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Potential structures for CO₂ geological storage in the Baltic Sea: case study offshore Latvia



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Abstract

This study is focused on two structures in the Baltic offshore region (E6 and E7 structures in Latvia) prospective for the geological storage of carbon dioxide (CO₂). Their CO₂ storage capacities were estimated recently with different levels of reliability. Petrophysical, geophysical, mineralogical and geochemical parameters of reservoir rocks represented by quartz sandstones of the Deimena Formation of Middle Cambrian in two wells and properties of Silurian and Ordovician cap rocks were additionally studied and interpreted in the present contribution. Extended methodology on rock measurements and estimation of conservative and optimistic storage capacity are presented. Uncertainties and risks of CO₂ storage in the offshore structure E6 estimated as the most prospective for CO₂ geological storage in the Baltic Region, and the largest among all onshore and offshore structures studied in Latvia, were discussed. We re-estimated the previous optimistic capacity of the E6 structure (265–630 Mt) to 251–602 Mt. Considering fault system within the E6 structure we estimated capacity of two compartments of the reservoir separately (E6-A and E6-B). Estimated by the optimistic approach CO₂ storage capacity of the E6-A part was 243–582 Mt (mean 365 Mt) and E6-B part 8–20 Mt (mean 12 Mt). Conservative capacity was 97–233 Mt (mean 146 Mt) in the E6-A, and 4–10 Mt (mean 6 Mt) in the E6-B. The conservative average capacity of the E6-B part was in the same range as this capacity in the E7 structure (6 and 7 Mt respectively). The total capacity of the two structures E6 and E7, estimated using the optimistic approach was on average 411 Mt, and using the conservative approach, 159 Mt.

Keywords: carbon dioxide, underground storage, offshore, reservoir rocks, sedimentary rocks, sandstone, physical properties, chemical composition, mineral composition, Latvia

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1. Introduction

Previous studies reported extremely high CO₂ emissions per capita in Estonia and need of carbon capture and storage technology (CCS) implementation to reduce the greenhouse gas effect and the Earth's climate change (Sliupa et al., 2008; Shogenova et al., 2009a, b, 2011a, b; Shogenov et al., 2013). According to these studies Estonia has unfavourable for CO₂ geological storage (CGS) conditions (shallow sedimentary basin and potable water available in all known aquifers) and storage capacity of Lithuanian geological structures was estimated as insufficient, due to small size of the structures (Fig. 1). The most suitable for CGS in the Eastern Baltic region (Estonia, Latvia and Lithuania) are 16 Cambrian onshore and 16 offshore deep anticline geological structures in Latvia. All the prospective Latvian structures are represented by uplifted Cambrian reservoir sandstones covered by Lower

Ordovician clayey carbonate rocks. In this study we focused on more detailed investigation of two offshore structures E6 and E7 (Fig. 2), which were briefly described in Shogenov et al., (2013). We expanded description of methods, measured petrophysical, geochemical and mineralogical properties of reservoir rocks, improved and clarified estimation of CO₂ storage capacity in the E6 structure.

2. Data and Methods

Two wells, E6-1/84 and E7-1/82, drilled in the Latvian offshore structures E6 and E7 respectively, were studied. Twelve samples from the Deimena Formation of Middle Cambrian sandstone reservoir were taken from two drill cores stored in the Latvian Environmental, Geological and Meteorological Centre (LEGMC) (Fig. 3). We interpreted an available seismic section of the E6 structure and,

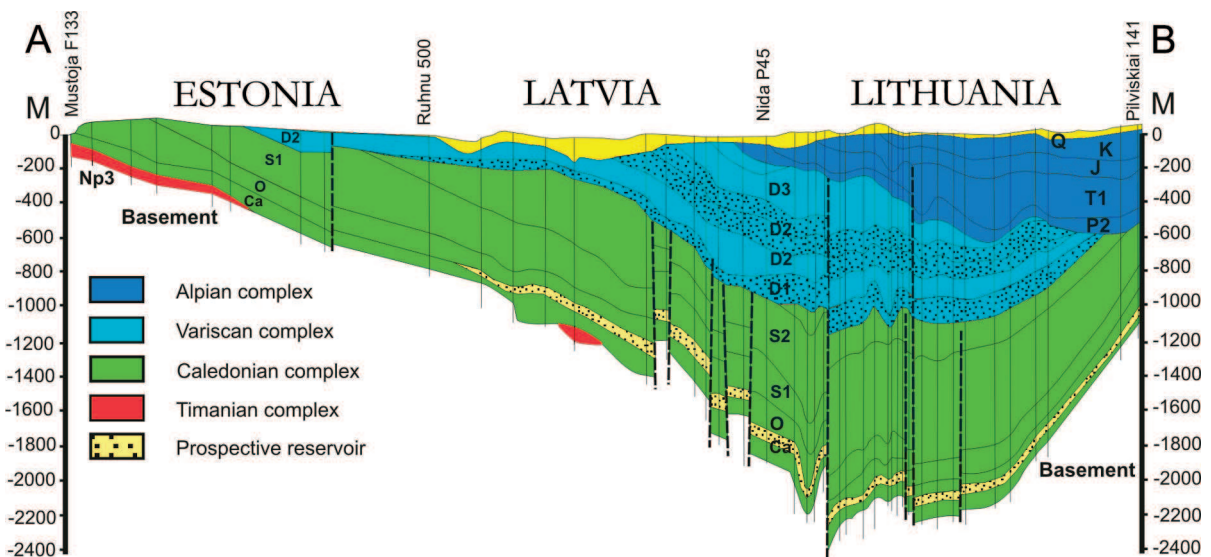


Fig. 1. Geological cross section across Estonia, Latvia and Lithuania. Cross section line A-B is shown on Fig. 2a. Major aquifers are indicated by dots. Dotted vertical lines show faults. The cross section clearly indicates that Estonia is out of the recommended depth frames for CGS (minimum recommended depth for CGS is 800 m). Devonian structures are unsuitable for CGS due to absence of impermeable cap rock formation that must overlay the reservoir. The size of Lithuanian Cambrian sandstone structures is too small for industrial scale. A number of structural uplifts in the Cambrian rocks bounded by faults are prospective reservoirs for CGS in Latvia. 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, respectively; P2 – Middle Permian; T1 – Lower Triassic; J – Jurassic; K – Cretaceous; Q – Quaternary (modified from Shogenova et al., 2009a).

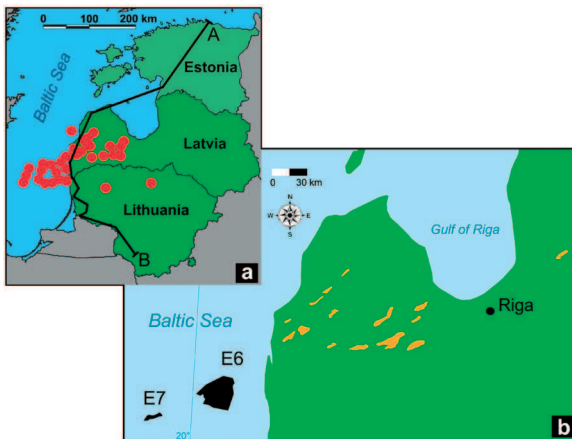


Fig. 2. (a) Approximate location of 16 onshore and 16 offshore Latvian structures in the Cambrian aquifer prospective for CGS (CO₂ storage potential exceeding 2 Mt), shown by red circles. Black line A-B represents geological cross section shown on Fig. 1. (b) 16 onshore (orange) and 2 studied offshore (E6 and E7) structures (black) in Latvia (maps built using ArcGis 9.2 software).

using structural maps of the E6 reservoir and cap rock top and cross section of the well E6-1/84, the geological cross section of the E6 structure was constructed (Fig. 4).

Two unpublished exploration reports (Babuke et al., 1983; Andrushenko et al., 1985), stored in the LEGMC, were used. According to these reports, open or effective porosity (W_{ef}) in the studied samples was estimated by saturation method (Zdanov, 1981). Permeability (K_{gas}) was determined when passing gas through the samples using the “GK-5” apparatus. More detailed description of K_{gas} measurements is given in Shogenova et al. (2009a). P-wave acoustic velocities of dry rock samples were measured with “DUK-20” equipment (100 KHz). Velocities were measured in two directions (X and Y) to consider anisotropy. Shogenov et al. (2013) reported petrophysical properties of new samples from reservoirs of the E6 and E7 structures, which were determined and compared to old data. More detailed description of petrophysical methods is presented here.

Helium density, helium porosity, gas permeability and acoustic wave velocities were measured in the petrophysical laboratory of IFP Energies nouvelles

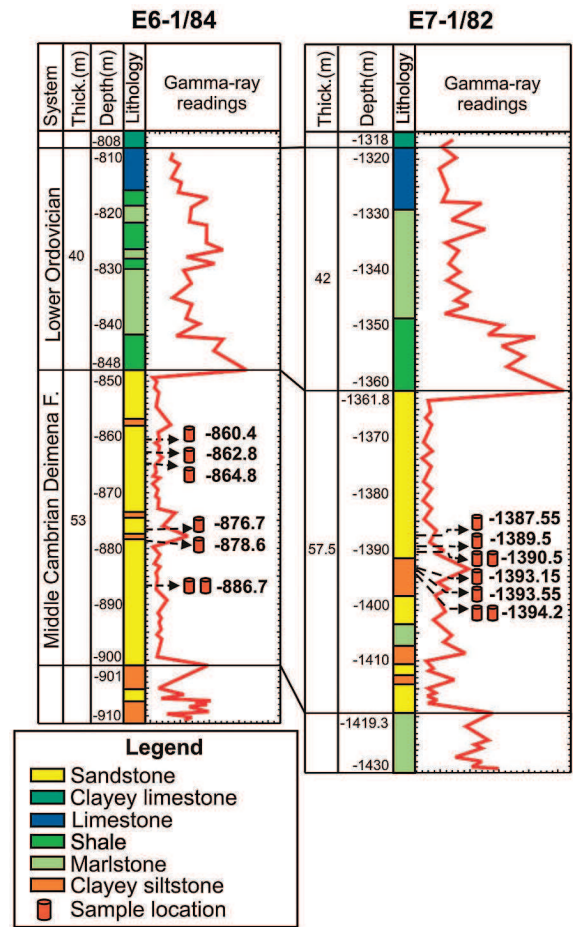


Fig. 3. Correlation of the E6 and E7 offshore structures based on drill core data (E6-1/84 and E7-1/82), focusing on the sandstone reservoir of the Deimena Formation and Lower Ordovician cap rocks. Location and depth of the studied samples are indicated by red cylinders. Gamma-ray readings were digitized from analogue gamma-ray logging data.

(IFPEN) following the American Petroleum Institute recommendations (American Petroleum Institute, 1998). Various rock properties were determined on 11 samples with 25 mm diameter and 11–27 mm height. After drying of samples the solid volume (V_s) was calculated by gas displacement helium pycnometer AccuPyc 1330 (Micrometrics). Using sample weight (m), the grain or matrix density was calculated

$$\rho_g = \frac{m}{V_s}, \tag{1}$$

Table 1. Studied parameters of the Middle Cambrian sandstones of the Deimena Formation.

Structure	E6 offshore structure				E7 offshore structure			
	Min	Max	Mean	N	Min	Max	Mean	N
Grain density, kg/m ³ estimated *	2630	2730	2690	12	2600	2930	2670	56
Grain density, kg/m ³ measured	2700	2730	2720	4	2670	2750	2700	7
Bulk density (dry), kg/m ³ estimated *	1810	2340	2090	45	2250	2940	2360	56
Bulk density (dry), kg/m ³ measured	1810	2170	2030	4	2310	2410	2370	7
Porosity, % estimated *	14	33.5	21	45	5	23	12	56
Porosity, % measured	21	33.5	25	4	9.5	14	12	7
Permeability, mD estimated *	10	440	160	34	0.13	170	40	52
Permeability, mD measured	290	440	380	3	0.13	70	20	7
P _w velocity (dry), m/s estimated *	1750	2850	2240	31	2130	3580	2920	15
P _w velocity (dry), m/s measured	2380	2380	2380	1	2130	3580	2815	6
S _w velocity, m/s measured	-	-	-	-	1725	2230	2050	3
XRF analysis, %								
SiO ₂	95	98	97	6	87	99	95	6
Al ₂ O ₃	0.2	1.9	0.6	6	0.3	5.3	1.8	6
Fe ₂ O ₃ total	0.06	0.6	0.2	6	0.06	1.9	0.6	6
K ₂ O	0.07	0.3	0.14	6	0.03	0.9	0.3	6
Na ₂ O	<0.01	0.04	0.03	6	<0.01	0.1	0.05	6
MnO	<0.01	<0.01	<0.01	6	<0.01	0.06	0.03	6
TiO ₂	0.09	0.18	0.13	6	0.06	0.5	0.23	6
P ₂ O ₅	<0.01	0.01	0.01	6	<0.01	0.04	0.02	6
Ba	0.07	0.28	0.16	6	<0.01	0.06	0.03	6
Titration method, %								
CaO	0.9	1.1	1.05	6	0.9	1.5	1.1	6
MgO	0.24	0.65	0.39	6	0.24	0.65	0.44	6
Gravimetric method, %								
Insoluble Residue	96.3	98.5	97.3	6	93.6	98.6	96.4	6

Chemical oxides measured in %: SiO₂, Al₂O₃, Fe₂O₃, K₂O, Na₂O, MnO, TiO₂, P₂O₅ and Ba by XRF, CaO and MgO by titration and insoluble residue by gravimetric methods. Min – minimum, max – maximum and mean – average values, N – number of samples.

* estimated rock properties were averaged from measured and reported data.

Table 2. Physical parameters of the Latvian offshore structural traps.

Structure	Reservoir parameters								CO ₂ storage capacity, Mt					
	Depth of top, m	Thickness, m	Trap area, km ²	Salinity, g/l	Pressure, mPa	T, °C	CO ₂ density, kg/m ³	S _{ef} Opt./Cons., %	Optimistic estimates			Conservative estimates		
									Min	Max	Mean	Min	Max	Mean
E6-A	848	53	553	99	9.3	36	658	10/4	243	582	365	97	233	146
E6-B	848	53	47	99	9.3	36	658	4/2	8	20	12	4	10	6
E6 total	848	53	600	99	9.3	36	658	10; 4/4; 2	251	602	377	101	243	152
E7	1362	58	43	125	14.7	46	727	20/4	14	66	34	3	13	7
Total CO ₂ storage capacity of E6 and E7, Mt									265	668	411	104	256	159

The S_{ef} Opt./Cons. is a storage efficiency factor used for optimistic (Opt.) and conservative (Cons.) capacity calculation.

investigated using X-ray fluorescence analysis (XRF), X-ray diffraction (XRD), chemical analysis using gravimetric and titration methods, and transmission electron microscope (TEM) and scanning electron microscope (SEM) studies. The XRF and XRD analyses were performed in the Acme Analytical Laboratories Ltd. (Vancouver, <http://acmelab.com>), using the pressed pellet method for sample preparation. The SEM and TEM studies were conducted in the Institute of Geology at Tallinn University of Technology (IGTUT) with a Zeiss EVO MA 15 scanning electron microscope, equipped with an energy dispersive spectrometer (EDS) INCA x-act (Oxford Instruments Plc) and ZEISS light electron microscope AxiosKop 40, respectively (Shogenov et al., 2013), gravimetric and titration analyses were made in the IGTUT (Shogenova et al., 2009b).

The theoretical storage capacity of the structures was estimated using a well-known formula for estimation of the capacity of a structural trap (Bachu et al., 2007):

$$M_{\text{CO}_2\text{t}} = A \times h \times NG \times \varphi \times \rho_{\text{CO}_2\text{r}} \times S_{\text{ef}}, \quad (6)$$

where $M_{\text{CO}_2\text{t}}$ 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 (m), 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 (%), $\rho_{\text{CO}_2\text{r}}$ is the in situ CO_2 density in reservoir conditions (kg/m^3), S_{ef} is the storage efficiency factor (for the trap volume, %). CO_2 storage efficiency factor is the volume of CO_2 that could be stored in reservoir per unit volume of original fluids in place. In our previous study we used a different S_{ef} for each structure based on its reservoir properties and employed different methods to estimate these factors (Shogenov et al., 2013). Following Bachu et al., (2007), the efficiency factors 10 % and 20 % in the E6 and E7 offshore structures were estimated respectively. Bachu et al., (2007) proposed simplified model to estimate S_{ef} for open and semi-closed aquifers according the stratigraphic limitations in the connectivity between the trapped aquifer volume and the bulk aquifer volume and quality of reservoirs. Quality of reservoir depends on its petrophysical parameters (porosity and permeability). According to Bachu et al., (2007) and Vangkilde-Pedersen et al., (2009) S_{ef} of high quality reservoir limited by faults on two sides is 20 % and on three sides is 10 %. In Shogenov et al., (2013) we termed this

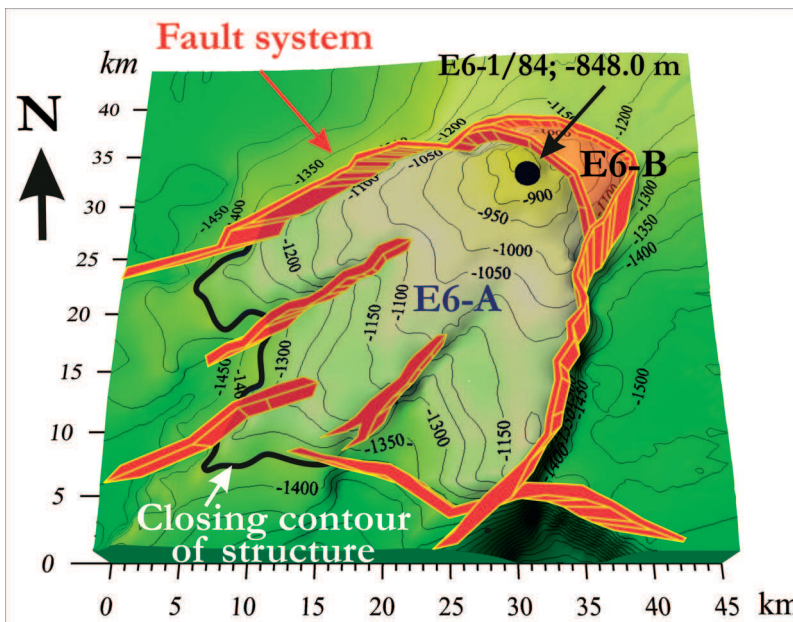


Fig. 5. 3D geological model of the top of the Deimena Formation in the E6 structure with the estimated closing contour of the structure (black contour is -1350 m). Faults bordering the structure are shown by a red wall. Location of the well is shown by a black circle with the depth of the top of the Deimena Formation (-848 m). Location of compartments E6-A and E6-B is indicated by red and green circle respectively (modified from Shogenov et al., 2013).

approach as “*optimistic*” due to the higher values of the factors in comparison with subsequent results obtained by other method. In this study we used the same optimistic S_{ef} for E7 structure (20 %), but we consider the E6 structure to be consisting of two different compartments divided by inner fault. We defined a bigger southern part as E6-A, and a smaller northern part as E6-B (Fig. 5). We determined the efficiency factors of 10 % and 4 % in the optimistic approach for the E6-A and E6-B respectively. The E6-A is limited by faults on three sides and the E6-B on four sides. High quality reservoirs bounded on all sides have S_{ef} 3–5 % (Vangkilde-Pedersen et al., 2009). Based on the US Department of Energy report (US DOE, 2008), we decided to lower and round the values of S_{ef} for the so-called “*conservative*” estimation approach (Shogenov et al., 2013). Obtained by US DOE, using Monte Carlo simulation, a range of S_{ef} values are between 1 % and 4 % for deep saline aquifers for a 15 to 85 % confidence range. The efficiency factor of 4 % was selected for the E6-A and E7 structures and 2 % for the E6-B in this simplified estimation model, which did not consider pressure change and compressibility within the reservoir due to CO₂ injection (van der Meer & Egberts, 2008). Optimistic and conservative M_{CO_2r} were calculated with minimum, maximum and average values (min-max/mean) of porosity determined using measured and reported data (Tables 1, 2). “Min-max/mean” approach was involved due to uncertainties related to lack of available experimental data (only one well within each structure). The average net to gross ratio was recorded from gamma-ray log readings (90 % in the E6, 80 % in the E7; Fig. 3).

The ρ_{CO_2r} value, which depends on in situ reservoir pressure and temperature, was estimated using a graph of the supercritical state of CO₂ under in situ conditions (Bachu, 2003). All measured laboratory data were compared with old exploration data for quality control (Figs. 6, 11). Using the reported and measured data, we estimated minimum, maximum and average values of physical properties for each structure (Shogenov et al., 2013).

All depths in our study are shown in meters below sea level.

3. Offshore structure E6

3.1 Geological background

The E6 offshore structure is already reported in our recent study as the largest suitable trapping structure offshore Latvia. It was explored in 1984 only by one well E6-1/84 (depth 1068 m), located 37 km from coast of Latvia (Shogenov et al., 2013). The structure is represented by uplifted Middle Cambrian 53 m thick reservoir rocks, covered by 40 m thick Lower Ordovician clayey cap rocks. The reservoir is overlain by Ordovician and Silurian (in total 266 m thick) clayey carbonate rocks and Devonian siliciclastic and carbonate rocks (Fig. 4). Reservoir quartz sandstones are fractured and all the E6 structure is bounded by faults on three sides. In addition the inner fault divided the E6 structure into two compartments, E6-A and E6-B (Fig. 5). We assumed that the E6-A and the E6-B are separated by the fault, which will prevent CO₂ move from one part to another during injection, and drilling of additional well in the part E6-B will be needed.

Upper part of the Ordovician succession is represented by 10.5 m thick oil-bearing limestone reservoir layer. Oil deposits are small and not significant for industrial use. The temperature within the reservoir is 36 °C, salinity of the Cambrian aquifer is 99 g/l (Table 2).

3.2 Petrophysical properties

The Deimena Formation of Middle Cambrian in the E6 structure could be subdivided into three depth intervals with slightly different petrophysical rock properties. Changes in reservoir properties are clearly reflected on the gamma-ray log and on porosity-permeability plots (Figs. 3, 6).

The uppermost interval (848–876 m) is characterized by very fine to medium-grained sandstones. Oil impregnation ranges from weak irregular to strong regular. The reservoir properties of sandstones of this interval were earlier reported as good: porosity 14–24 % (mean 21 %), permeability 10–300 mD (mean 140 mD), P_w of

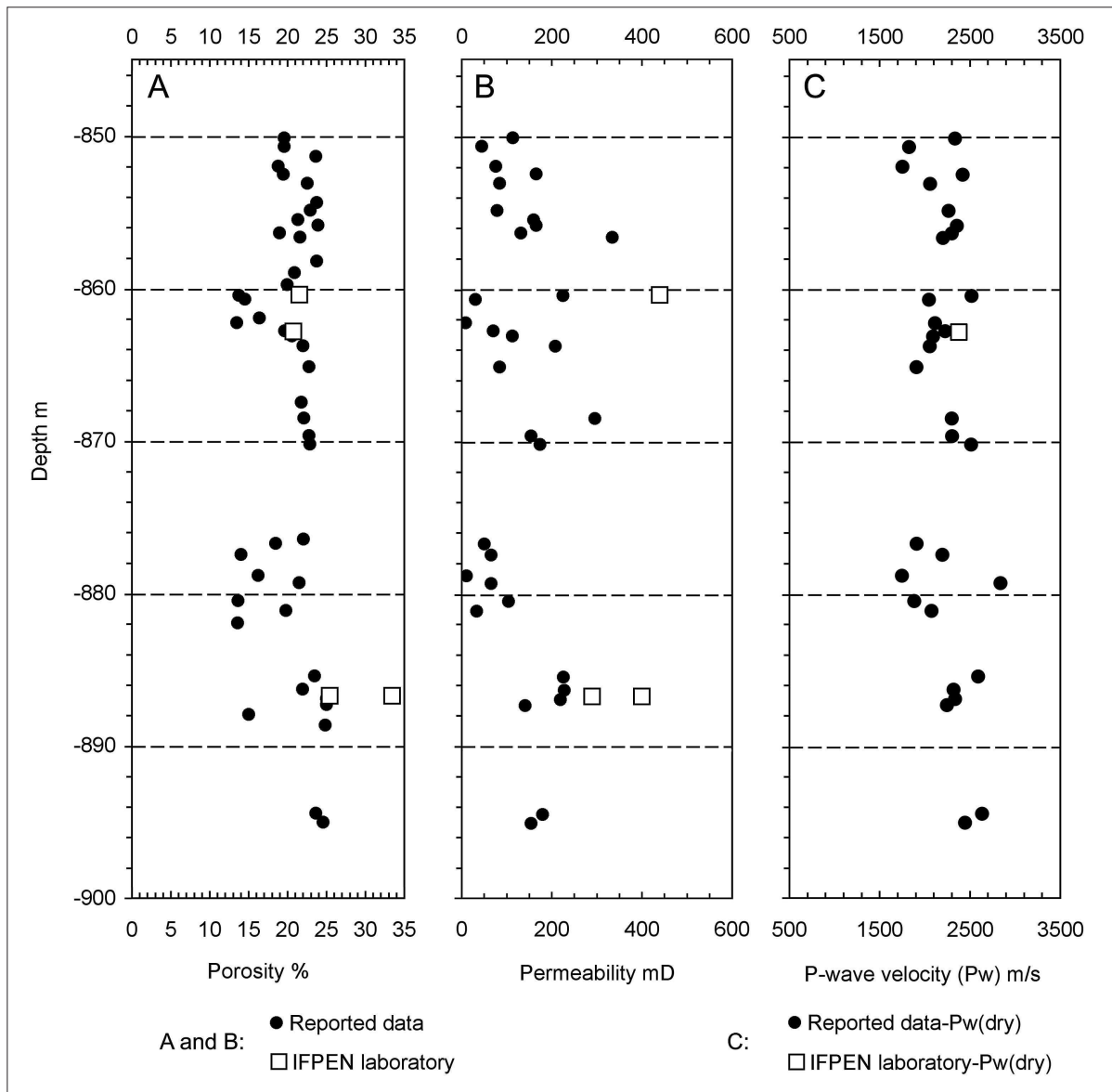


Fig. 6. Comparison plots of porosity, permeability and P-wave velocity versus depth of the measured samples (white squares) with the old reported data (black coloured figures) in the well E6-1/84 (modified from Shogenov et al., 2013).

dry samples 1750–2530 m/s (mean 2190 m/s), P_w of wet samples 1150–2440 m/s (mean 1800 m/s) (Andrushenko et al., 1985). Recently measured porosity (21–22 %) and P_w velocity of dry samples (2383 m/s) were in the range of the earlier data but new permeability was higher (440 mD) (Fig. 6, Shogenov et al., 2013).

The core interval 876–885 m is represented by very fine-grained silty sandstones interbedded by

silty clays. Oil impregnation is weak and irregular. Earlier the following characteristics have been reported: porosity 13–22 % (mean 17 %), permeability 10–100 mD (mean 55 mD), P_w of dry samples 1750–2850 m/s (mean 2110 m/s), P_w of wet samples 2120–2620 m/s (mean 2345 m/s). The reservoir properties of this interval are lower than in the upper level because of silty admixture in the rocks (about 30 % of reported samples), clayey

interlayers (no more than 5 cm) and poor sorting of the material.

The lower part of the formation (885–901 m) has regular but weak oil impregnation due to very well sorted sandstones and low clay content. The rocks are mostly massive, loosely cemented, strongly fractured and with very good reservoir properties: porosity 22–25 % (mean 24 %), permeability 140–230 mD (mean 190 mD), P_w of dry samples 2251–2643 m/s (mean 2435 m/s) (Andrushenko et al., 1985). New data on both porosity (25–33 %) and permeability (290–400 mD) were in the upper range of the old data or higher (Fig. 6, Shogenov et al., 2013).

Recently measured porosity of all samples from the well E6-1/84 was 21.5–33.5 % and gas permeability 290–440 mD. P_w of dry samples could be measured on only one sample, E6-862.8 m (2383 m/s). The properties of the E6 structure, estimated on the basis of reported and measured data, are as follows: total porosity 14–33.5 % (mean 21 %), permeability 10–440 mD (mean 180 mD), range of P_w velocity for dry samples 1750–2850 m/s (mean 2240 m/s) (Fig. 6, Table 1, Shogenov et al., 2013).

According to the classification of clastic oil and gas reservoirs by Hanin (1965), the reservoir rocks of the E6 structure are related to the 3rd and 4th classes of reservoir rocks (3rd class has permeability of 100–500 mD, 4th class permeability 10–100 mD). The residual water saturation of the 3rd class rocks is below 54.9 %, of the 4th class rocks more than 60 %.

Reported porosity and permeability of Upper Ordovician oil-bearing limestones are in the range of 10–23.5 % (mean 18 %) and 0.2–24 mD (mean 6 mD) respectively. Petrophysical measurements of other parts of Ordovician and Silurian cap rocks were not presented in the E6 exploration report. According to E7 report (Babuke et al., 1983) and reported measurements of more than 2000 samples from Baltic sedimentary basin (Shogenova et al., 2010) average porosity and permeability of Lower Ordovician (1) shales are 3 % and 0.001 mD respectively; (2) marlstones 3 % and 0.15 mD, respectively; (3) limestones 3 % and 6 mD respectively. Very few measurements of properties

of overlain Silurian rocks samples of the studied area are available in publications.

3.3 Chemical and mineralogical composition

Essentially pure sandstone samples (Table 1) studied from the E6 structure showed good interparticle and sometimes intraparticle open porosity (21–33.5 %). These sandstones include 95–98 % SiO₂ and 2–5 % other oxides, indicating clay (Al₂O₃ and TiO₂) and carbonate (CaO and MgO) cementation, and potassium feldspar admixture (K₂O) (Table 1, Fig. 7). Using SEM analyses accessory minerals were found in the cement matrix of the Deimena sandstone (iron sulphate, barite, anatase and brookite). However, cement content in the studied sample is insignificant (about 2–5 %). The results of XRD analyses supported the data obtained by XRF, chemical and SEM analyses. In general, sandstone samples from the E6 structure are considered as “high-quality” reservoir rocks (Shogenov et al., 2013).

3.4 CO₂ storage capacity

Shogenov et al. (2013) increased the closing contour of the E6 structure and determined it by the top depth contour of 1350 m (Fig. 5). The closing contour, reported by the LEGMC, was at 950 m (http://mapx.map.vgd.gov.lv/geo3/VGD_OIL_PAGE/). The line 76033 of the cross section, built on the basis of seismic data, crosses the Deimena Formation at a depth of 950 m. A propagation of a slope within the Deimena Formation could be clearly detected between the lines 76033 and Line1 (Fig. 4). We took into account depth range of the Deimena Formation and structural uplift within the E6 and fault system that separate the E6 structure from environing deposit surfaces. The total area of the structure is 600 km². With the 1350 m closure of the reservoir top, an approximate area of the larger part of the structure E6-A is 553 km², while the smaller part E6-B is 47 km². The thickness of the reservoir in the well is 53 m. The efficiency factor was taken to be 10 % (E6-A) and 4 % (E6-B) for

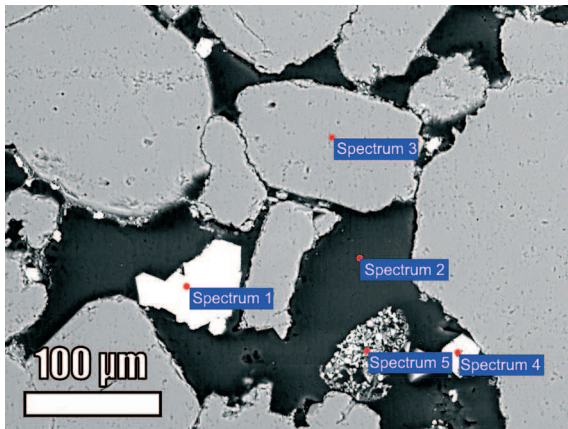


Fig. 7. SEM microphotograph of a thin section of the fine-grained porous (26–33 %) Deimena sandstone sample from the E6 structure, depth 886.7 m, and an example of SEM energy-dispersive x-ray spectroscopy (EDX) analyses (all results in weight %). The chemical composition of the sample is 97.4 % Si_2O , 0.3 % Al_2O_3 by XRF, and 1.1 % CaO and 0.25 % MgO by titration method. The white angular grain pointed by red called “Spectrum 1”, showing the content of Fe and S, is interpreted as iron sulphate. The black area (Spectrum 2) is porous space. Spectrum 3, located in grey subrounded to subangular grains (SiO_2), is quartz. The angular white grain analysed in point 4 with 33 % TiO_2 content (Spectrum 4) and the conglomeratic subrounded grain studied with 37 % TiO_2 in Spectrum 5 were interpreted as anatase and/or brookite accessory minerals.

Spectrum	C	Al	Si	P	S	Cl	Ca	Ti	Fe	Zr	O
Spectrum 1	8	-	2.6	-	18	-	-	-	15	0.94	56
Spectrum 2	25	-	4	-	0.08	0.07	-	0.09	0.07	-	71
Spectrum 3	10	-	29	-	-	-	-	-	-	-	60.6
Spectrum 4	8	0.6	6	-	-	-	-	33	0.18	-	51.7
Spectrum 5	-	3.4	11	2	0.5	-	0.5	37	0.6	-	44.5

the “optimistic” approach (Bachu et al., 2007) and 4 % (E6-A) and 2 % (E6-B) for the “conservative” approach (US DOE, 2008). In our previous study the optimistic CO_2 storage capacity of the E6 structure was estimated with efficiency factor 10 % (Shogenov et al., 2013). The NG was estimated as 90 % according to gamma-ray log data (Fig. 3). The value of ρ_{CO_2} was 658 kg/m^3 , corresponding to a depth of 848 m and temperature 36 °C. The estimated minimum, maximum and average porosities of 14–33.5 % (mean 21 %) were used for calculation (Table 1). Estimated earlier theoretical CO_2 storage capacity of the E6 structure was 265–630 Mt (mean 395 Mt) based on the optimistic approach, and 105–250 Mt (mean 160 Mt) based on the conservative approach (Shogenov et al., 2013). In this study we reduced the optimistic storage capacity of the entire structure to 251–602 Mt (mean 377 Mt) (Table 2). We estimated the theoretical optimistic and conservative CO_2 storage capacity of two split parts of the reservoir separately. Based on the optimistic approach CO_2 storage capacity of the E6-A part was 243–582 Mt (mean

365 Mt) and E6-B part 8–20 Mt (mean 12 Mt). Conservative capacity of the E6-A was 97–233 Mt (mean 146 Mt) and capacity of the E6-B part was 4–10 Mt (mean 6 Mt).

4. Offshore structure E7

4.1 Geological background

The E7 structure is a brachyanticline fold within the Deimena Formation, stretching from NE to SW and bounded by faults at two sides (north and east) (Fig. 8). It was explored in 1982 only by one well E7-1/82 (depth 1623 m) located 85 km from the coast of Latvia (Shogenov et al., 2013). The structure is represented by uplifted Middle Cambrian 58 m thick reservoir rocks covered by 42 m thick Lower Ordovician clayey cap rocks (Fig. 3). The reservoir is overlain by Ordovician and Silurian (in total 322 m thick) clayey carbonate rocks and Devonian siliciclastic and carbonate rocks. The temperature within the reservoir is 46 °C, salinity of the Cambrian aquifer is 125 g/l (Table 2).

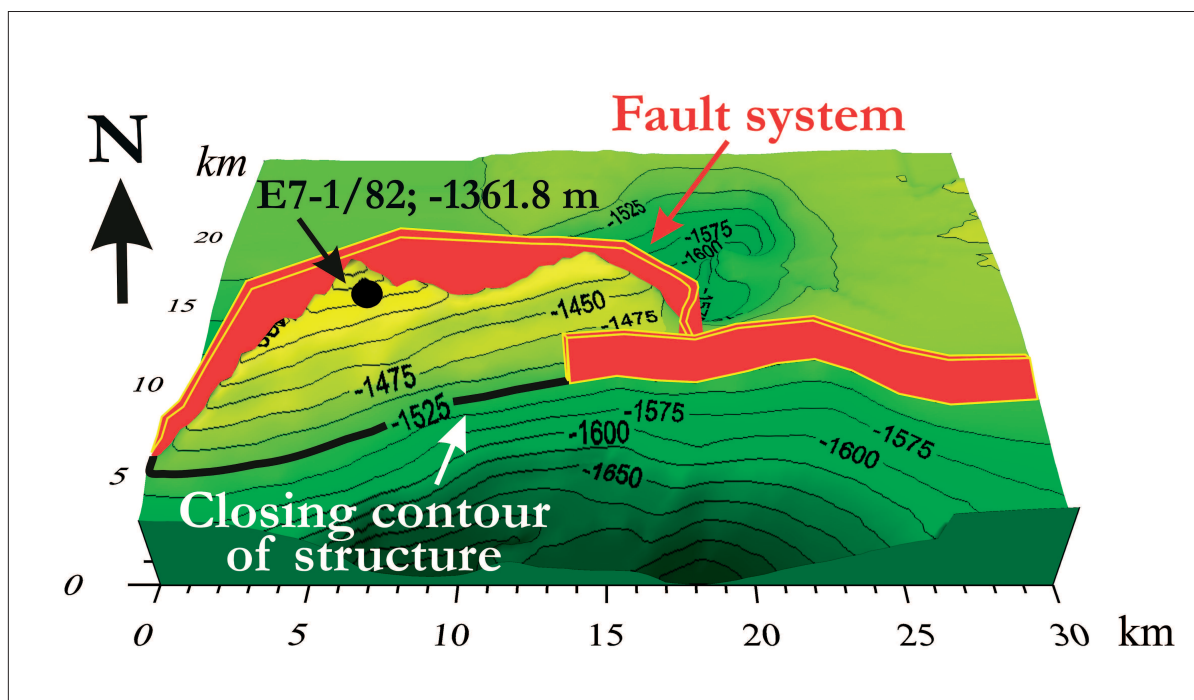


Fig. 8. 3D geological model of the top of the Deimena Formation in the E7 structure with the estimated closing contour of the structure (black contour -1525 m). Faults bordering the structure are shown by a red wall. Location of the well is shown by a black circle with the depth of the top of the formation (-1361.8 m) (modified from Shogenov et al., 2013).

4.2 Petrophysical properties

According to the reported in Babuke et al., (1983) data, sandstones from the E7 drill core have relatively good reservoir properties: porosity 5–23 % (mean 12 %), permeability 0.2–170 mD (mean 50 mD), P_w velocity in dry samples 2200–3515 m/s (mean 2990 m/s). The average porosity of siltstones presented in the reservoir is 12 % and permeability 20 mD (Fig. 9). Recently measured P_w velocity of dry samples was 2130–3580 m/s (mean 2814 m/s), S_w velocity of dry samples 1725–2230 m/s (mean 2050 m/s) (Shogenov et al., 2013). Considering both the reported and measured data, the range of porosity in the E7 structure is 5–23 % (mean 12%), gas permeability 0.1–170 mD (mean 40 mD), P_w velocity of dry samples 2130–3583 m/s (mean 2920 m/s), range of S_w velocity of dry samples 1725–2230 m/s (mean 2050 m/s) (Table 1, Fig. 9). Figure 9 clearly shows that measured values are totally in the range of reported data.

Oil impregnation within the E7 reservoir was

not observed. Reservoir properties of the E7 trapping rocks are significantly lower than in the E6 sandstones. According to the classification of clastic oil and gas reservoirs by Hanin (1965), the reservoir rocks of the E7 structure are related to the 3rd, 4th and 5th classes of reservoir rocks (5th class rocks have permeability of 1–10 mD).

Average porosity and permeability of Ordovician (1) shales are 3 % and 0.001 mD respectively; (2) marlstones 7 % and 0.29 mD, respectively; (3) limestones 3 % and 0.06 mD respectively. Very few measurements of Silurian shales properties are presented in the report (Babuke et al., 1983). Several measured marlstone samples showed good porosity (7–9 %) but very low permeability (0.001 mD).

4.3 Chemical and mineralogical composition

The Deimena Formation is represented by light-grey and beige-grey fine-grained quartz sandstones

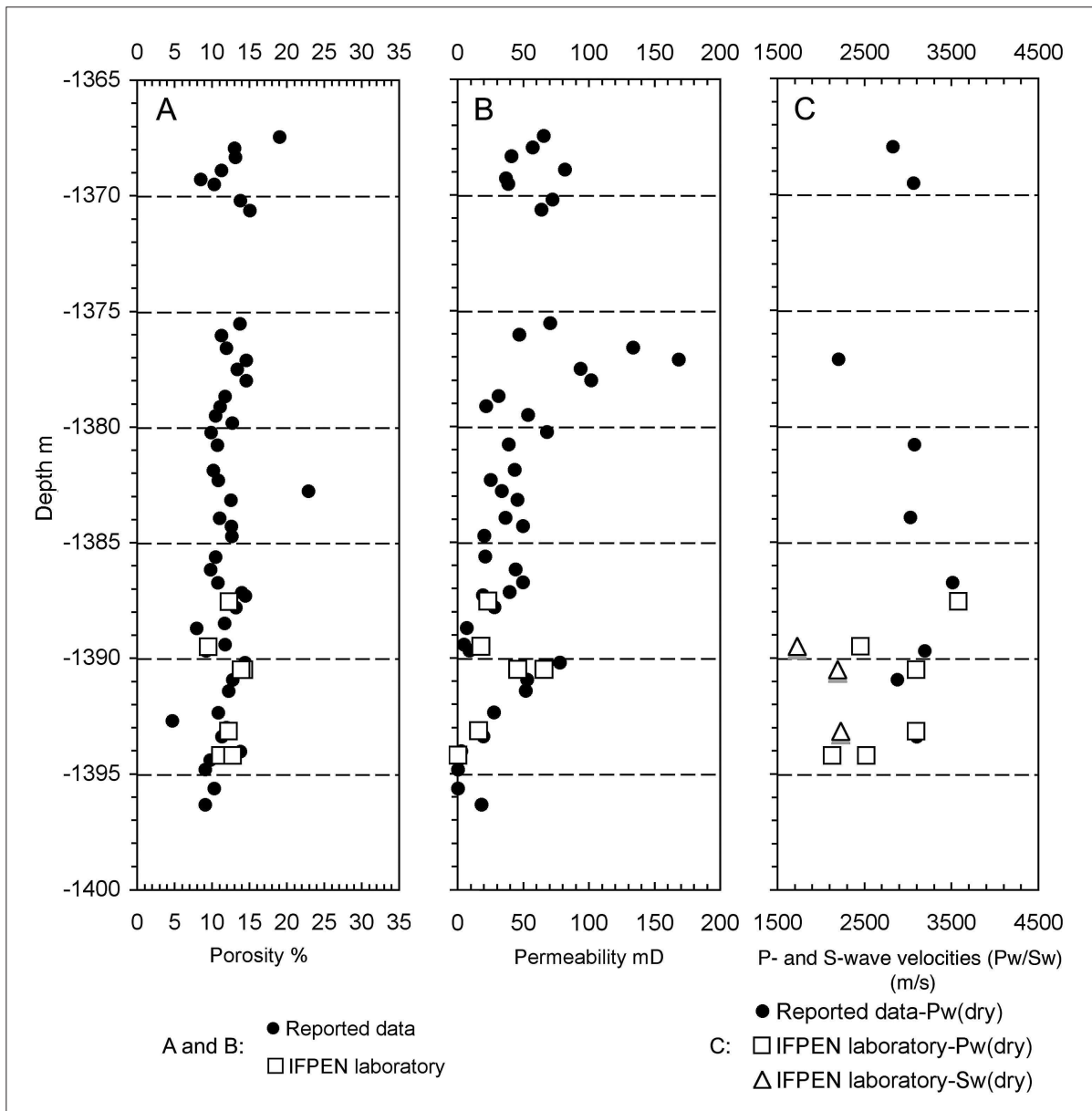


Fig. 9. Comparison plots of porosity, permeability and P-wave velocity of dry samples versus depth of the measured samples (white squares) with the old reported data (black circles) in well E7-1/82. S-wave velocity of the measured samples (white triangles) are shown on the velocity plot.

interbedded by thin layers of sandy marlstones and clayey siltstones (4–5 cm), reflected by increased readings of the gamma-ray log compared to pure sandstones (Fig. 3). Sandstones are well sorted and subrounded, partly fractured. Compared to the essentially pure quartz sandstone samples from the

E6-1/84 well, the samples from E7-1/82 showed an increase in clay content and a decrease in free pore space. Especially high clay cement content was observed in samples from the clayey siltstone interbeds. Rocks of the upper part of the Deimena Formation are mostly cemented by quartz-regenerated

cement, those of the lower part by conformation of quartz grains due to dissolution under the pressure (Shogenov et al., 2013).

Samples from the E7 structure contain on average 87–99 % SiO₂ and 1–13 % other oxides, indicating clay and carbonate cementation (Table 1). In two samples (1393.55 and 1394.2 m) the SiO₂ content was 90 and 87 %, Al₂O₃ content, indicating clay cement, 4 and 5 %, and Fe₂O₃ content 0.9 and 1.9 %, respectively. The content of carbonate minerals was lower (on average 1 % CaO and 0.4 % MgO). Samples also include admixture of feldspar and mica. Accessory minerals such as zircon, tourmaline and pyrite are present. Clay

fraction is represented by illite and kaolinite (Fig. 10).

Sandstones (depths 1389.5 and 1390.5 m), studied also by the SEM and XRD methods, showed lower porosity (14.3 and 9.5 % respectively) and higher cement content than the E6 sandstones (Fig. 10).

4.4 CO₂ storage capacity

The closing contour of the E7 reported by the LEGMC is 1450 m (http://mapx.map.vgd.gov.lv/geo3/VGD_OIL_PAGE/). According to depth range of the Deimena Formation and faults system

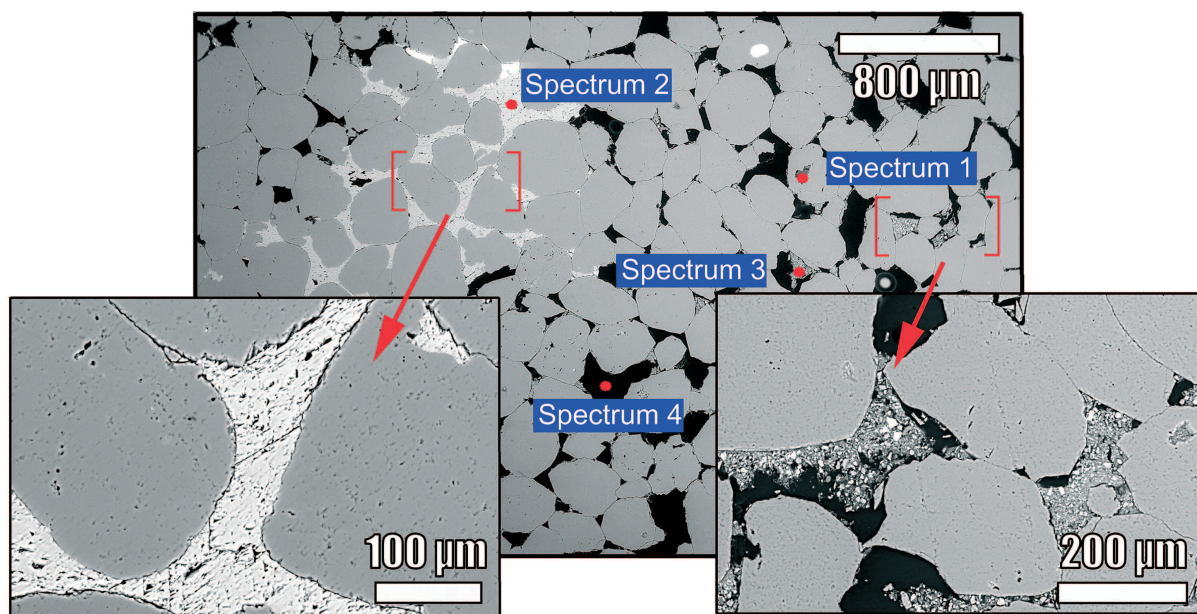


Fig. 10. SEM microphotographs of the thin section of the fine-grained porous Deimena sandstones sample in well E7/1-82 (1390.5 m) and an example of SEM energy-dispersive X-ray spectroscopy (EDX) analysis results (in weight %). Porous media studied by Spectrum 1 is partly filled by quartz cement (30 % SiO₂). White cement studied by Spectrum 2 is composed of iron-rich carbonate cementation including ankerite (15 % Ca, 5 % Mg and 8 % Fe). Some pores are filled by clay cement (4.5 % Al) and feldspar admixture (3 % K) (Spectrum 3). The black area studied by Spectrum 4 is porous media.

Spectrum	C	Mg	Al	Si	S	Cl	K	Ca	Mn	Fe	Ba	O
Spectrum 1	9.7	-	0.4	29.7	-	-	-	-	-	-	-	60
Spectrum 2	13.5	4.7	-	5	-	-	-	15	1	8	-	53
Spectrum 3	-	2	4.5	34	0.7	-	2.7	3.6	-	2.4	2.5	48
Spectrum 4	25.7	-	-	3	-	0.06	-	-	-	-	-	71.5

bounding the structure, and structural uplift within the E7 structure, we increased the boundaries of the structure and took the 1525 m depth as the closing contour of the reservoir top. In case of the 1525 m level, an approximate area of the E7 structure (43 km²) is 14 times less than that of the E6 (Shogenov et al., 2013).

The thickness of the reservoir in the well is 58 m. The efficiency factor of 20 % was taken for the “optimistic” approach (Bachu et al., 2007) and 4 % for the “conservative” approach (US DOE, 2008). The NG was found to be 80 % according to the gamma-ray log data (Fig. 3). The value of ρ_{CO_2} was taken 727 kg/m³, corresponding to a depth of 1362 m and temperature 46 °C. The estimated minimum, maximum and average porosities of 5–23 % (mean 12 %) were used for calculation (Table 1). The assessed CO₂ storage capacity of the E7 structure was 14–66 Mt (mean 34 Mt) by the optimistic approach and 3–13 Mt (mean 7 Mt) by the conservative approach (Table 2, Shogenov et al., 2013).

5. Discussion

In this study we used old exploration reports of years 1983–1985 (Babuke et al., 1983; Andrushenko et al., 1985). The quality of these reports is satisfactory, but characteristics of the E7 structure are worse than of E6. Earlier studies were made only in the frame of oil exploration. As the aims of the old and present studies are different, we lack necessary data and face uncertainties in existing information (only one well drilled in each structure, insufficient level of fault study, lack of necessary rock physical measurements, the reported values of the same parameters vary in different parts of the exploration reports, low quality of seismic map profiles). Complete seismic data on these structures were not available for this and previous (Shogenov et al., 2013) studies, which added uncertainties into the created 3D geological models and storage reservoirs quality estimates. The E6 structure contains multiple faults, and uncertainties in the fault structure could cause significant difficulties in the assessment and modelling of CO₂ storage risks. Due to fact of oil

accumulation in the Upper Ordovician limestone formation and Cambrian Deimena sandstones, and Devonian sandstones oil impregnation, the hypothesis of oil leakage from the E6 reservoir via faults could be assumed. There are two possible scenarios of the faults behaviour: (1) the faults still have open structure and (2) due to timing and geological processes the faults were locked. The origin of faults and reservoirs architecture need more detailed study, which would largely contribute to estimation of reservoirs integrity.

There are two ways to clarify these uncertainties: (1) to conduct a modern geophysical exploration in the studied structures area or (2) to make pilot CO₂ injection into the structure and monitor its behaviour. If the reservoirs are destructed and the faults have open structure, the CO₂ leakage could be determined using known monitoring methods. Seismic survey is the most effective method that has been implemented in the well-known world's largest CO₂ storage project in the Norwegian North Sea (Sleipner) for monitoring injected CO₂ plume. This method enables observation from the surface of the formation and migrating of CO₂, injected into the storage site, under impermeable layers (Chadwick et al., 2009; Hermanrud et al., 2009; Alnes et al., 2011).

Besides practical study, wide modelling possibilities are available in the field. In addition, a number of papers have been published during last years, including numerical modelling of CO₂ plume dissolution mechanisms in an aquifer (Audigane et al., 2011), CO₂ fluid flow studies and 2D/3D modelling, associated with the fault system in long and short terms (Audigane et al., 2007; Chang et al., 2008; Grimstad et al., 2009; Chadwick & Noy, 2010). The last seismic numerical modelling results represent performance of seismic techniques and methods in detection of presence, evolution, migration and leakage of CO₂ in the storage reservoir (Rossi et al., 2008; Picotti et al., 2012).

The existing fault system, interpreted by seismic data and oil impregnation of Cambrian sandstones revealed in drill core E6-1/84, would suggest two optional cases. The first case is possible leakage of the geological trap. The opposite one is that the

reservoir has good trapping mechanisms, but trapped oil in the reservoir could be lacking due to specific in situ conditions and geological history of the area. The first case is discussed by Chang et al., (2008). They developed a single-phase flow model to examine CO₂ migration along faults. The model simulated CO₂ migration from the fault into permeable layers. Reaching these layers, CO₂ continued migration along the fault above them. The developed 1D model was compared with full-physics simulations in 2D. It was concluded that although more CO₂ escapes from a deeper storage formation through a fault, less CO₂ reaches the top of the fault. Thus, attenuation can reduce the risk associated with CO₂ reaching the top of the fault (Chang et al., 2008).

However, the presence of faults does not mean that there would be an impact on security of storage. If the offset of a fault is less than the thickness of the cap rock the likelihood of providing a migration pathway through the cap rock is lower (Bentham et al., 2013). As well, faults integrity plays crucial role in reservoir security. According to available studies in the region, faults could propagate through the all cap rocks (Ordovician and Silurian) reaching Devonian sandstone layer. Nevertheless, the largest onshore Inčukalns structure with the relevant for the Baltic Basin fault offset has been successfully used for underground gas storage for many years and is applied for gas supply of Latvia, Estonia and Lithuania. This fact gives us opportunity to suggest that faults in the region could have enclosed, impermeable structure (LEGMC, 2007). The conditions of every reservoir for geological storage of different gases should be studied individually. For example properties of CO₂ and methane in deep in situ conditions could significantly vary. Migration of CO₂ via faults to depths shallower than 800 m is classified as a risk due to the properties of CO₂. In normal geothermal and pressure regimes CO₂ below 800 m is likely to be in its highly dense phase, above approximately this depth (depending on the exact pressure and temperature) the migrating CO₂ may undergo a phase change due to the decreasing pressure and temperature and become gaseous. The CO₂ would then expand and migrate faster. This

could cause a more serious leakage of CO₂ depending on the surrounding geology (Bentham et al., 2013).

Understanding of faults capacity is a key for further studies that should clarify the storage potential and integrity risk of the studied structures. As was mentioned above the pilot injection of several thousands of CO₂ could clarify this uncertainty.

Due to splitting of the E6 structure by faults into the two compartments the E6-A and the E6-B with area of 553 km² and 47 km² respectively, we propose the E6-A to be the main CO₂ storage site within the structure and the E6-B an additional reserve structure. Using the both substructures should be economic considering the location of the E6-A next to the E6-B and the common infrastructure to be used. Nevertheless, the E6-A, as a largest storage site in the region, will be an object of study in our next fluid flow and seismic numerical simulations.

6. Conclusions

Two offshore geological structures of Latvia E6 and E7 were estimated as prospective reservoirs for gas storage. These structures have structural closing contour within the Cambrian saline aquifer and are overlain by an impermeable seal. They are therefore suitable for CO₂ storage. Nevertheless, the lack of modern seismic data makes additional uncertainties of structural integrity. The Deimena Formation of Middle Cambrian is clearly indicated by low natural radioactivity on gamma-ray log readings. Clayey interbeds and siltstone layers in the reservoir can be easily determined (from 10 % to 20 % of reservoir rocks) by increased gamma-ray readings (Shogenov et al., 2013). The average net to gross ratio of the aquifer in the trap was defined by gamma-ray log readings (90 % in E6, 80 % in E7). Cap rock is represented by Ordovician and Silurian clayey carbonate sediments.

New estimated total optimistic CO₂ storage capacity in the most prospective for CGS in the Baltic Region offshore structure E6 was in the range of 251–602 Mt (average 377 Mt). However, the risk of CO₂ leakage due to uncertainties of fault system should be considered and further fault

integrity risk assessment work is required.

New re-estimated total capacity of two offshore structures E6 and E7 by the optimistic approach was 265–668 Mt (on average 411 Mt). The optimistic maximum (602 Mt) and average (377 Mt) storage potential of the E6 structure is higher and nearly the same respectively as previously reported total potential of all 16 onshore Latvian structures (400 Mt). Even its average conservative capacity (152 Mt) is the largest among all the onshore and offshore structures studied until now in Latvia.

Two split by faults compartments of the E6 structure were considered as separate substructures defined as E6-A and E6-B. Estimated theoretical CO₂ storage capacity of the E6-A was 243–582 Mt (mean 365 Mt) and E6-B part 8–20 Mt (mean 12 Mt) according to optimistic approach. Estimated conservative capacity of the E6-A was 97–233 Mt (mean 146 Mt) and of E6-B part 4–10 Mt (mean 6 Mt). Estimated area and conservative average capacity of E6-B part were in the same range as the area and conservative capacity of E7 structure (47 km² and 6 Mt in E6-B, respectively and 43 km² and 7 Mt in E-7, respectively).

This study is a basis for new 3D static geological, lithological and petrophysical numerical modelling of the E6-A substructure that will be applied in CO₂ storage fluid flow simulation. The last will be integrated into time-lapse (4D) rock physics and seismic numerical modeling.

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