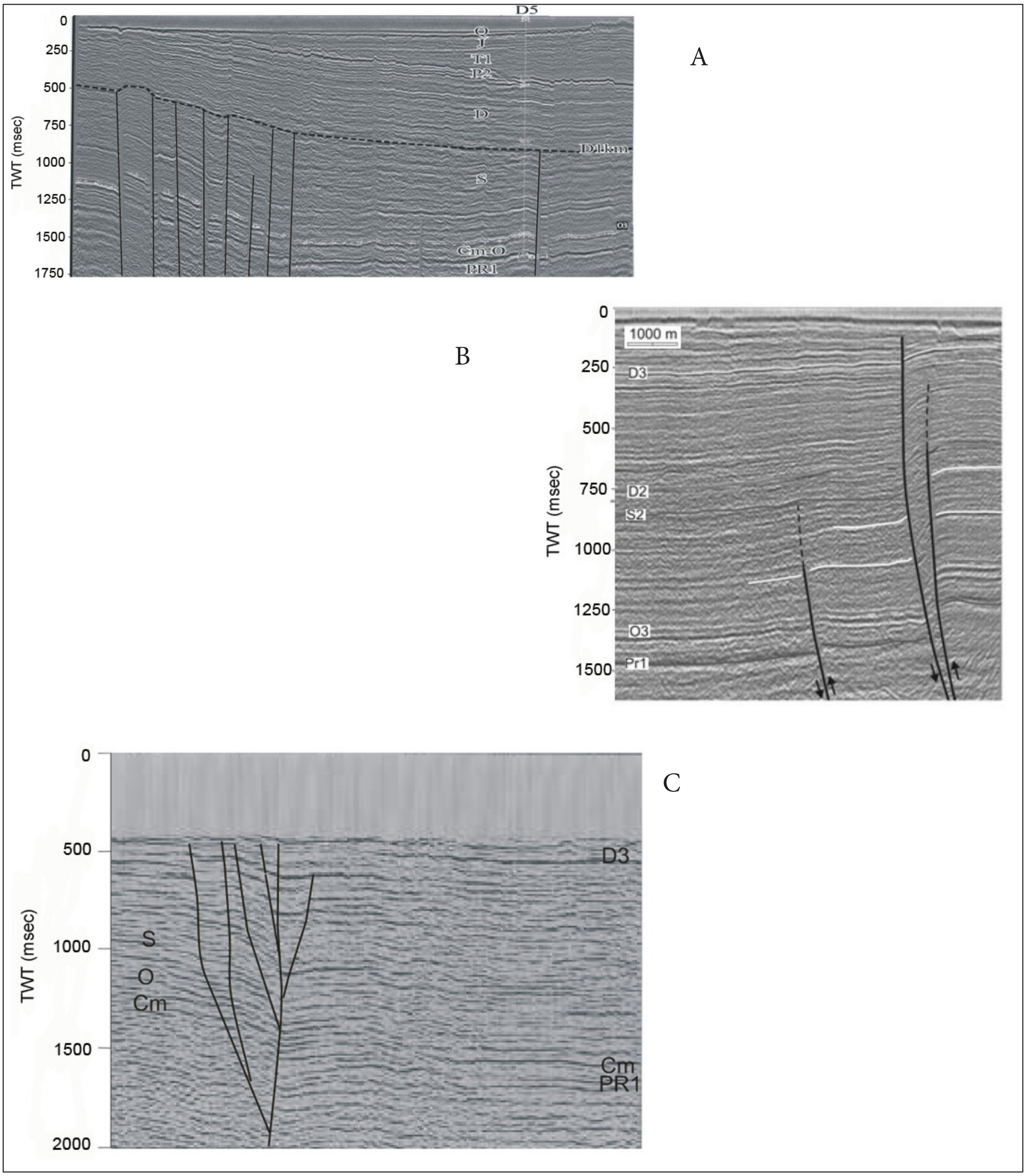

Fig. 14. Seismic profiles S1, S2 and S3 (see Fig. 13 for locations). The upper S1 profile (A) crosses the compressional NNE–SSW-trending west Nida fault of Caledonian age. The middle S2 profile (B) crosses the transpressional fault zone bordering the Liepaja–Saldus ridge in the south. Faulting took place there during the Late Silurian to the Early Devonian; the zone was reactivated during the Permocarboniferous tectonic phase; it is covered by a thin Quaternary succession. The lower figure S3 (C) shows the southern fault (flower structure) of the Liepaja–Saldus ridge
14 pav. S1, S2, S3 seisminiai profiliai (jų vietą žemėlapyje žr. 13 pav.). Viršutinis S1 profilis (A) kerta spaudimo tipo šiaurės-šiaurės rytų–pietų-pietvakarių krypties kaledoninę Nidos lūžių zoną. Vidurinis S2 profilis (B) kerta įžambaus spaudimo lūžių zoną, ribojančią vėlyvojo silūro–ankstyvojo devono amžiaus Liepojos-Saldaus tektoninę zoną pietuose; zona buvo reaktyvuota permo–kreidos metu ir ją dengia plonas kvartero nuogulų sluoksnis. Apatiniame paveikslėlyje S3 (C) profilis kerta pietinį lūžį (gėlės struktūra) Liepojos-Saldaus tektoninėje zonoje

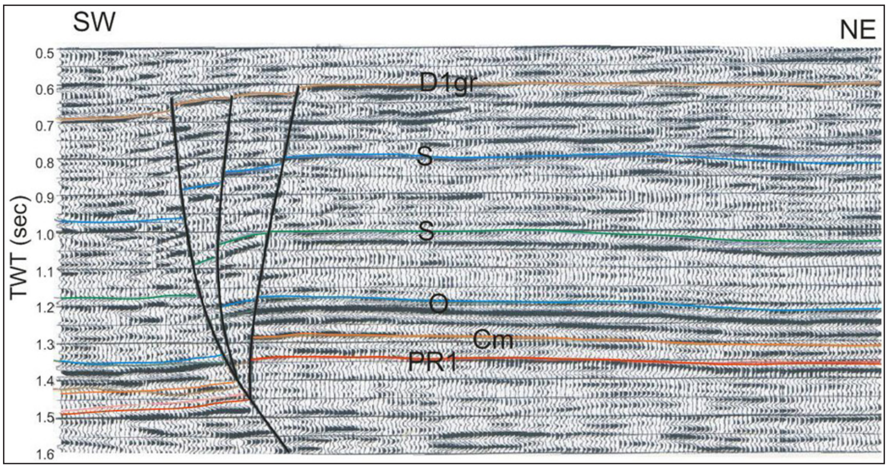

Fig. 15. Seismic profile S4 crossing the Telšiai fault zone (flower structure) and associating the Girkliai uplift (oil field) located on the hanging wall (west Lithuania) (after Poprawa et al., 2006)
15 pav. S4 seisminis profilis, kertantis Telšių lūžio zoną (gėlės struktūra) ir su ja susijusią Girkalių pakilumą (naftos telkinys, Vakarų Lietuva) (pagal Poprawą ir kt., 2006)

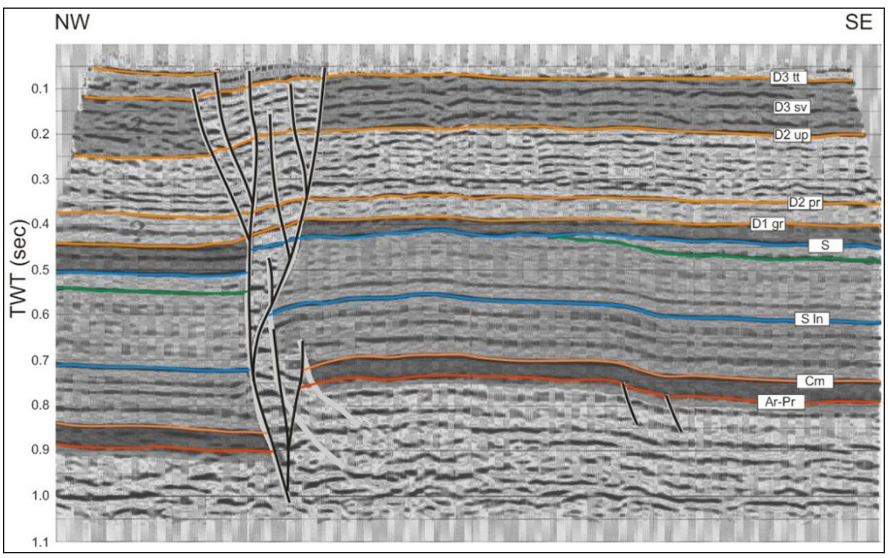

Fig. 16. Seismic profile S5 crossing the Telšiai fault zone and associating the Vaškai uplift located on the hanging wall (north Lithuania) (after Poprawa et al., 2006)
16 pav. S5 seisminis profilis, kertantis Telšių lūžio zoną ir su ja susijusią Vaškų pakilumą (Šiaurės Lietuva), esančią ant pakelto bloko (pagal Poprawą ir kt., 2006)

The most prospective structural traps for CO_2 storage were also formed mainly during the Caledonian tectonic phase. In most cases they associate with reverse faults that increase the potential CO_2 leakage risks. Three types of structural traps can be defined as related to fault risk.

Minority of large local uplifts show no obvious association with faults (Fig. 17). This type of structures is considered as having no CO_2 leakage risk associated with structuring of the sedimentary layers. The Degole (central Latvia) large uplift of 55 m amplitude and 15 km^2 area is an example of such potential traps (Fig. 17).

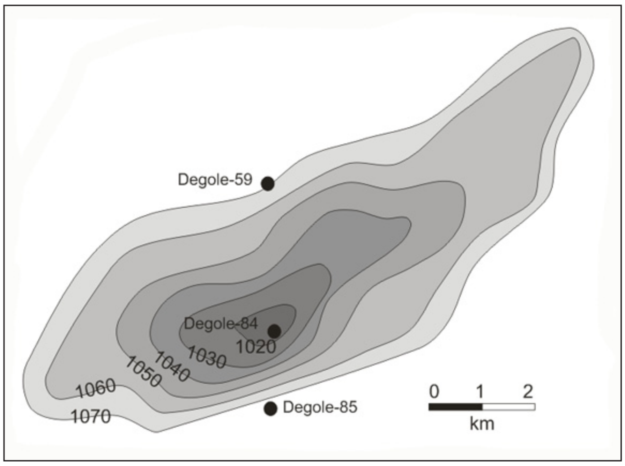

Fig. 17. Structural map of the Degole (Latvia) uplift, top of the Cambrian reservoir (m, MSL). Deep wells are shown

17 pav. Degolės pakilumos (Latvija) kambro kraigo struktūrinis žemėlapis (m). Taškai žymi giliuosius gręžinius

The second type of prospective uplifts predominates in the Baltic Region showing a special association with one or several intersecting (or paralleling) faults (Fig. 18). The amplitude of faults is rather different. In most cases the amplitude of the offset of the Cambrian reservoir exceeds its thickness; therefore the Cambrian sandstones are tectonically juxtaposed to the Ordovician–Silurian shales of a foot wall. Such association of potential structural Cambrian traps with faulted structures is viewed as the potential CO_2 leakage risk, essentially in case of presence of faults of the complex geometry.

The third group of structures is represented by Cambrian local uplifts cut by faults. It is less common in the Baltic sedimentary basin. The E6 structure located in the Latvian Economic Zone of the Baltic Sea is one of the largest local uplifts defined in the Cambrian reservoir (Fig. 19). It is as large as 585 km^2, the structure is elongated WNW–ESE. We calculate the storage capacity of the structure about 600 Mt of CO_2 that exceeds the total storage capacity of all onshore prospective uplifts. The detailed seismic studies, however, unravelled a highly complex geometry of the uplift that is complicated by a number of cutting faults of different size, the largest one of 70 m amplitude striking NNW–SSE. Furthermore, the uplift is bounded by ENE–WSW trending faults in the north and the south. The structure was initiated during the Caledonian tectonic phase and was reactivated during the Devonian. Most of faults penetrate the Devonian succession reaching the upper part of the sedimentary

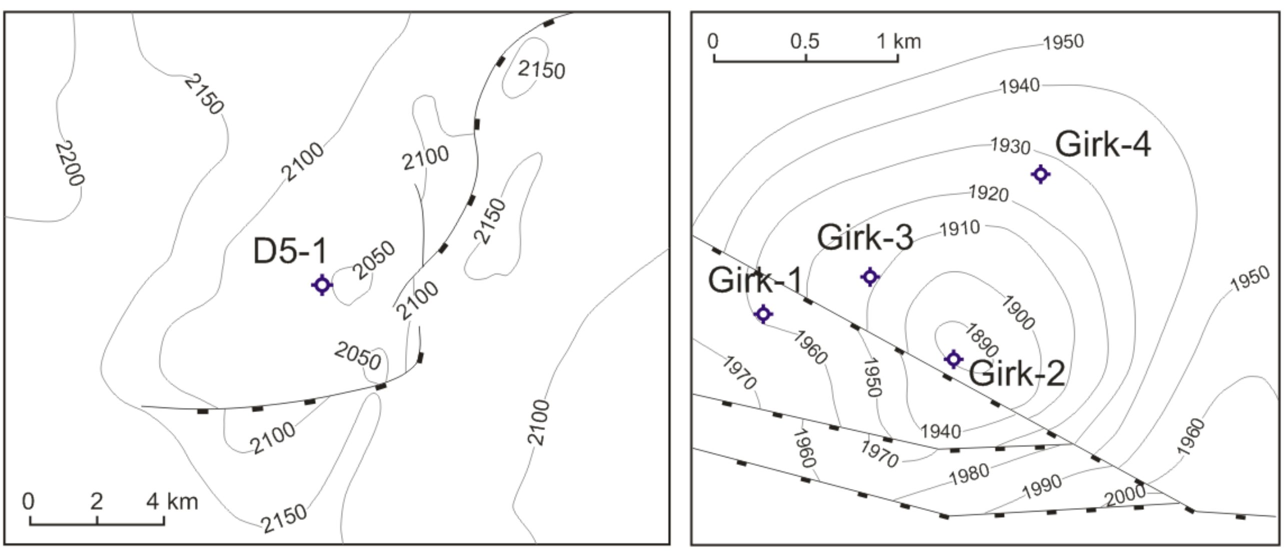

Fig. 18. Structural maps of the D5 uplift (offshore) and the Girkaliai uplift (onshore), top of the Cambrian reservoir (m, MSL). Seismic profiles S1 and S3 crossing the structures are shown in Fig. 13

18 pav. D5 ir Girkalių pakilumų kambro kraigo struktūriniai žemėlapiai (m). Struktūras kertančius S1 ir S3 seisminius profilius žr. 13 pav.

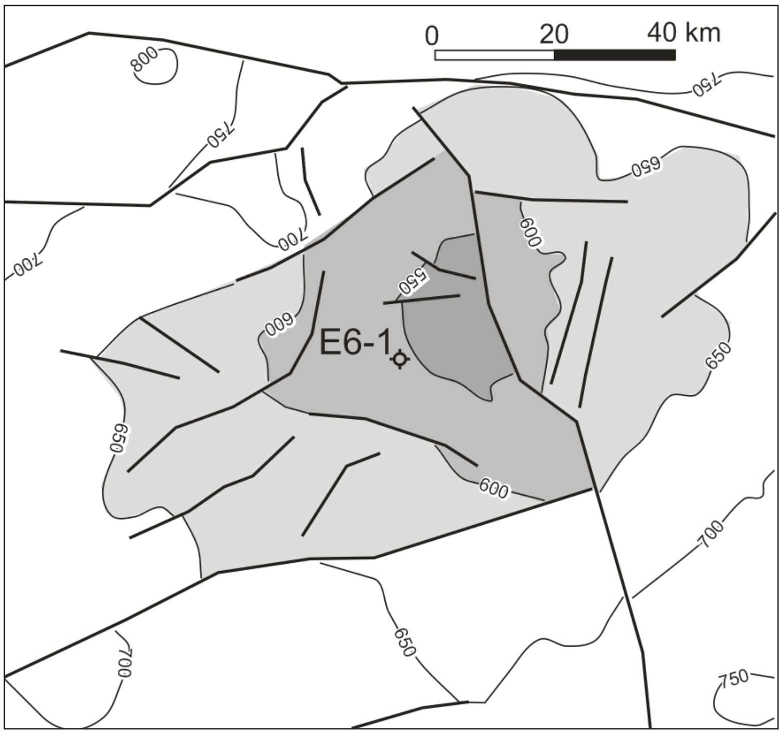

Fig. 19. Structural map (msec) of the E6 uplift (Latvian offshore), top of the Ordovician
19 pav. E6 pakilumos (Latvijos jūrinė dalis) ordoviko kraigo struktūrinis žemėlapis (msek)

cover. Therefore this type of structures is regarded as having a high potential risk in storing CO_2. It is notable that oil impregnation is characteristic in the Middle Cambrian sandstones of the well E6-1, while some accumulation of oil (reported oil inflow of 2.7 m^3/day) in the Porkuni RSt carbonate sandstones of Upper Ordovician age is documented that may suggest leakage of the oil from the underlying Cambrian reservoir into the Ordovician reservoir through the clayey package of more than 90 m thick. Furthermore, several oil impregnations were identified at the depths of about 120 m, 260 m, and 560 m in the Lower and Middle Devonian sandstones and sands separated by 110 m thick marlstone aquitard which may suggest some openness of the fault system.

EVIDENCES OF FAULT TIGHTNESS IN THE BALTIC REGION

A number of oil fields were defined in the Cambrian reservoir of the Baltic basin (Brangulis et al., 1997). Furthermore, several gas fields were discovered in the Polish offshore of the Baltic Sea. In most cases the local uplifts associate with faults cutting the Lower Palaeozoic succession, including the Ordovician–Silurian shales. Often the oil-water contact is juxtaposed to a fault plain. It proves the tightness of associated faults throughout the geological evolution of the basin.

The Inčukalns underground gas storage operates since 1968. It is located in Central Latvia and utilises the Cambrian sandstones at the depth of about 700 m. The highest capacity of the Inčukalns Underground Gas Storage Facility reached 4.47 billion m^3, 2.32 billion m^3 of which are active. It is still possible to increase the capacity of the Inčukalns Underground Gas Storage Facility to 3.2 billion m^3 of active natural gas. The uplift is located on the northern hanging wall bounded by W–E trending fault (Geological structures…, 2001). The water-gas contact is juxtaposed to the fault plane. The long term exploitation of this facility did not cause any gas leakage to the shallower aquifers and the surface, thus proving the tightness of the fault.

EVIDENCES OF FLUID LEAKAGE ALONG FAULTS IN THE BALTIC REGION

The upward migration of salty fluids from the deeper aquifers to the shallow aquifers (and the surface) along the faulted pathways is well known, for example, from Druskininkai and Birštonas mineral water resorts of Lithuania (Kaveckis, 1929). It points to openness of some faults for fluid migration.

There is abundant hydrochemical information on the aquifers of the Baltic basin available. The analysis of north–west Lithuanian faults system unravelled that some faults or their segments can be rather permeable for fluid migration. 5 hydrochemical anomalies were identified along the Akmenė fault trending W–E in the shallow Quaternary, Upper Permian, and Upper Devonian aquifers that are exploited for supply of the potable water (Fig. 20). The salinity of the water anomalies is in the range of 0.8–1.2 g/l.

By contrast, no evidences of upward migration of the saline water were documented along the paralleling Mažeikiai fault. No anomalies were reported from the western part of the Telšiai fault controlling oil fields (Girkaliai, Genčiai, Kretinga, Nausodis) either. Further east (east of Telšiai town), however, four hydrochemical anomalies of salinity 0.9–1.0 g/l were obtained. Moreover, the well Tyras-1, drilled as the oil exploration well in 2003, hit the Telšiai fault (well is located between Kretinga and Plungė towns). Several intervals of Ordovician shales were drilled with coring. The inspection of drill cores unravelled a number of fractures that contain smears of oil.

CALCULATION OF SOME FAULT CHARACTERISTICS

Faults cutting the Ordovician and Silurian layers are exposed in the shallowest parts of the Baltic basin that are dominated by carbonaceous lithofacies. Furthermore, they are of low amplitudes. Therefore those models cannot be transposed to the deeper parts of the basin, despite of clear evidences of fluid migration along faults (dolomitisation of limestones, brecciacion, sulphide mineralization, etc.). No drill cores of deep wells (except a few intervals) are available to study in detail the structural features of faults.

Some basic parameters of faults of deep parts of the basin can be derived from geological observations from other regions. Models of fault growth (Sammis et al., 1987; Cox, Scholz, 1988) predict a linear increase of local fault gouge (fault gouge is

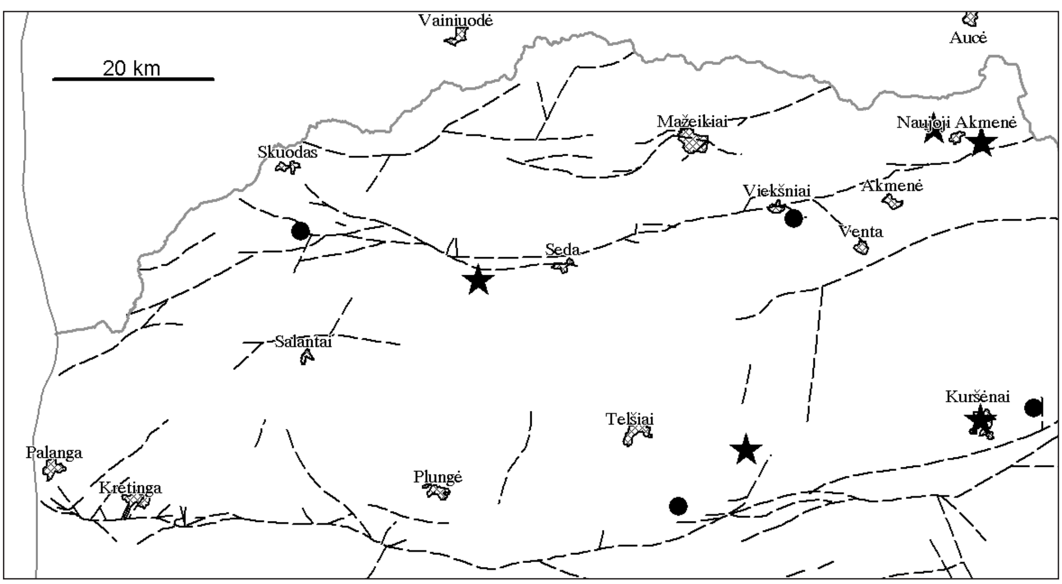

Fig. 20. Faults crossing the Ordovician–Silurian aquitard, North–west Lithuania. Ground water hydro-chemical anomalies in the range of 0.7–1.0 g/l (dots) and 1–1.2 g/l (stars)
20 pav. Ordoviko–silūro storymę kertantys lūžiai Šiaurės vakarų Lietuvoje. Gruntinio vandens hidrocheminės anomalijos: 0,7–1,0 g/l (taškai) ir 1–1,2 g/l (žvaigždutės)

noncohesive, multiply fractured material formed by brittle shear failure of rock) thickness (t) with local displacement (D) and data from cataclastic faults with displacements ranging from 10^{-2} m to 10^4 m are consistent with this hypothesis (Scholz, 1987; Hull, 1988):

$$D = c_1 \times t,$$

where D is the fault displacement (m), c_1 is a function of the magnitude of normal stress on the fault plane, the hardness of the rock, and the nature of the wear process (Scholz, 1987). Empirical data for fault gouge vs. thickness indicate that c_1 is about 60 to 70.

The calculation of the fault gouge thickness of the major fault zone of the Baltic sedimentary basin shows the range from 0.8 to 8 m, increasing for large faults.

POTENTIAL CO_2 LEAKAGE ALONG WELLS

The deep wells might potentially cause the leakage of CO_2 from the reservoir. There are a large number of wells that penetrated the Cambrian reservoir and overlying layers in the region, owing mainly to intense oil exploration activities. For instance, there are about 500 wells that reached the Cambrian sandy reservoir in Lithuania; 330 wells are located within the prospective area for the CO_2 geological storage (Fig. 21). The highest concentration of wells is related to West Lithuania, essentially along the Gargždai and Telšiai fault zones controlling the major oil fields of Lithuania. The majority of wells were drilled in sixties – eighties of the past century. The non-operating old wells were closed following the existing for this time USSR rules that should have ensured the closeness of wells. However, one should consider a possibility of incorrect closure operations. Also, the corrosion and other processes should not be excluded to take place in the wells leading to integrity loss. Therefore those wells should be monitored with high precision in case of operation of the CO_2 storage site.

DISCUSSION AND CONCLUSIONS

The Baltic sedimentary basin is relatively little affected by tectonic structuring owing to cratonic setting of the region. However, numerous faults cutting the sedimentary layers are identified. The distribution of faults is highly variable, showing some concentration within the particular areas. It is accounted to structural inheritance and peculiar mechanical parameters of the lithosphere (Šliaupa, Hoth, 2010). The areas most affected by faulting are related to Middle Latvia (Liepaja–Sal-

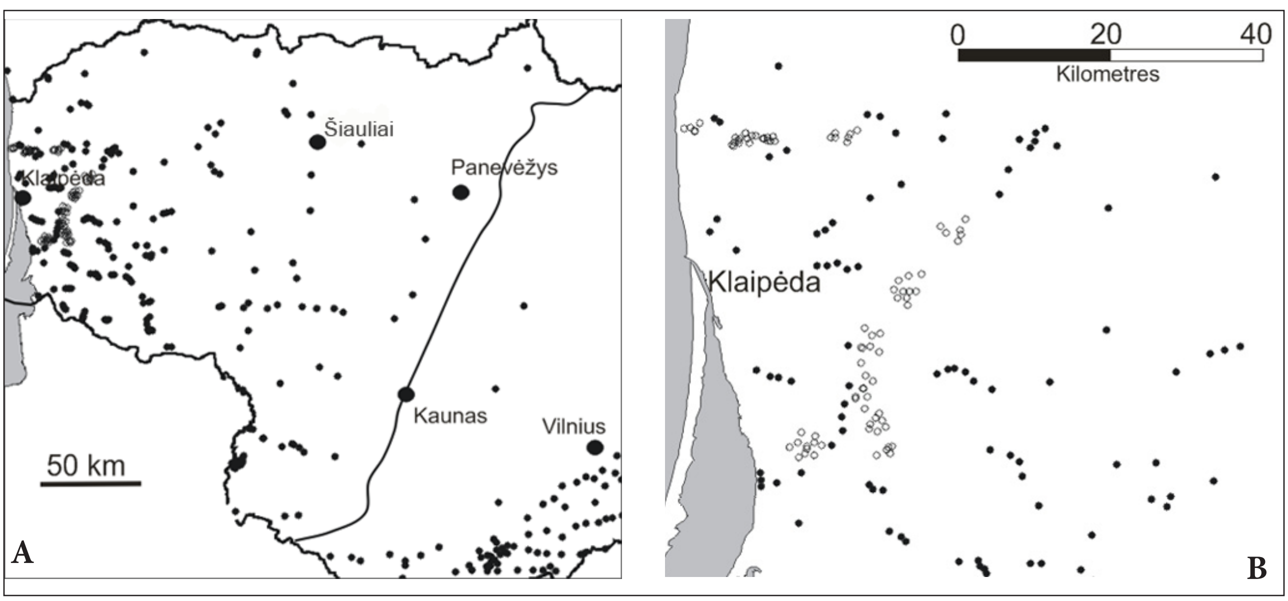

Fig. 21. Abandoned wells (black circles) and wells of producing oil fields (open circles) of Lithuania (A) and West Lithuania (zoom-in, B)

21 pav. Likviduoti gręžiniai (juodi skrituliukai) ir naftos eksploatacijos gręžiniai (apskritimai) Lietuvoje (A) ir Vakarų Lietuvoje (B, žemėlapio fragmentas) dus ridge zone), West Lithuania (Telšiai, Gargždai fault zones, other smaller-scale faults) and Polish offshore area of the Baltic Sea (Leba ridge). It is notable that the major local uplifts prospective for CO_2 geological storage are associated mainly with those faulted structures. Therefore the risk of the CO_2 leakage from the potential storage sites should be considered.

The main prospects of the CO_2 geological storage are related to the Cambrian siliciclstics that represent the basal part of the Baltic sedimentary basin. The depth of the aquifer ranges from outcrops along the northern margin of the basin to more than 3 km in the west. The temperatures are also increasing to the west attaining 90 °C and more. In terms of the hydrostatic pressure and temperature conditions, the most part of the Baltic sedimentary basin is favourable for CO_2 storage in the Cambrian saline aquifer. This prospective area is characterised by a rather thick (in access of 0.5 km) clayey package of the Ordovician–Silurian age that provides a reliable seal (cap-rock) which is a very important parameter for safe storing CO_2 in Cambrian sandstones. However, some potential risk of CO_2 escape should be considered, essentially in regard to faults.

The main faulting of the sedimentary cover of the Baltic basin took place during the latest Silurian – earliest Devonian referred to as the Caledonian phase of the tectonic activity. Some faults were reactivated and some new faults were formed during the later tectonic phases, though to much lower extent. Different types of faults are defined that show different geometries which, in turn, may affect the tightness of faults. The compressional reverse faults of predominating NW–SE orientation show rather simple geometries, while flower structures are typical for the transpressional faults striking mainly in sub-latitudinal direction. Accordingly, the former type of faults is considered of lower risk in terms of CO_2 leakage compared to the latter type of faults.

Furthermore, three types of local uplifts prospective for CO_2 storage were defined, i. e. (1) uplifts associated with no faulted structures, (2) uplifts associated with fault(s), and (3) uplifts dissected by faults. The second type of structures predominates in the Baltic sedimentary basin. It is therefore not

Table. **Number of old wells and structural setting of major uplifts prospective for CO_2 geological storage in the Cambrian formation**

Lentelė. **Seni gręžiniai ir pagrindinių kambro pakilumų, perspektyvių geologiniam CO_2 saugojimui, struktūrinė padėtis**

No.	Structure	Number of wells	Association with fault(s)	Type of faulting T (transperssional) C (compressional)	Cutting fault(s)	Protected area
			Latvia (onshore)			
1	N. Blidene	2	Yes	T	No	
2	N. Ligatne	0	No	–	No	
3	Luku-Duku	2	Yes	T	No	
4	Viesatu	1	Yes	C	No	
5	Degole	3	No	–	No	
6	Kalvene	2	Yes	T/C	No	
7	Dobele	15	Yes	T/C	No	
8	Snepele	1	Yes	C	No	
9	Liepaja	3	No	–	No	
10	S. Kandava	3	Yes	C	No	
11	Usma	2	Yes	C	No	
12	Aizpute	4	Yes	C	No	
13	Vergale	4	Yes	T	No	
14	Edole	5	Yes	C	No	
15	Blidene	1	Yes	T	No	
			Lithuania (onshore)			
17	Syderiai	1	Yes	T/C	No	No
17	Vaškai	5	Yes	T	No	No

surprising that majority of the largest and most prospective local uplifts are located in Latvia that is affected by the largest scale Liepaja–Saldus fault zone.

Analysis of fifteen major uplifts of Latvia and two potential storage sites of Lithuania indicates that only two structures (Degole and Liepaja) do not have any evident control by faults (Table). The rest uplifts were formed along the fault or the intersection of several faults of either transperssional (higher risk) or compressional (lower risk) types.

The other important parameter that may affect the isolation of the storage structure relates to drilling. The Cambrian reservoir is rather well studied by drilling in the Baltic Region. About 500 wells reached the Cambrian reservoir in Lithuania, most of them within the prospective storage area. They are mainly 30–40 years old therefore some might lose the integrity.

The prospective storage structures are drilled to a different degree (Table). The number of wells ranges from 1 to 15 wells; in most cases structures were investigated by 2–4 wells. These wells should be carefully monitored during the operation of the storage site.

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CO_2 GEOLOGINIO SAUGOJIMO BALTIJOS SEDIMENTACINIAME BASEINE RIZIKOS VEIKSNIAI

Santrauka

Baltijos sedimentacinis baseinas yra kratono dalis, todėl palyginti nedaug paveiktas tektoninių procesų. Visgi jo storymę kerta lūžių tinklas, kurių pasiskirstymas labai kaitus. Pagrindinės lokalios pakilumos, perspektyvios CO_2 geologiniam saugojimui, pastebimai susijusios su lūžinėmis struktūromis, todėl būtina įvertinti nutekėjimo iš potencialių anglies dioksido saugojimo vietų riziką.

Perspektyviausios geologiniam saugojimui yra kambro siliklastinės uolienos, sudarančios Baltijos sedimentacinio baseino bazinę dalį. Didžioji dalis kambro sūraus vandeningojo sluoksnio dėl aukšto hidrostatinio slėgio ir temperatūros yra tinkama CO_2 geologiniam saugojimui. Jį dengia palyginti stora (per 400–500 m) molinga ordoviko–silūro storymė, sudaranti patikimą nepralaidžią dangą CO_2 geologiniam saugojimui kambro smiltainiuose.

Pagrindiniai tektoniniai procesai Baltijos sedimentaciniame baseine vyko kaledoninės fazės metu vėlyvojo silūro–ankstyvojo devono laikotarpiu. Nustatytiems įvairių tipų lūžiams būdinga skirtinga geometrija, lemianti lūžių uždarumą. Spaudimo lūžiai, orientuoti dažniausiai šiaurės vakarų–pietryčių kryptimi, pasižymi palyginti paprasta geometrija, o žiedinės struktūros būdingos įžambaus spaudimo subplatumos lūžiams. Pastarieji sudaro didesnę anglies dvideginio dujų nutekėjimo riziką, o pirmojo tipo lūžiai CO_2 geologinio saugojimo požiūriu laikomi saugesniais.

Be to, buvo išskirtos trijų rūšių lokalinės pakilumos: 1) pakilumos, nesusijusios su lūžiais; 2) pakilumos, susijusios su lūžiais; 3) pakilumos, kurias kerta lūžiai. Baltijos sedimentaciniame baseine vyrauja antro tipo struktūros, todėl nenuostabu, kad dauguma didžiausių ir perspektyviausių pakilumų yra Latvijos teritorijoje, kuri patyrė itin stambios Liepojos-Saldaus tektoninės zonos poveikį. Penkiolikos didžiausių struktūrų Latvijoje ir dviejų potencialių saugyklų Lietuvoje analizė rodo, kad tik dvi struktūros (Degole ir Liepojos) neturi jokio akivaizdaus ryšio su lūžiais. Likusios struktūros susiformavo išilgai dominuojančių lūžių ar keleto įžambaus spaudimo tipo (didesnės rizikos) ar spaudimo (mažesnės rizikos) lūžių sankirtos.

Kitas svarbus saugyklos uždarumo parametras yra susijęs su gręžiniais. Kadangi gręžiniai daugiausia yra 30–40 metų senumo, dalis jų jau gali būti praradę uždarumą. Perspektyvios struktūros turi skirtingą gręžinių kiekį; kai kuriose jų yra nuo 1 iki 5 gręžinių, bet dauguma buvo tiriamos 2–4 gręžiniais.

Raktažodžiai: CO_2 geologinis saugojimas, rizika, lūžis, gręžinys, Baltijos baseinas