The Baltic Basin: structure, properties of reservoir rocks, and capacity for geological storage of CO_2

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Abstract. Baltic countries are located in the limits of the Baltic sedimentary basin, a 700 km long and 500 km wide synclinal structure. The axis of the syneclise plunges to the southwest. In Poland the Precambrian basement occurs at a depth of 5 km. The Baltic Basin includes the Neoproterozoic Ediacaran (Vendian) at the base and all Phanerozoic systems. Two aquifers, the lower Devonian and Cambrian reservoirs, meet the basic requirements for CO_2 storage. The porosity and permeability of sandstone decrease with depth. The average porosity of Cambrian sandstone at depths of 80–800, 800–1800, and 1800–2300 m is 18.6, 14.2, and 5.5%, respectively. The average permeability is, respectively, 311, 251, and 12 mD. Devonian sandstone has an average porosity of 26% and permeability in the range of 0.5–2 D. Prospective Cambrian structural traps occur only in Latvia. The 16 largest ones have CO_2 storage capacity in the range of 2–74 Mt, with total capacity exceeding 400 Mt. The structural trapping is not an option for Lithuania as the uplifts there are too small. Another option is utilization of CO_2 for enhanced oil recovery (EOR). The estimated total EOR net volume of CO_2 (part of CO_2 remaining in the formation) in Lithuania is 5.6 Mt. Solubility and mineral trapping are a long-term option. The calculated total solubility trapping capacity of the Cambrian reservoir is as high as 11 Gt of CO_2 within the area of the supercritical state of carbon dioxide.

Key words: Baltic Basin, reservoir rocks, CO_2 geological storage, structural trapping.

INTRODUCTION

The composition and properties of reservoir rocks of the Baltic Cambrian basin were studied within the frame of the German–Baltic project GEOBALTICA ‘Characterisation of reservoir rocks and their fluids in the Baltic States’ and of the Estonian project ‘Physical properties of Estonian Palaeozoic sedimentary rocks: complex studies and systematic data base’ (Shogenova et al. 2001, 2002a, 2002b; Sliaupa et al. 2001, 2003; Jõeleht et al. 2002; Raidla et al. 2006).

Carbon dioxide capture and storage (CCS) is a new area of investigation in the three Baltic States (Estonia, Latvia, Lithuania). In 2006–2008 the Institute of Geology at Tallinn University of Technology, Institute of Geology and Geography (Vilnius), and Latvian Environment, Geology and Meteorology Agency participated in EU GEOCAPACITY and CO2NET EAST projects supported by the European Commission through Framework Programme 6 (FP6). As a result of the study several scientific articles were published (LEGMA 2007; Shogenova et al. 2008, 2009; Sliaupa et al. 2008), and the presently working CO2NET EAST information portals for CCS technologies were created (www.gi.ee/co2net-east).

The aim of this article is to give an overview of the final results of several international and national projects focusing on the structure of the Baltic Basin, reservoir properties of rocks, and their application for CO_2 geological storage. Compared to the previously published data, a more precise formula was used for the estimation of CO_2 storage capacity in saline aquifers, which was also applied in capacity estimates by all partners of the EU GEOCAPACITY project.

STRUCTURE

The Baltic Basin (Baltic Syneclise) is a large marginal synclinal structure in the southwestern part of the East European Craton, but a major structure of the three Baltic States (Fig. 1). The structure is about 700 km long and 500 km wide (Paškevičius 1997). The axis of the syneclise plunges to the southwest. Depth below sea level of the Precambrian basement increases from a few hundred metres in Estonia to 1900 m in southwestern

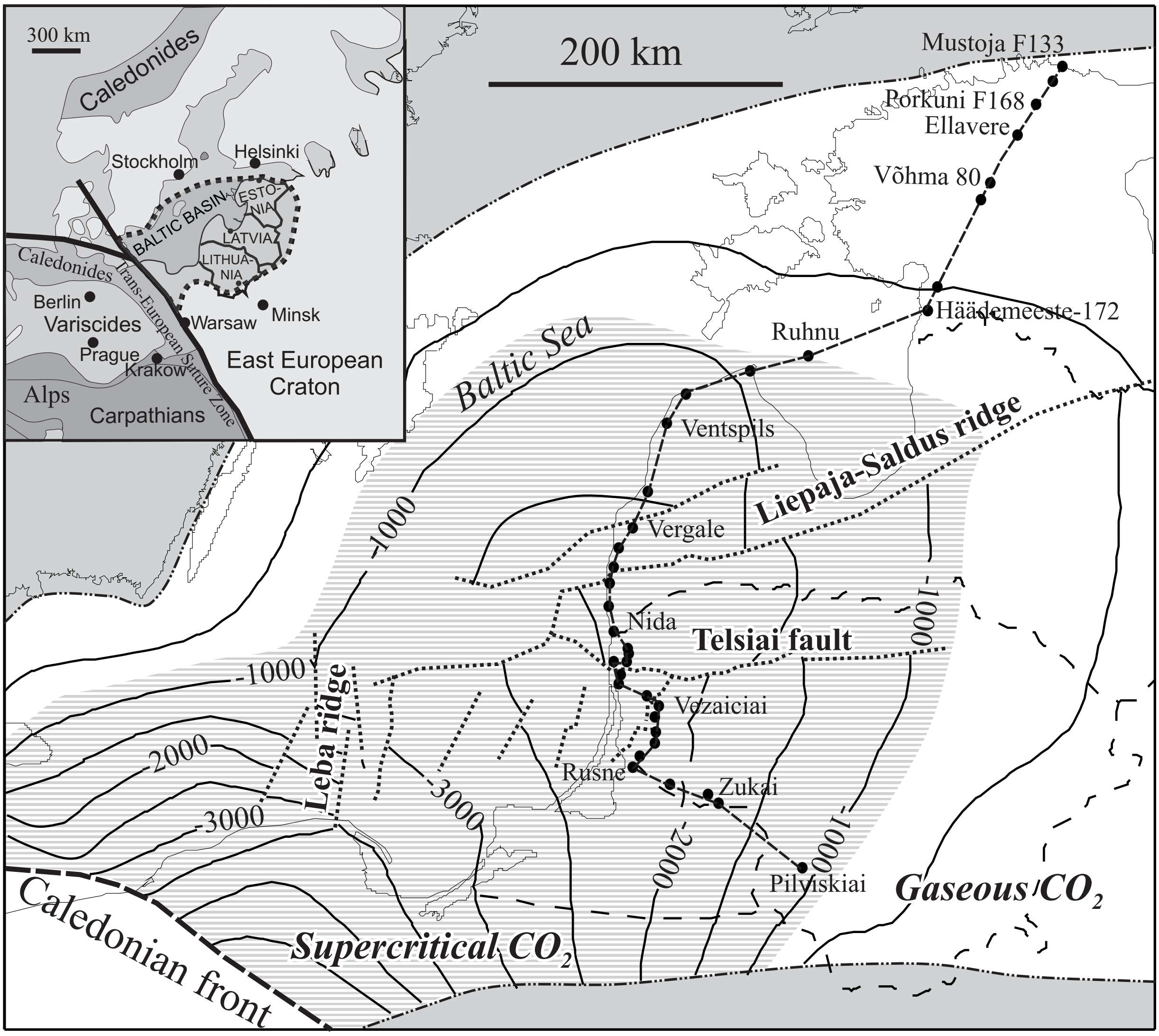

Fig. 1. Structure map of the Baltic Basin (modified after Sliaupa et al. 2008). The contour lines indicate the depth of the top of the Cambrian. The dotted lines denote major faults. The pressure–temperature fields of gaseous (white) and supercritical (hatched) state of CO_2 are shown. The line of the geological cross section shown in Fig. 3 is indicated.

Latvia, 2300 m in western Lithuania, and 5000 m in Poland.

The Baltic Basin includes the Neoproterozoic Ediacaran (Vendian) at the base and all Phanerozoic systems. In this succession four structural complexes are distinguished, separated from each other by angular unconformity.

The Timanian (Baikalian) complex is composed of up to 200 m thick Ediacaran sandstone, siltstone, and claystone, and up to 120 m thick lowermost Cambrian claystone (‘Blue Clays’). They are distributed in the eastern half of the East Baltic countries.

The Caledonian complex includes the rest of the Cambrian succession (up to 170 m thick sandstone, siltstone, and shale); 40–250 m thick Ordovician shaly-carbonaceous rocks; up to 800 m thick Silurian shale (in the shallow periphery of the basin carbonates predominate); and over 200 m thick lowermost Devonian claystone, sandstone, and marlstone.

The Variscan (Hercynian) complex contains rest of the Devonian sequence (up to 1100 m thick marly-carbonaceous rocks alternating with sandstone) and the lowermost Carboniferous siliciclastic-carbonaceous rocks.

The Alpine complex includes an about 100 m thick Upper Permian succession of carbonates and evaporates; up to 250 m thick Lower Triassic mudstone; up to 120 m thick Jurassic sandstone, claystone, and limestone; 140 m thick Cretaceous glauconite sand and chalky marl; and 80 m thick Cenozoic siliciclastic rocks. The Cenozoic part of the section is known only in southwestern Lithuania. The bedrock is covered by Quaternary sediments varying in thickness from a few centimetres to a few hundred metres.

The end of the Caledonian tectonic stage was marked by the extensive faulting of the basin. The Variscan structural complex is less deformed (Fig. 2). Major faults are shown in Fig. 1. Numerous local structures (uplifts) have been detected in the Baltic Syneclise. In Lithuania 130 local Cambrian uplifts were identified (Šliaupa et al. 2005). On the tectonic map of Latvia (Misāns 1981) 109 local structures are indicated. Location of the 17 major Latvian local structures is shown in Fig. 3.

MATERIAL AND METHODS

The composition and physical properties were studied in samples collected during the GEOBALTICA project from 33 wells representing shallow (Estonia, 80–800 m), middle (Latvia and central Lithuania, 1–1.8 km), and deep (western Lithuania, 1.8–2.3 km) parts of the buried basin (Shogenova et al. 2001, 2002a, 2002b; Sliaupa et al. 2001, 2003; Jõeleht et al. 2002). Wet and grain density and effective porosity of 270 samples of Cambrian sandstones, siltstones, and claystones were studied together with their bulk chemical composition in all three countries (Jõeleht et al. 2002). Bulk chemical composition of rocks was determined by X-ray-fluorescence (XRF) analysis in the All-Russian Geological Institute, St Petersburg.

Physical properties of 270 samples cut into cubes of 24 mm × 24 mm × 24 mm were measured in the Petrophysical laboratory of Research Institute of Earth Crust of St Petersburg University using the following methods. Samples were dried at a temperature of 100–110 °C, and the weight of dry samples was determined (q_d). Next the samples were saturated with ordinary water for 7 days and then weighed in air (q_w) and water (q_{ww}). From the obtained measurements the following parameters were calculated: wet density

$$\delta_w = q_w / V = q_w / (q_w - q_{ww}),$$

where V represents sample volume; grain density

$$\delta_g = q_d / (q_d - q_{ww}),$$

and effective porosity

$$\Phi_e = (q_w - q_d)/(q_w - q_{ww}).$$

Gas permeability was measured in 36 Cambrian samples from Estonia, cut into cubes of 1 cm size,

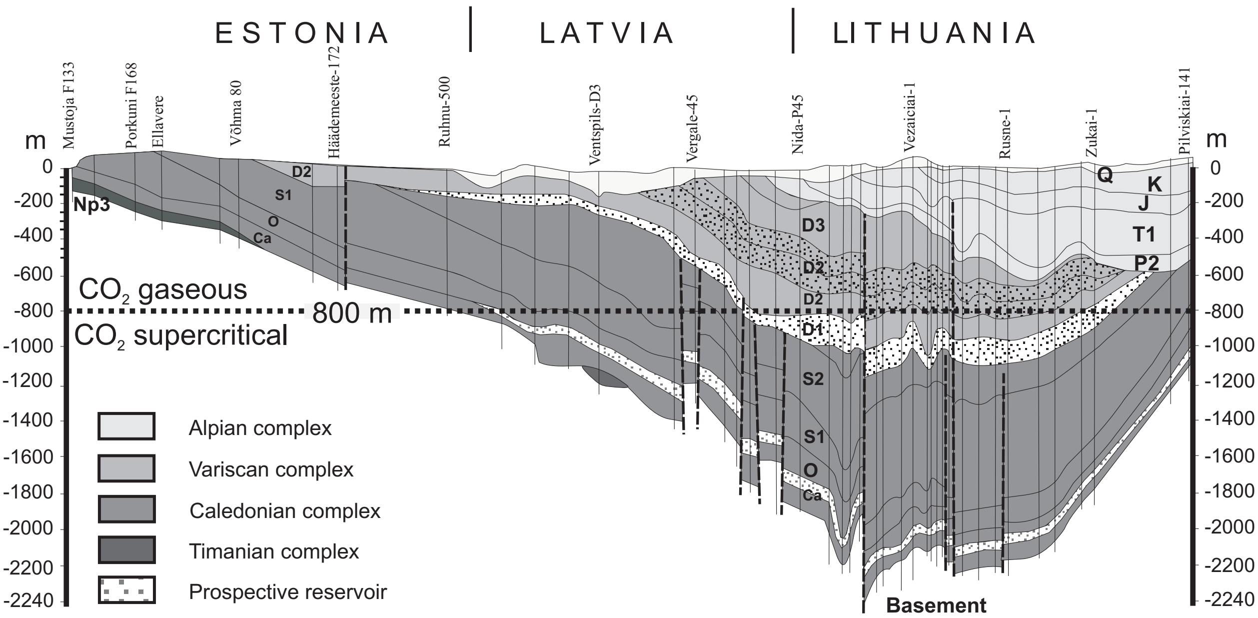

Fig. 2. Geological cross section across Estonia, Latvia, and Lithuania (modified after Sliaupa et al. 2008). Major aquifers are indicated by dots. Np3, Ediacaran (Vendian); Ca, Cambrian; O, Ordovician; S1, Lower Silurian (Llandovery and Wenlock series); S2, Upper Silurian (Ludlow and Pridoli series); D1, D2, and D3, Lower, Middle, and Upper Devonian; P2, Middle Permian; T1, Lower Triassic; J, Jurassic; K, Cretaceous; Q, Quaternary.

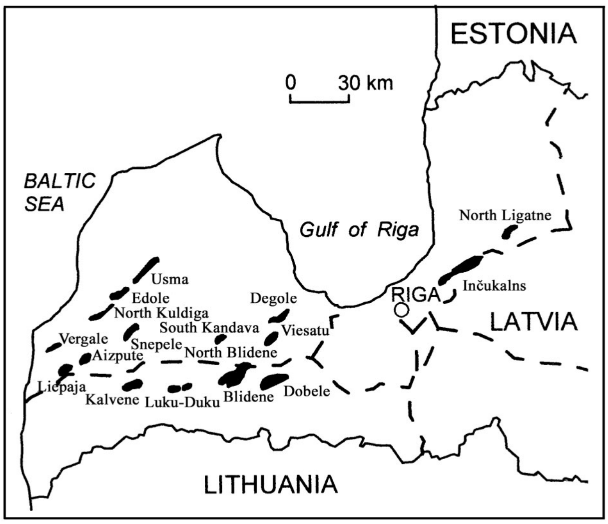

Fig. 3. Major Cambrian aquifer structures (CO_2 storage potential exceeding 2 Mt) of Latvia and Inčukalns underground gas storage (modified after LEGMA 2007). The dashed line shows gas pipelines.

at the Hydrocarbon and Mineral Research Group, Danish Technical University using a DGP 2000 digital gas permeameter and the Software GASPERM V1.0 for Windows.

The permeability of 288 Lithuanian samples from 28 boreholes of central and western Lithuania and 68 Latvian samples from 6 boreholes was determined by the saturation method. The permeability and total weight of Cambrian rocks were measured on cubes of 2–4 cm size (depending on the diameter of the core). The samples were dried at a temperature of 105–110 °C during 24 h and weighed (q_d).

Permeability (in darcy) was determined during passing the gas through the sample using Zaks apparatus and calculated by the formula

$$K = Q \times l \times \eta / S \times t \times (P_1 - P_2),$$

where Q is the gas volume passing through the sample (in cm^3); l is sample length (cm); η is the dynamic viscosity of the gas; S is the square area of the cross section of the sample (cm^2); t is time (in seconds); P_1 is gas pressure in front of the sample (Mpa), P_2 is gas pressure behind the sample (Mpa). After that the samples were saturated with kerosene in vacuum and weighed in kerosene (q_k). Then the samples were dried and weighed in the air (q_s). Effective porosity (%) was calculated by the formula

$$\Phi_e = (q_s - q_d)/(q_s - q_k).$$

PHYSICAL PROPERTIES

A number of aquifers have been identified in the Baltic sedimentary basin. Deep (more than 800 m) saline aquifers, not suitable for drinking water supply, are considered as prospective ones for CO_2 storage. Only two large aquifers of the Baltic States meet these requirements, the Lower–Middle Devonian (Kemeri, Rėzekne, and Pärnu regional stages) and Cambrian (Series 3, Deimena Formation).

The depth of the **Cambrian reservoir** (aquifer) exceeds 800 m in western Latvia, western Lithuania, northern Poland, and in the Baltic offshore, while Estonia is beyond the limit of the supercritical state of CO_2 (Fig. 1). The thickness of the aquifer ranges from 20 to 70 m. The reservoir consists of quartz sandstone including interbeds of siltstone and shale (claystone). The **wet density** of these rocks increases with depth. The average density of samples from depths of 80–800, 800–1800, and 1800–2300 m is 2260 kg/m^3 (60 samples), 2300 kg/m^3 (111), and 2530 kg/m^3 (98), respectively (Table 1). The **porosity**, on the contrary, decreases with depth (Fig. 4). The average porosity of samples from

Table 1. Values of physical and chemical parameters of the Baltic Cambrian rocks (modified after Sliaupa et al. 2003)

Parameter	Depth, m											
	80–800				800–1800				1800–2300			
	Min	Max	Mean	*N*	Min	Max	Mean	*N*	Min	Max	Mean	*N*
Wet density, kg/m^3	2070	2680	2260	60	2130	2810	2300	111	2400	2640	2530	98
Porosity, %	1.5	39.8	18.6	60	8.0	22.5	14.2	111	0.4	12.4	5.5	95
Permeability, mD	0.001	1292	311	38	0.02	1106	251	83	0.003	957	12	273
SiO_2, %	62.0	88.6	83.3	60	57.0	99.4	89.3	115	61.1	99.8	89.7	98
Al_2O_3, %	0.4	17.7	5.3	60	0.05	16.6	3.6	115	0.05	14.6	4.3	98
CaO, %	0.03	16.5	2.2	60	0.03	11.1	0.6	115	0.03	6.4	0.7	98

Min, minimum; max, maximum; mean, average; *N*, number of measured samples.

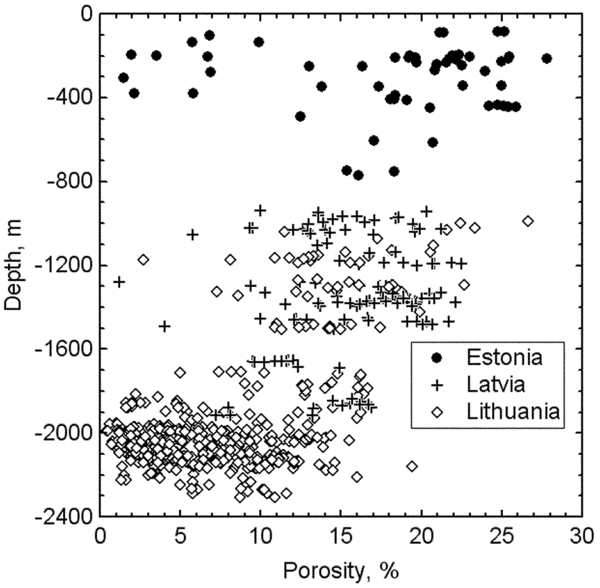

Fig. 4. Porosity of Baltic Cambrian rocks versus depth.

depths of 80–800, 800–1800, and 1800–2300 m is 18.6% (60 samples), 14.2% (111), and 5.5% (95), respectively. The **permeability** has positive correlation with porosity and also decreases with depth (Figs 5, 6). Sandstone and siltstone samples showing the porosity of 20–32% have permeability in the range of 50–1300 mD. Rocks with the porosity of 1–6% have permeability of 0–10 mD. The Cambrian aquifer is sealed by a 500–900 m thick Ordovician–Silurian argillaceous carbonate cap rock.

The depth of the Lower–Middle **Devonian reservoir** (aquifer) exceeds 800 m only in western Lithuania (Fig. 7). The thickness of the aquifer ranges from 100 to 160 m.

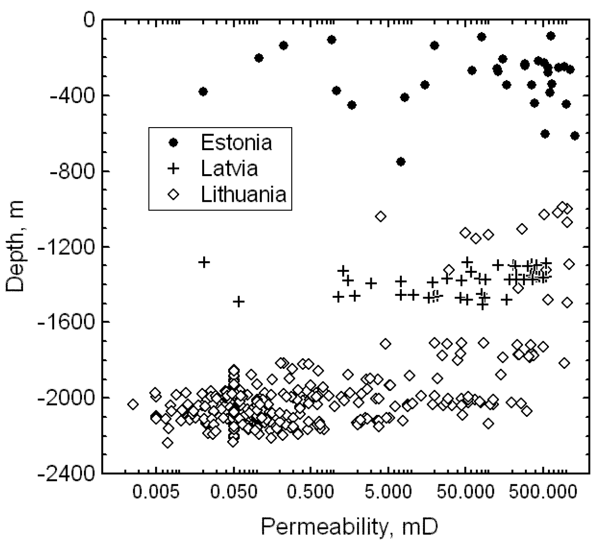

Fig. 5. Permeability of Baltic Cambrian rocks versus depth.

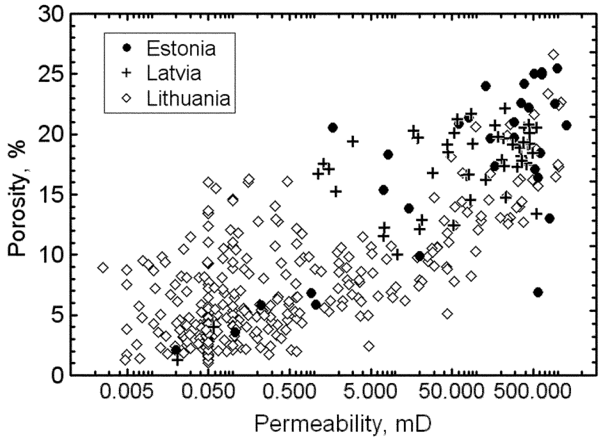

Fig. 6. Permeability of Baltic Cambrian rocks versus porosity.

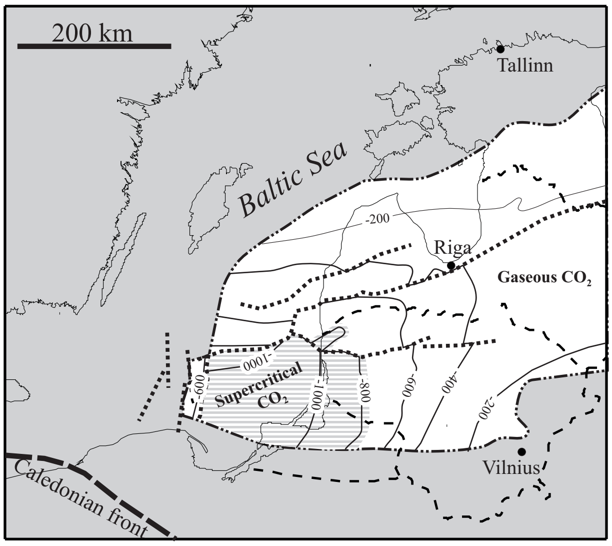

Fig. 7. Depths of the top of the Lower–Middle (Pärnu–Kemeri) aquifer (after Sliaupa et al. 2008), shown by contour lines. The dotted lines show major faults. The pressure–temperature fields of gaseous (white) and supercritical (hatched) state of CO_2 are indicated.

The reservoir consists of arkosic sandstone including interbeds of siltstone and shale (claystone). The average porosity is 26%, permeability ranges from 0.5 to 2 D. The aquifer is sealed by an 80–120 m thick Middle Devonian (Narva Formation) marlstone as cap rock (Sliaupa et al. 2008).

CAPACITY FOR STORAGE OF CO_2

Carbon dioxide may be stored in deep saline aquifers, or hydrocarbon reservoirs at depths below 800 m, being there in liquid or supercritical state ($P > 73.8$ bars,

$T > 31\,°C$) depending on the formation pressures and temperatures. In such conditions the density of CO_2 is about 50–80% of the density of water. Carbon dioxide injected underground will fill the pore space by partial displacement of 'in situ fluids'. The storage potential in saline formations ranges from a few per cent to more than 30% of the total rock volume. In hydrocarbon reservoirs most of the pore space is available for CO_2 storage. After injection CO_2 can be kept underground by a combination of physical and geochemical trapping mechanisms (Metz et al. 2005). Physical trapping includes structural (hydrodynamic) and residual trapping, while geochemical trapping consists of solubility and mineral trapping (Bachu et al. 1994; Metz et al. 2005; Suekane et al. 2008).

Structural trapping is the most important mechanism for storing CO_2 in geological formations, when a huge amount of gas could be stored in domes covered by impermeable cap rocks. For structural trapping of CO_2 local anticlinal structures are available in Latvia (LEGMA 2007). One of the 17 major West Latvian structures (Inčukalns, Fig. 3) has been used for underground gas storage since 1968, proving thus a long-range stability of the sealing cap rock (Davis et al. 2006).

The storage capacity of the structural trap is estimated by the formula (Vangkilde-Pedersen et al. 2009; Vangkilde-Pedersen & Kirk 2009)

$$M_{\mathrm{CO2t}} = A \times h \times \mathrm{NG} \times \phi \times \rho_{\mathrm{CO2r}} \times S_{\mathrm{eff}},$$

where M_{CO2t} is storage capacity (kg), A is the area of an aquifer in the trap (m^2), h is the average thickness of the aquifer in the trap, NG is an average net to gross ratio of the aquifer in the trap, ϕ is the average porosity of the aquifer in the trap, ρ_{CO2r} is the in situ CO_2 density at reservoir conditions, S_{eff} is the storage efficiency factor (for trap volume).

The area of the structures has been determined from contour maps of stratigraphic horizons near or at the top of the reservoir formation. Thickness, net to gross ratio, and porosity have been evaluated using data from exploration wells drilled on the structure or extrapolating information from wells on nearby structures. The CO_2 density varies with depth, depending on pressure and temperature and is in the range of 600–750 kg/m^3 in Lithuania and Latvia. The aquifer systems surrounding and connected to the reservoir formations in the individual traps have been assumed to be open (unconfined) aquifers. The storage efficiency factor of 40% has been assumed corresponding to open high-quality reservoirs (Sliaupa et al. 2008; Vangkilde-Pedersen & Kirk 2009).

The 16 largest structures of Latvia have an estimated capacity of 2–74 Mt (Table 2). Their total estimated capacity exceeds 400 Mt. The depth of the reservoir is within the range of 900–1100 m, thickness 25–70 m, permeability of sandstone 300–700 mD, and average porosity 22%. Evaluation of the capacity of 116 Lithuanian local structures of the Cambrian aquifer showed that the two largest (Vaskai and Syderiai) can store only 8 and 21 Mt of CO_2, respectively (Šliaupa et al. 2005). Capacity of the other structures is far less. No prospective structural traps have been found in the Lower–Middle Devonian aquifer.

Part of CO_2 is trapped in the rock pores owing to capillary pressure. This trap mechanism is referred to as residual gas or capillary trapping (Dullien 1992, pp. 333–486; Suekane et al. 2008). **Stuctural and residual trapping mechanisms** of CO_2 are available

Table 2. Physical parameters of the Latvian structural traps

Structure	Depth, m	Thickness, m	Area, km^2	CO_2 storage capacity, Mt
Aizpute	1096	65	51	14
Blidene	1050	66	43	58
Degole	1015	52	41	21
Dobele	950	52	67	56
Edole	945	71	19	7
Kalvene	1063	45	19	14
Liepaja	1072	62	40	6
Luku-Duku	937	45	50	40
North Kuldiga	925	69	18	13
North Ligatne	750	50	30	23
North Blidene	920	40	95	74
South Kandava	983	25–30	69	44
Snepele	970	30	26	17
Usma	975	50	20	2
Vergale	981	65	10	5
Viesatu	1020	50	19	10
Total				404

not only in aquifers, but also in depleted oil fields. They are represented by local anticlinal traps (mostly brachy-anticlines) containing oil. Some oil shows and a small Kuldiga oil field were discovered in Cambrian and Ordovician reservoirs in Latvia (Brangulis et al. 1993). In Lithuania, 15 commercial oil fields are associated with Cambrian sandstone, 3 are located in Silurian reefs, and 1 lies in the Ordovician reservoir. Oil of all fields is light (807–836 kg/m^3), of methane type. Preliminary geological reserves range from 0.15 to 3.11 million tonnes (Zdanavičiūtė & Sakalauskas 2001). Eleven oil fields are presently exploited. The storage potential of the two largest oil fields in West Lithuania reaches 2 Mt CO_2. Another option is utilization of CO_2 for enhanced oil recovery (EOR). Most of the oil fields have reached the tail phase, and EOR can prolong their life. The estimated total EOR net volume of CO_2 is 5.6 Mt.

A small oil deposit was discovered in western Latvia in 1963 (Kuldiga area). The oil pool is associated with the top of Cambrian sandstone. The reserves were evaluated in the range of 0.08–0.31 million cubic metres. More than 10 anticlinal structures prospective for oil exploration were identified in the Latvian offshore area. Potential CO_2 storage in the prospective offshore oil fields is a task for future study.

Geochemical trapping is not restricted to particular structures. It occurs when CO_2 reacts with in situ fluids (solubility trapping) and host rock (mineral trapping) over time scales of hundreds to thousands of years. At the aquifer scale dissolution is relatively slow due to the difference in the densities of water saturated with CO_2 and unsaturated water (Ennis-King & Paterson 2003). The solubility of CO_2 in the Cambrian aquifer varies from 25–30 kg/m^3 in West Lithuania to 40–50 kg/m^3 in East Lithuania and Latvia. The CO_2 storage potential changes westwards from 0.4 to 0.05 Mt/km^2. The calculated total solubility trapping capacity is as high as 11 Gt CO_2 within the area of the supercritical state of carbon dioxide (Sliaupa et al. 2008).

The Lower–Middle Devonian aquifer is characterized by better reservoir properties, but has a smaller area than the Cambrian reservoir. Carbon dioxide solubility ranges from 36 kg/m^3 in the deep part of the basin to 60 kg/m^3 in the periphery of the basin. In West Lithuania the storage capacity of the reservoir is about 1 Mt CO_2 in a 1 km^2 area. The total onshore potential of this formation is estimated as high as 1 Gt CO_2 (Sliaupa et al. 2008).

Mineral trapping that involves a series of interactions between the formation mineralogy and CO_2-enriched aquifer waters, can convert CO_2 to carbonate. The Cambrian reservoir comprises quartz sandstone that is practically not reactive to carbon dioxide. The Lower–Middle Devonian sandstone contains clay admixture (up to 10%) and feldspar grains (up to 15%). Therefore they have a potential for permanent immobilization of carbon dioxide in mineral form. Assuming the rock capacity of 10 kg/m^3, the sequestration potential can be evaluated to reach 5.6 Gt CO_2 (onshore) (Sliaupa et al. 2008).

CONCLUSIONS

Baltic countries are situated within the Baltic sedimentary basin, which is a large marginal synclinal structure in the southwestern part of the East European Craton. The axis of the syneclise plunges to the southwest, and depth below sea level of the Precambrian basement increases to 2300 m in western Lithuania. The Baltic Basin includes the Neoproterozoic Ediacaran (Vendian) at the base and all Phanerozoic systems. In this succession four structural complexes (Timanian, Caledonian, Variscan, and Alpian) are distinguished.

Two aquifers, the Lower–Middle Devonian and Cambrian reservoirs, meet the basic requirements for CO_2 storage. Only Latvia has prospective structural traps. The 16 largest ones have the storage capacity of 2–74 Mt CO_2, whereas the total capacity exceeds 400 Mt. The structural trapping is not an option for Lithuania as the uplifts are too small. The storage potential of the largest oil fields in West Lithuania reaches 2 Mt CO_2. Another option is utilization of CO_2 for enhanced oil recovery (EOR). The estimated total EOR net volume of CO_2 (part of CO_2 remaining in the formation) is 5.6 Mt.

Alternatively, the solubility trapping could be considered as having a high potential. The calculated total solubility trapping capacity is as high as 11 Gt CO_2 within the area of the supercritical state of carbon dioxide. Lower–Middle Devonian sandstone has a potential for permanent immobilization of carbon dioxide in mineral form, the sequestration potential can reach 5.6 Gt CO_2 (onshore). The solubility trapping together with the mineral trapping should cover industry needs for hundreds of years. However, solubility and mineral trapping technologies are still immature. Several problems have to be solved to activate this potential, such as dissolution enhancement, monitoring, etc.

Estimation of storage potential offshore in the Baltic Sea needs new exploration data and research.

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Balti bassein: ehitus, reservuaarikivimite omadused ja CO_2 geoloogilise ladustamise võimalused

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Balti bassein on 700 km pikkune ja 500 km laiune sünekliis. Aluskorra pinna sügavus suureneb edela suunas ja on Poolas kuni 5 km. Pealiskord koosneb neoproterosoilise Ediacara kihistu ja kõigi Fanerosoikumi kihistute kivimitest. Vaid Devoni ja Kambriumi põhjaveekihid kõlbavad CO_2 ladustamiseks. Selleks sobivaid püüniseid on Kambriumi kivimites ainult Lätis, kus neist 16 suurema mahutavus on 2–74 Mt CO_2. Kogumahutavus ületab 400 Mt. Teine ladustamisvõimalus on CO_2 pumpamine maasse naftatoodangu suurendamiseks. Seejuures on maa alla jääva CO_2 hinnanguline hulk Leedus 5,6 Mt.