Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 114 (2017) 3564 – 3571

Energy Procedia

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

3D geological and petrophysical numerical models of E6 structure for CO_2 storage in the Baltic Sea

Kazbulat Shogenov[1,]*, Edy Forlin[2], Alla Shogenova[1]

[1]*Institute of Geology, Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia*
[2]*Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante, 42/c, 34010 Sgonico, Trieste, Italy*

Abstract

Two models with different area and 3D volumetric grid size dimension of the E6 oil-bearing structure were built. The bigger model should allow visualization of complete migration of CO_2 plume within the developed 3D grid model using fluid-flow simulation (cell size 500 m). The smaller model is focused on the uppermost part of the Cambrian Series 3 Deimena Formation reservoir close to the drilled well, assuming that CO_2 injection will take place in this area. The model with a finer gridding (cell size 30 m) was adopted for seismic numerical modelling. The grid size of this in the model was reduced as much as possible to satisfy seismic modelling needs.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: 3D geological modelling, Cambrian Series 3 Deimena Formation, CO_2 geological storage, E6 structure, Baltic Sea

1. Introduction

Effective application of CO_2 Capture and Storage (CCS) technology to ensure efficient climate change abatement need estimation of reservoir properties of storage site and possible risks due to injection of CO_2 in supercritical state into the deep saline aquifer. To monitor behaviour of CO_2 plume in the deep geological trap a number of modelling routines could be applied.

* Corresponding author. Tel.: +372-55-89-001.
E-mail address: kazbulat.shogenov@ttu.ee

Peer-review under responsibility of the organizing committee of GHGT-13.
doi:10.1016/j.egypro.2017.03.1486

Previous studies show that the most prospective structures for CO_2 geological storage (CGS) in the Baltic region (Estonia, Latvia and Lithuania) are available in Latvia represented by number of onshore and offshore anticline structures [1, 2, 3, 4]. The main target is the Baltic Basin (700 km × 500 km synclinal structure), a Late Ediacaran–Phanerozoic polygenetic sedimentary basin that developed in a peri-cratonic setting in the western part of the East European Platform. It overlies the Palaeoproterozoic crystalline basement of the East European Craton [5]. Basin fill consists of Ediacaran–Lower Palaeozoic, Devonian–Carboniferous and Permian–Mesozoic successions, coinciding with what are referred to as the Caledonian, Variscan and Alpine stages of the tectonic development of the basin, respectively. These are separated by regional unconformities and overlain by a thin cover of Cenozoic deposits [6]. Freimanis and colleagues stated that several structures have been singled out in the Latvian part of the Baltic Syneclise. The Estonian–Latvian and Lithuanian monoclines are the marginal structures of the Baltic syneclise. The Liepaja depression (Fig. 1) is a distinctly asymmetrical depression (length 200 km, width up to 70 km, trough amplitude 800 m) with a gentle northern and a steep near-fault southern edge. The Liepaja–Saldus zone of highs crosses the Baltic syneclise, stretching from the Swedish offshore towards the northeast for about 400 km (Fig. 1). The width of the zone is 25–80 km. From northeast to southwest, the basement submerges from 500 to 1900 m. The Liepaja–Saldus zone is a complex system of disjunctive-plicative dislocations, the intensity of which exceeds that in other areas of the Baltic syneclise. The amplitude of uplift in the anticline structures reaches 600 m. The Gdansk–Kura depression (Fig. 1) is only represented by its northern peripheral part. The South Latvian step, about 100 km long, is a sublatitudinal tectonic block in southern Latvia. The amplitudes of boundary faults reach 400–500 m [7].

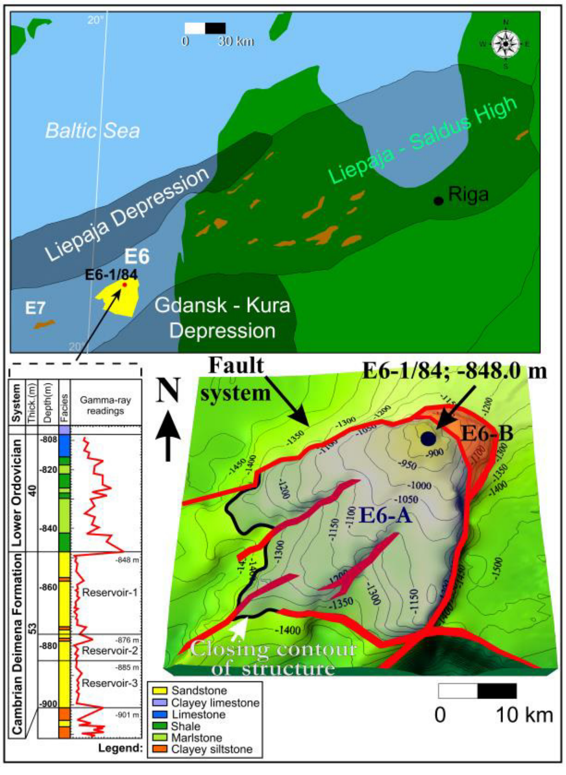

Fig. 1. Locations of Latvian onshore structures and the E7 structure offshore Lithuania (orange) prospective site for CGS (CO_2 storage potential exceeding 2 Mt) in the Cambrian aquifer, and the studied E6 structure offshore Latvia (yellow), with the location of the well, lithological cross-section and gamma-ray logging data, and the 3D geological model of the top of the Cambrian Deimena Formation of the E6 structure. Large regional structures complicating the Baltic Syneclise in the study area are shown on the map according to [7]. Estimated closing contour of the structure is indicated (black contour is –1350 m BSL). 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 BSL). Location of smaller compartment E6-B is indicated by red transparent colour (modified after [8, 9]).

The offshore E6 structure (Fig. 1) was assessed as the largest among all the studied in the Baltic Region structures. Conservative and optimistic CO_2 storage capacity of the structure was estimated in the range of 160–400 million tonnes (Mt), respectively [4, 10]. Prospective for CGS reservoir is represented by the Cambrian Series 3 Deimena Formation (848–901 m depth at the well E6-1/84) composed by dark- and light-grey, fine-grained, loosely and medium-cemented quartz oil-impregnated sandstones. The structure is an anticline fold bounded on three sides by faults. The E6 structure consists of two different compartments divided by inner fault (Fig. 1).

The total area of the structure is 600 km^2 considering the closing contour of the reservoir top located at a depth of 1350 m below sea level (BSL). An approximate area of the larger part (E6-A) of the structure is 553 km^2, while the smaller part (E6-B) is 47 km^2 (Fig. 1). The average thickness of the reservoir unit is 53 m. The E6-A was considered for the modelling. The Deimena Formation unconformably covered by 146 m thick impermeable Ordovician rocks, consisting mainly of shales, marlstones and limestones. Upper part of the Ordovician is formed by Saldus Formation carbonate rocks (10.5 m of thickness) of Porkuni Stage and represents oil deposit [4, 10].

The owner of the license for oil exploitation in the E6 structure is Danish oil company Odin Energi A/S.

2. 3D structural model

Three main surfaces were considered in the model, corresponding to stratigraphic boundaries interpreted using well logs and seismic data: (1) top of the Ordovician Formation (part of the secondary cap rock), (2) top of the reservoir–the Cambrian Series 3 Deimena Formation and (3) bottom of the reservoir. Points' sets representing geological horizons were then converted into gridded surfaces. All the obtained surfaces (faults and horizons) were edited in order to obtain a watertight configuration. After editing of the surfaces, the volumetric grid has been created. Two main zones have been defined in the model representing, respectively, (1) cap rock and (2) reservoir units. More precise internal layering within the reservoir and the primary cap rock were integrated into the model using log data from the E6-1/84 well. The layering was set up in order to increase the vertical resolution of the grid and to take the lithological and petrophysical partitioning of the reservoir into account. Thus, we could accurately populate our geological models with both lithological and petrophysical parameters (porosity and permeability). We defined five layers within the cap rock (10, 56, 44, 26 and 10 m of thickness) and also five layers within the 53 m thick reservoir (10, 3, 15, 6 and 19 m of thickness). The proportional layering method was employed in stratigraphic modelling, resulting in the grid proportional to the corresponding top and base surfaces.

The existing fault system in the E6 structure, 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 a possible leakage of the geological trap. The opposite case is that the reservoir has good trapping mechanisms, but there is no trapped oil in the reservoir due to specific in situ conditions and geological history of the area. The first case was discussed by [11]. They developed a single-phase flow model to examine CO_2 migration along faults. The model simulated CO_2 migration from the fault into permeable layers. Reaching these layers, CO_2 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 CO_2 escapes from a deeper storage formation through a fault, less CO_2 reaches the top of the fault. Thus, attenuation can reduce the risk associated with CO_2 reaching the top of the fault [11].

However, the presence of faults does not pose adverse impact on the 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 [12]. The integrity of faults also plays a crucial role in reservoir security. According to studies carried out in the region, faults can propagate through all cap rocks (Ordovician and Silurian), reaching the Devonian sandstone layer. Thereby, faults were considered to be propagating through the cap rock in the 3D geological model of the E6 structure. No transmissivity values are available for the faults in the area. The vintage seismic reflection data were insufficient for a detailed geometrical characterization of faults. Nevertheless, the largest onshore Inčukalns structure, with a structural setting comparable to E6, has been successfully used for underground gas storage for many years, serving for gas supply to Latvia, Estonia and Lithuania. This fact indicates that faults in the region may have enclosed, impermeable structure [13] and as suggested in [3], faults in the E6 structure can act as sealing surfaces.

3. Facies and petrophysical modelling

Geological lithofacies were modelled first in order to constrain the distribution of porosity and permeability in the geological model. These petrophysical properties depend both on the primary sedimentation environment and following diagenetic processes. Because of the relatively low degree of diagenetic alterations of the reservoir rocks in the E6 structure [3, 4, 14], these alterations were not considered in the model.

Stochastic modelling was applied to populate the volumetric grid with data obtained from composite log analysis, core measurements and bibliography [3, 4, 8, 9, 14, 15, 16, 17, 19]. This type of approach was applied due to lack of analytical data for this study: only one well was drilled in the structure and only one 2D seismic profile was available from the vintage oil exploration survey. Eight facies with a specific range of petrophysical properties (porosity and permeability) were identified within the model (limestone, oil-bearing limestone, shale, marlstone, sandstone-1, sandstone-2, siltstone and silty sandstone) by analysing core data (four facies for both the cap rock and reservoir) and assigned to the model (Fig. 2 b, c; 3; 4 a; Table 1). Layers 1−5 of the cap rock are mainly represented by oil-bearing limestone, shale, limestone, marlstone and shale, respectively. Reservoir layers 6−10 consist mainly of sandstone, siltstone, sandstone, silty sandstone and sandstone-2, respectively (Fig. 2 b, c; 4 a).

Table 1. The facies and the range of petrophysical properties used to populate the 3D geological static model

	Facies	Porosity (mD)			Permeability (mD)		
		min	**max**	**mean**	**min**	**max**	**mean**
Cap rock	Limestone	2	4	3	-	-	6*
	Oil-bearing limestone	10.8	23.6	18.3	0.2	24	5
	Shale	3.2	3.9	3.6	-	-	0.0001*
	Marlstone	2	4	3	-	-	0.15*
Reservoir	Sandstone-1	16.5	23.9	21	45	334	140
	Sandstone-2	21.9	33.5	25	141	400	230
	Siltstone	14.5	21.5	19	30	440	230
	Silty sandstone	13.6	21.5	17	10	104	56

* Constant data were implemented in the algorithm

In order to populate the model with facies and petrophysical properties, three modelling algorithms of Geostatistical Software Library were applied [18]: (1) *Truncated Gaussian Simulation*, (2) *Sequential Indicator Simulation* and (3) *Gaussian Random Function*. For facies distribution within the cap rock and reservoir layers the *Truncated Gaussian Simulation* and *Sequential Indicator Simulation* methods were used, respectively. The *Gaussian Random Function* simulation was applied to the porosity distribution in all formations. Constant average values reported for all cap rock facies, except for oil-bearing limestone were assigned to permeability distribution. The *Gaussian Random Function* simulation was used for permeability distribution in the reservoir facies and oil-bearing limestone of the cap rock.

4. 3D geological and petrophysical models

Two 3D geological static models were built for the E6-A compartment of the E6 oil-bearing structure (Model-1 and Model-2, Fig. 2 a, b, c) with different area and 3D volumetric grid size dimension. The bigger one (Model-1, Fig. 2 a, b; 3) should allow visualization of complete migration of CO_2 plume within the developed 3D grid model using fluid-flow simulation (cell size of 500 m x 500 m). The smaller one (Model-2, Fig. 2 a, c) is focusing on the uppermost part of the Cambrian Series 3 Deimena Formation reservoir close to the drilled well, assuming that CO_2 injection will take place in this area. The Model-2 with a finer gridding (cell size 30 m) was adopted for seismic numerical modelling purpose. We reduced grid size in the Model-2 as much as possible, to satisfy seismic modelling requirements. The Cambrian Series 3 Deimena Formation reservoir and the Ordovician primary cap rock in E6-A were modelled and populated with both lithological and petrophysical parameters (porosity and permeability). A summary of meshing data and statistics of petrophysical properties in the cap and reservoir rock implemented in the model is shown in Tables 2 and 3, respectively.

Table 2. Porosity and permeability statistics of the model of the E6 structure

	Porosity (%)						
	Min	**Max**	**Delta**	**Mean (μ)**	**Std (σ)**	**Var (σ^2)**	**Sum**
Cap rock	2	23.6	21.6	5.9	5.9	34.7	69 256
Reservoir	13.6	33.5	19.9	20.8	3.9	15.1	245 905
	Permeability [mD]						
	Min	**Max**	**Delta**	**Mean (μ)**	**Std (σ)**	**Var (σ^2)**	**Sum**
Cap rock	0.0001	24.2	24.2	2.2	4.5	20.5	25 372
Reservoir	10.2	440	429.7	168.3	107.1	11 471.7	1 986 070

Total number of cells defined in the entire property: 11800
Std – standard deviation
Var – variance
Delta=Max-Min

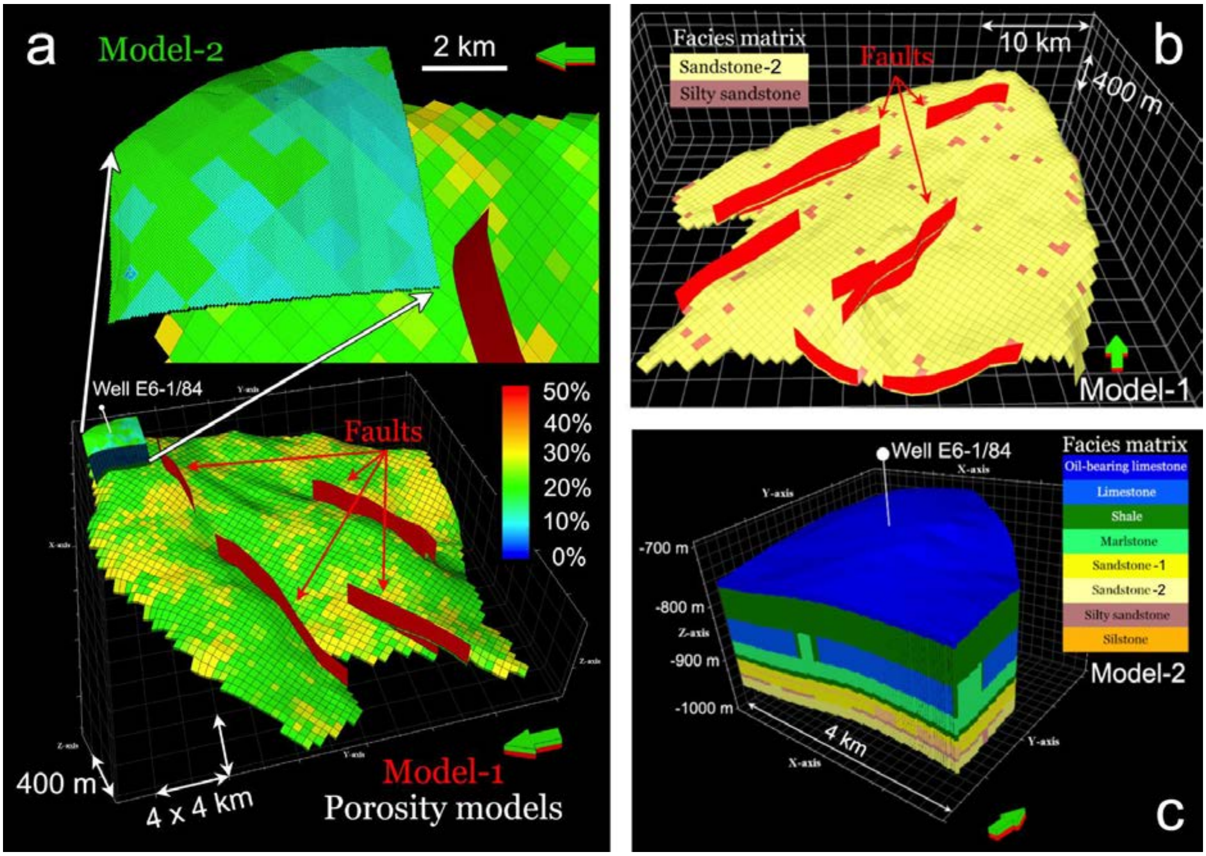

Fig. 2. 3D geological models of E6-A compartment: (a) Porosity models "Model-1" and "Model-2" together. The figure is focusing on the Model-2 (Upper layer–Oil-bearing limestone). Main faults in the Model-1 are shown; (b) Model-1. Lowermost layer (number 10) of the Deimena Sandstone-2 reservoir formation with rare clusters of silty sandstones; (c) Model-2. All layers of the Model-2 are shown. Results of simulated facies distribution from the Model-1 were downscaled and manually corrected in order to obtain a more realistic appearance according to the smaller grid size (modified after [19]).

Table 3. Volumetric grid parameters implemented in the 3D geological modelling

Model-1	Model-2
Size (X-Y-Z): 29372-26534-826 m *	Size (X-Y-Z): 4392-4254-556 m *
Depth range: 693-1519 m	Depth range: 693-1250.3 m
Cells dimension: 500 x 500 m	Cells dimension: 30 x 30 m
Cells: 67 x 59 x 10	Cells: 146 x 188 x 10
Total number of 3D cells: 39530	Total number of 3D cells: 274480
Number of faults: 8	

** Delta=Max-Min*

The reliability of geological static model depends on the amount of input data obtained during the exploration phases. Usually, modellers integrate large sets of various data into 3D numerical models: e.g. geological, structural, geophysical and borehole logging data and all measured parameters of rock samples, (e.g. [20, 21, 22, 23, 24, 25]). In our study we used a limited set of data from the vintage exploration survey [8, 14, 15, 17] and new laboratory measurements [4, 10, 14, 19]. Ideally, to provide a more realistic structural, geological, lithological and petrophysical representation of the E6 structure, additional exploration and new laboratory data are needed, including modern seismic surveys, borehole drilling, and laboratory studies of reservoir and cap rocks. Modern seismic exploration of the E6 structure was ordered in 2006 by the Danish oil company Odin Energi A/S, the owner of the license for oil exploitation in the structure, but the results are not available yet to the third parties. In many cases when the available data are scarce or irregular, an engineering software package such as Schlumberger's Petrel E&P software platform can improve the quality of the geological models. The well-known mathematical algorithms of Geostatistical Software Library [18] implemented in the Petrel platform provide a statistically justified image of the area.

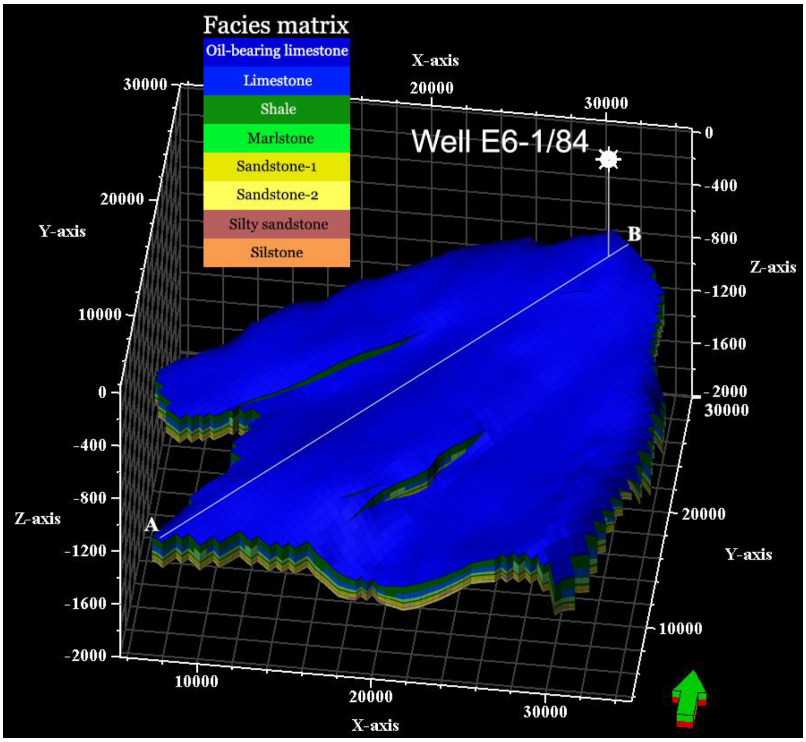

Fig. 3. 3D geological static facies model of the E6-A compartment of the E6 offshore structure with location of the well E6-1/84. All layers of the 3D model are shown. The white line A−B represents the geological cross section shown in Fig. 4 a-c (modified after [19]).

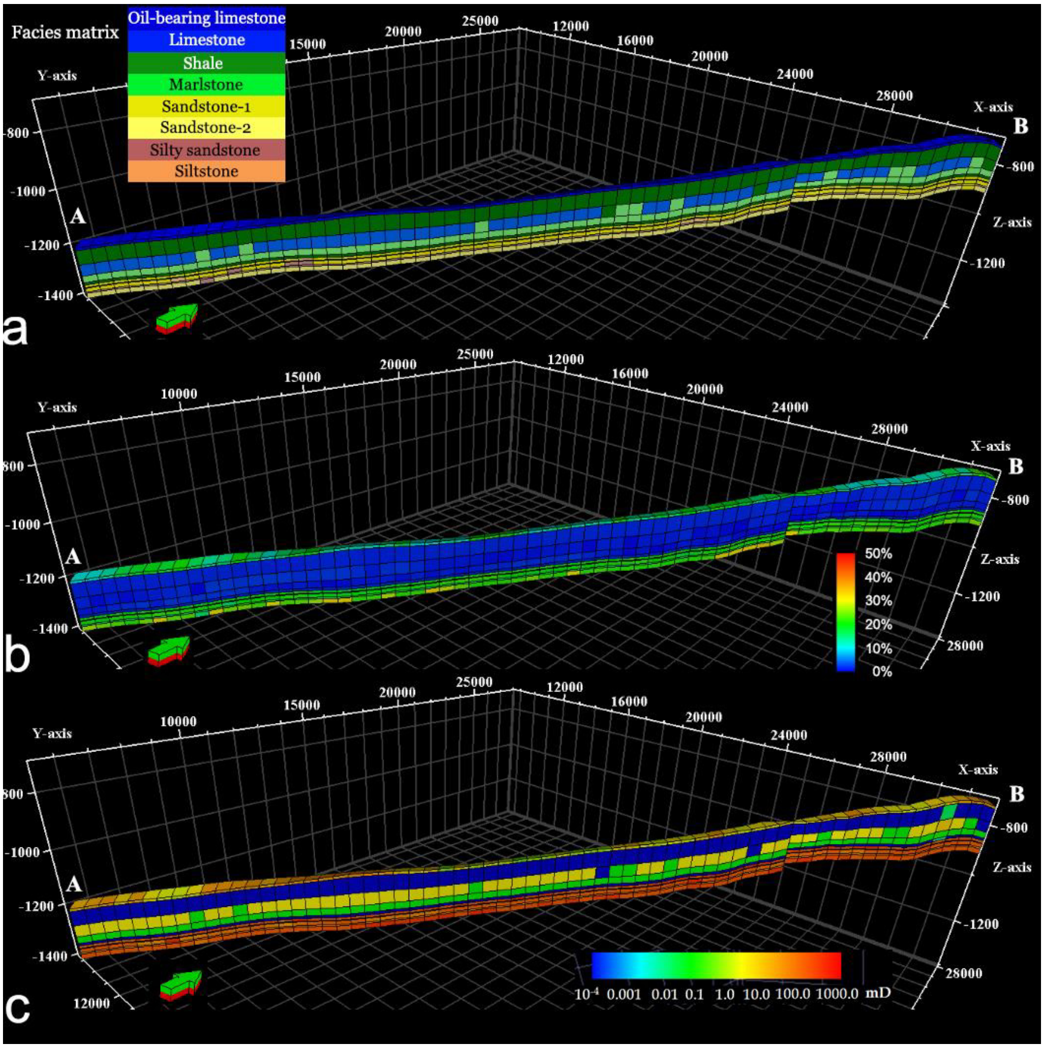

Fig. 4. Cross sections of (a) facies, (b) porosity and (c) permeability distribution along the line A−B in the E6 numerical model shown in Fig. 3 (modified after [19]).

5. Conclusions

Proposed 3D models have significant importance and play linking role for coupling fluid-flow simulation and seismic numerical modelling. Therefore, present study has crucial role in developing an optimal offshore storage seismic monitoring plan in the studied area. Results of this work could be applied in fluid-flow simulations to predict CO_2 plume evolution and migration within the studied area. Plume evolution model consequently could be integrated into the seismic numerical modelling procedure to compute synthetic seismograms before and after CO_2 injection.

This will permit to predict seismic response to the CO_2 plume migration at different time scales within the studied reservoir structure, and, will support basis for the further monitoring plan design in the region. This study offers new possibilities for economic, petrophysical and geochemical modelling of regional transboundary CCS scenarios in the Baltic Sea Region. However, lack of faults transmissivity data together with the uncertainties in facies distribution call for further investigations in order to increase the accuracy of the geological static model for the E6 offshore structure.

Acknowledgements

We would like to thank Schlumberger who provided an academic license for Petrel Software and for permission to publish this study. The work was also supported by the institutional research funding programme (project IUT19-22) of the Estonian Ministry of Education and Research.

References

[1] Šliaupa S, Lojka R, Tasáryová Z, Kolejka V, Hladík V, Kotulová J, Kucharič L, Fejdi V, Wojcicki A, Tarkowski R, Uliasz-Misiak B, Šliaupienė R, Nulle I, Pomeranceva R, Ivanova O, Shogenova A, Shogenov K. CO_2 Storage Potential Of Sedimentary Basins of Slovakia. The Czech Republic, Poland, And Baltic States. Geological Quarterly 2013; 2:219-232.
[2] Shogenova A, Sliaupa S, Vaher R, Shogenov K, Pomeranceva R. The Baltic Basin: structure, properties of reservoir rocks and capacity for geological storage of CO_2. Tallinn: Estonian Academy Publishers, Estonian Journal of Earth Sciences 2009; 58(4):259-267.
[3] Shogenova A, Shogenov K, Vaher R, Ivask J, Sliaupa S, Vangkilde-Pedersen T, Uibu M, Kuusik R. CO_2 geological storage capacity analysis in Estonia and neighboring regions. Elsevier, Energy Procedia 2011; 4:2785-2792.
[4] Shogenov K, Shogenova A, Vizika-Kavvadias O. Potential structures for CO_2 geological storage in the Baltic Sea: case study offshore Latvia. Bulletin of the Geological Society of Finland 2013; 85(1):65-81.
[5] Gorbatschev R, Bogdanova S. Frontiers in the Baltic References Shield. Precambrian Research 1993; 64:3-21.
[6] Poprawa P, Šliaupa S, Stephenson R, Lazauskiene J. Late Vendian-Early Palaeozoic tectonic evolution of the Baltic basin: regional tectonic implications from subsidence analysis. Tectonophysics 1999; 314:218-239.
[7] Freimanis A, Margulis LS, Brangulis A, Kanev S, Pomerantseva R. Geology and hydrocarbon prospects of Latvia. OGJ 1993; 91(49):71-74.
[8] Shogenov K, Gei D, Forlin E, Shogenova A. Petrophysical and numerical seismic modelling of CO_2 geological storage in the E6 structure, Baltic Sea, Offshore Latvia. Petroleum Geoscience 2016; 22:153–164. DOI:10.1144/petgeo2015-017
[9] Shogenov K, Shogenova A, Vizika-Kavvadias O, Nauroy JF. Experimental modeling of CO_2-fluid-rock interaction: The evolution of the composition and properties of host rocks in the Baltic Region. Earth and Space Science 2015; 2:262-284.
[10] Shogenov K, Shogenova A, Vizika-Kavvadias O. Petrophysical properties and capacity of prospective structures for geological storage of CO_2 onshore and offshore Baltic. Elsevier, Energy Procedia 2013; 37:5036-5045. DOI:10.1016/j.egypro.2013.06.417
[11] Chang KW, Minkoff S, Bryant S. Modeling leakage through faults of CO_2 stored in an aquifer. SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA; 2008.
[12] Bentham MS, Green A, Grammer D. The occurrence of faults in the Bunter Sandstone Formation of the UK sector of the Southern North Sea and the potential impact on storage capacity. Energy Procedia 2013; 37:5101-5109.
[13] LEGMC. Geological structures for the establishment of underground gas storages. Geological description for the information material "On the possibilities of use of the Latvian geological structures". Riga, Latvia; 2007, p. 1-16.
[14] Shogenov K, Shogenova A, Vizika-Kavvadias O, Nauroy, JF. Reservoir quality and petrophysical properties of Cambrian sandstones and their changes during the experimental modelling of CO_2 storage in the Baltic Basin. Estonian Journal of Earth Sciences 2015; 64(3):199-217.
[15] Andrushenko J, Vzosek R, Krochka V, Lobanov V, Hafenshtain K. Report on the results of drilling and geological and geophysical studies in the exploration well E6-1/84. Unpublished exploration report of E6-1/84 offshore well. Latvian Environmental, Geology and Meteorology Centre (LEGMC). Latvia, Riga (In Russian); 1985.
[16] Shogenova A, Kleesment A, Shogenov K, Põldvere A, Jõeleht A. Composition and properties of Estonian Palaeozoic and Ediacaran sedimentary rocks. 72nd EAGE Conference & Exhibition incorporating SPE EUROPEC 2010, 14-17 June 2010, Barcelona. EAGE, The Netherlands; 2010. p. 1-5.
[17] Shogenov K, Gei D. Seismic numerical modeling to monitor CO_2 storage in the Baltic Sea offshore structure. 10-13 June 2013, London, UK, Extended Abstract. EAGE, ID 16848, Tu-P08-13; 2013. p. 1-4. DOI:10.3997/2214-4609.20130631
[18] Deutsch CV, Journel AG. GSLIB. Geostatistical Software Library and Users Guide, 2nd. Oxford, New York: Oxford University Press; 1998.
[19] Shogenov K. Petrophysical models of the CO_2 plume at prospective storage sites in the Baltic Basin. PhD thesis, Tallinn University of Technology: TUT Press; 2015. http://digi.lib.ttu.ee/i/?2520
[20] Brun JP, Guennoc P, Truffert C, Vairon J. Cadomian tectonics in northern Brittany: a contribution of 3-D crustal-scale modelling. Tectonophysics 2001; 331:229-246.
[21] Courrioux G, Nullans S, Guillen A, Boissonnat JD. 3D volumetric modelling of Cadomian terranes (Northern Brittany, France): an automatic method using Voronoi diagrams. Tectonophysics 2001; 331:181-196.
[22] Ledru P. The Cadomian crust of Britanny (France): 3D imagery from multisource data (Géofrance 3D). Tectonophysics 2001; 331:300-320.
[23] Zanchi A, Francesca S, Stefano Z, Simone S, Graziano G. 3D reconstruction of complex geological bodies: examples from the Alps. Computers and Geosciences 2009; 35(1):49-69.
[24] Salvi F, Spalla MI, Zucali M, Gosso G. Three-dimensional evaluation of fabric evolution and metamorphic reaction progress in polycyclic and polymetamorphic terrains: a case from the Central Italian Alps. Geological Society Special Publication 2010, 332:173-187.
[25] Bigi S, Conti A, Casero P, Ruggiero L, Recanati R, Lipparini L. Geological model of the central Periadriatic basin (Apennines, Italy). Marine and Petroleum Geology 2013; 42:107-121.