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Potential Triassic and Jurassic CO_2 Storage Reservoirs in the Skagerrak-Kattegat Area

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Abstract

Regional assessment studies for CO_2 storage plays have been carried out in the Norwegian-Danish Basin of the Central North Sea and in the Skagerrak-Kattegat area. The development of the reservoir models is a part of an ongoing interdisciplinary project with the overall goal to establish a basis for large-scale handling of CO_2 in this area, including regional CO_2 source and capture possibilities, transportation and infrastructure, possible storage sites as well as legal aspects relating to the whole CCS chain. The study shows that all the necessary premises for a safe, long term CO_2 storage, are present in the area. Two trap types for storage have been studied more closely: 1) large gently inclined, unfaulted reservoirs in the northern Skagerrak area and 2) dome structures with four-way closures above salt pillows in the Norwegian Danish Basin. We have closely focused on the Upper Triassic-lowermost Jurassic Gassum Formation and the Middle Jurassic Haldager Sand Formation. The current study presents reservoir characteristics of the sandstones of the Gassum and Haldager formations in the Fjerritslev Trough and on the Skagerrak-Kattegat Platform.

Keywords: geological CO_2 storage, sedimentology, Skagerrak Norway, reservoir properties, salin acquifers

1. Introduction

To establish a CCS infrastructure in Skagerrak-Kattegat region it is necessary to identify and characterize potential CO_2 storage sites within reasonable distances to keep the transport costs low. Although the geology of the North Sea is fairly well known through the past 40 years of oil and gas exploration, the Skagerrak-Kattegat region has not been opened for such exploration and its geology and reservoir characteristics is by far less known. Therefore the aim here is to study the sedimentary sequences in Kattegat, Skagerrak and northeastern North Sea, as well as on-shore Denmark, to identify and characterize potential subsurface reservoirs for geological storage of CO_2.

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The main criteria for selecting a site for geological CO_2 storage are adequate CO_2 storage capacity and injectivity, safety and security of storage (i.e. minimization of leakage), and minimal environmental impact [1]. A suitable CO_2 storage play thus requires that the combined reservoir, seal and trap conditions are fulfilled.

This study consisted of an initial screening of potential CO_2 plays based on previous published work, [2] then new seismic mapping and interpretation tied to available well-logs and cores to select the best potential traps/structures for CO_2 storage, petrophysical analyses and estimation of reservoir properties, and finally reservoir simulation of a few selected sites. The only wells on Norwegian shelf outside the areas where petroleum exploration is permitted, are the scientific drillings performed by IKU in the 1980's [3]. However, they are quite shallow, and only one well penetrated down to the most promising reservoir unit (Gassum Fm). Instead, the only well control is from older Danish exploration wells, so extrapolations have been made from those wells to predict the petrophysical properties.

1.1. Geological Setting

This study includes the Skagerrak-Kattegat Platform, the Fjerritslev Trough and the north-east part of the Norwegian-Danish Basin which are located in the eastern part of Central North Sea, in between current Danish and Norwegian coasts. The Fjerritslev Fault, which belongs to the major NW-SE striking Sorgenfrei-Tornquist Zone, separates these areas (Figure 1).

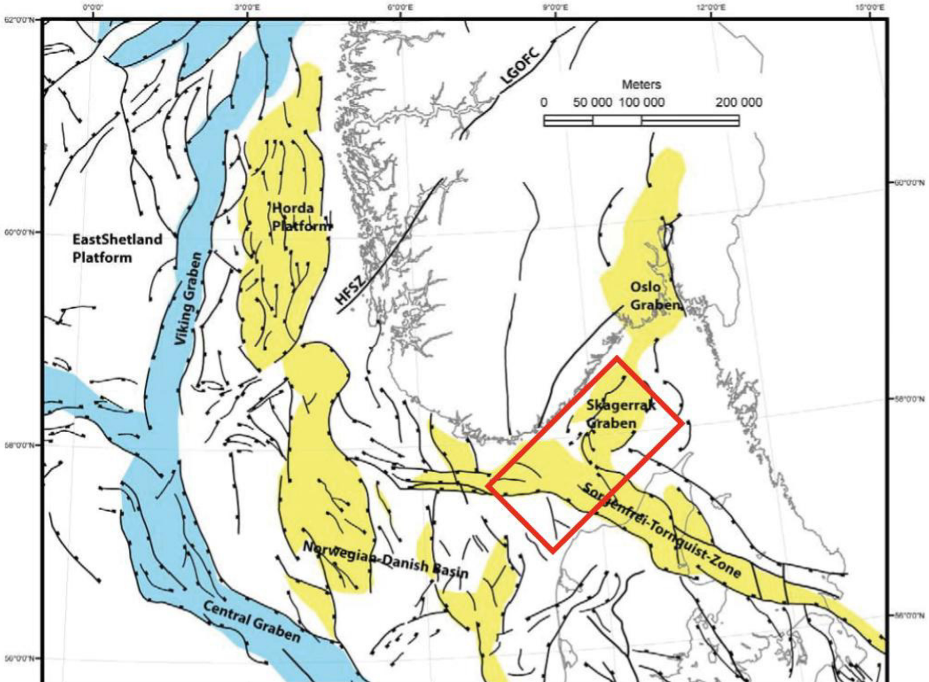


Figure 1. Overview map of the main study area with the main structural elements. The principal structural elements of southern Scandinavian including the Danish Basin (i.e. eastern part of the Norwegian-Dansih Basin), the Sorgenfrei-Tornquist Zone, Skagerrak-Kattegat Platform, and the Ringkøbing-Fyn High [4]. Red box indicates the studied area.

The Sorgenfrei-Tornquist strike-slip fault zone is a major discontinuity that initiated during the Precambrian and underwent intermittent reactivations until the Cenozoic [5-9]. Its tectonic activity during the Early Permian contributed to the opening of the Oslo and Skagerrak Grabens [5, 9, 10]. This main rifting phase followed a major Late Carboniferous-Early Permian magmatic and volcanic event that spread in the central North Sea [5, 11]. During the Late Permian and the Triassic, The Norwegian-Danish Basin, part of the Northern Permian Basin subsided in response to the thermal relaxation of the lithosphere [12] and was filled up by thick sequences of Upper Permian salt and continental Triassic sediments. The deposition of Upper Permian Salt extended to the North until the Fjerritslev Trough but is absent in Skagerrak-Kattegat platform where the continental Triassic sediments rest unconformably on tilted and eroded Paleozoic sediments [6, 9]. Salt tectonics started during the Triassic until Miocene in the Norwegian-Danish Basin and in the Fjerritslev trough [13, 14] and strongly affected sediment deposition.

The Norwegian-Danish Basin and in particular its southern Ringkøbing Fyn High structure were uplifted at the transition between the Early and Middle Jurassic. Triassic and Early Jurassic successions resting in the South part of the Norwegian-Danish Basin were deeply eroded whereas this uplift only modified sediments facies close to the Sorgenfrei-Tornquist fault zone where subsidence was still occuring. In the Middle Jurassic, the Fjerritslev trough received a large amount of sediments from the eroded areas.

The Late Jurassic-Early Cretaceous rifting phase occurred more to the West and did not affect the studied area, which was continuously subsiding. In the Late Cretaceous-Early Cenozoic, the Alpine collision is the cause of a main structural inversion and consequent erosion of the Cretaceous chalk [10]. A Neogene uplift in the order of 500 to 1500 meters is also well documented in the Skagerrak area by an erosional unconformity where the Base Quaternary rest on Triassic, Jurassic and Lower Cretaceous rocks [15].

1.2. Screening of CO_2 storage plays

The adjoining onshore areas of southern Norway and Sweden consist of old crystalline basement rocks without storage potential. Thus the only place to look for storage is within the sediments offshore. The main study area of this project is restricted to 6° - 10° East and 56° - 58° North and comprises several major structural elements as outlined in Figure 1.

1.3. Data Base and Methodology

The two most promising Gassum and Haldager aquifers in our study area are mapped on regional 2D seismic data in the Norwegian-Danish Basin, the Fjerritslev Trough and at the Skagerrak – Kattegat Platform. The seismic data were tied to Danish hydrocarbon exploration and geothermal energy wells. The Gassum and Haldager formations are found at a depth range of 750 – 2050 and 550 – 1750 m below sea level, respectively (Figure 2). Both formations are affected by salt tectonics (salt pillows, diapirs) in the south but form gently dipping reservoir units towards north.

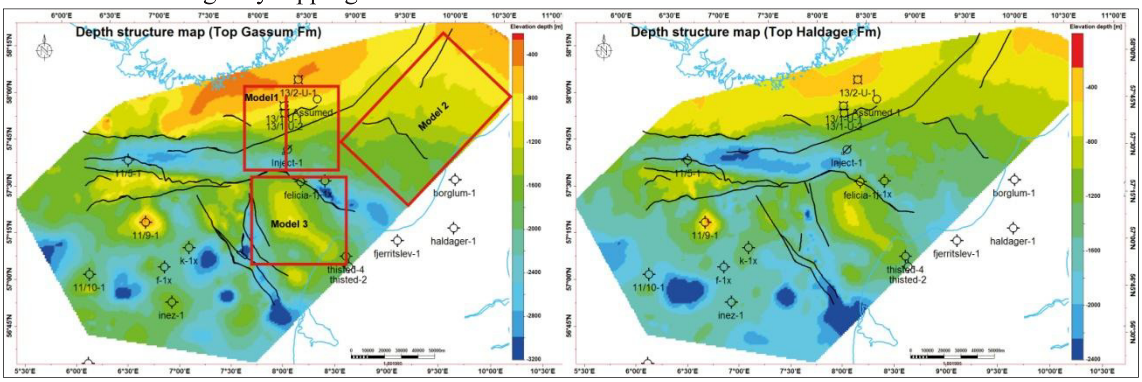


Figure 2. Top Haldager and Gassum formations depth structure map, the surfaces are dipping away from the Norwegian coast in the north. Both formations are affected in the south west by the movements of Upper Permian Zechstein salt. The location of the seismic section and three modelled areas discussed later, are shown in red.

The new interpretation suggests that these formations are widely distributed on the platform areas and thicknesses are controlled by some local faults at places. Seismic characteristics of these formations show bright amplitude reflections on the Skagerrak-Kattegat Platform, which may be due to greater proportion of coarse grained sediments in this area. The Fjerritslev Formation, which is a transgressive marine mudstone between the Haldager and Gassum formations, displays more sandy characters on the seismic data towards N and NE. The Haldager Formation shows discontinuous and shingled off-lapping reflection patterns, which may be due to more fluvial activities towards paleo-coastal areas. On some seismic sections, erosion truncations are evident at the top and base of the Haldager Formation towards the North and NE. The Gassum Formation reflectors are relatively continuous and parallel. The top Gassum Formation reflector interpreted from Danish wells was also traced on Skagerrak-Kattegat platform which correlates with the base of core unit of 13/1-U-1 well. According to GEUS's interpretation [16], this base unit represents the ravined top of Gassum Formation and overlain by transgressive marine mudstones of the Fjerritslev Formation.

Isopach map of the Haldager formation shows larger thicknesses in the Fjerritslev Trough and Farsund Basin. Thicknesses in the basin areas reach up to 250-300 m in some places. Relatively large thicknesses are observed along the Fjerritslev Fault. On the Skagerrak-Kattegat platform, the Haldager Formation is approximately 40 – 50 m thick in the vicinity of Sorgenfrei Torquist Zone. The Haldager Formation is thinning and truncating below the Quaternary sediments towards North and NE. The Gassum Formation is approximately 400 m thick in the Fjerritslev Trough and Farsund Basin. On the Skagerrak-Kattegat platform, the Gassum Formation is ~150 m thick and thinning towards North and NE. The Gassum Formation is also truncating below the Norwegian channel sediments (Figure 3, 7).

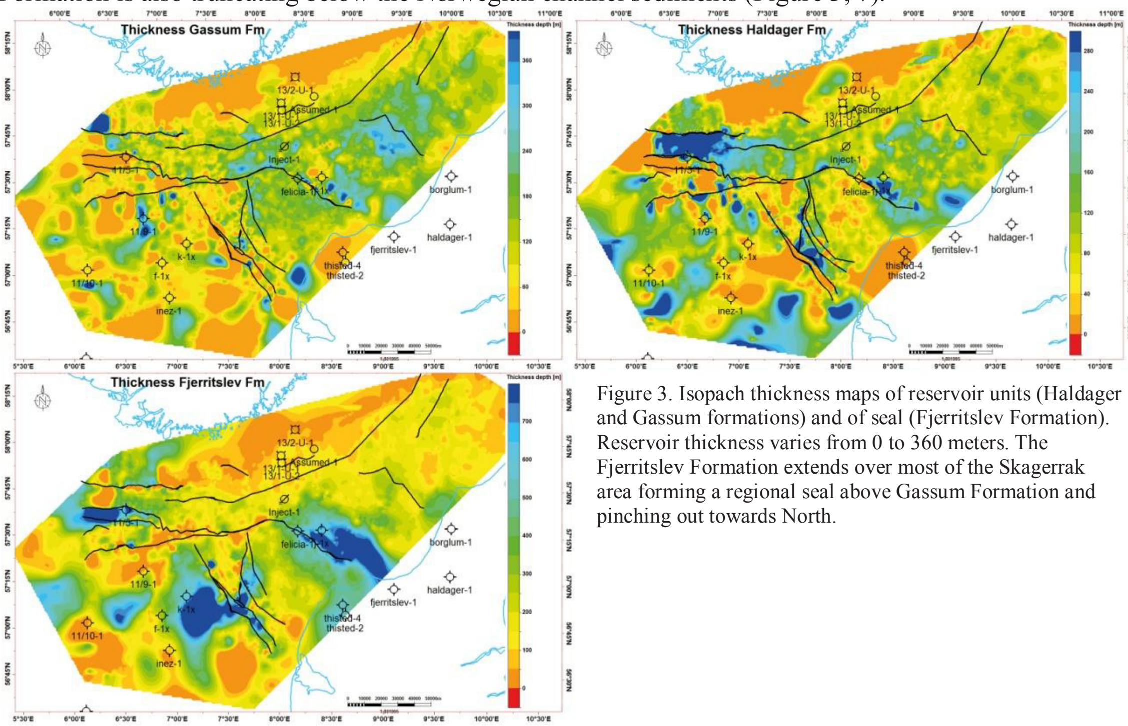
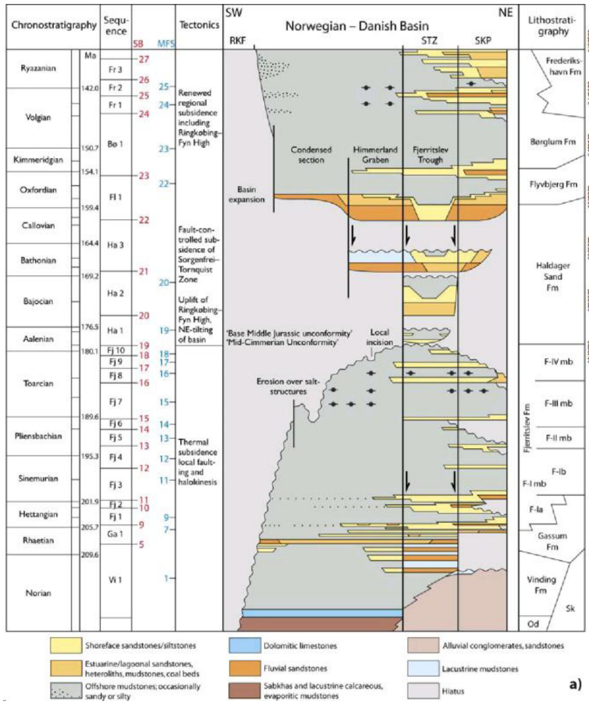


Figure 3. Isopach thickness maps of reservoir units (Haldager and Gassum formations) and of seal (Fjerritslev Formation). Reservoir thickness varies from 0 to 360 meters. The Fjerritslev Formation extends over most of the Skagerrak area forming a regional seal above Gassum Formation and pinching out towards North.

1.4. Reservoir properties

The Gassum Formation mainly consists of shallow marine shoreface and fluvial-estuarine sandstones possibly deposited during several episodes of relative sea-level fall (Figure 4a). The average thickness of Gassum Formation as seen in offshore Danish wells is about 70 m with an average porosity of 20 % and net/gross ratios of 0.30 - 0.70 (Figure 4b). The Gassum Formation is overlain by thick marine mudstones of the Fjerritslev Formation, which is characterized by large lateral continuity, forming a highly competent cap rock unit probably making the Gassum Formation one of the most promising reservoirs for CO_2 storage in the study area. The sandstone of the Haldager Formation consists of fluvial and shallow marine sandstones interbedded with thin mudstones. The thickness of Haldager Formation sandstone towards northwest under the Norwegian channel as taken from one well drilled in the Norwegian sector (IKU well 13/1-U-1) in the study area is 32 m and the net/gross ratio of 0.5. The average thickness of Haldager Formation sandstones in the offshore Danish wells is about 25 m, with an average porosity of more than 26 % and a net/gross ratio of 0.5 – 0.8. The Haldager Formation sandstone is overlain by the marine mudstones of the Børglum Formation. Regional distribution of the mudstones with good sealing capacity above makes also the Haldager Sand Formation a good potential reservoir for CO_2 storage in the area.



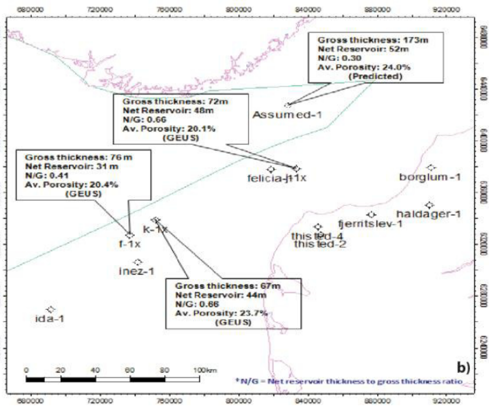


Figure 4a. Mesozoic stratigraphy of the study area with their environment of deposition and major sequence bounderies. Also showing dominant tectonic events in the area from [17].
Figure 4b. Existing wells on the Danish side and a pseudo well "Assumed-1" in the north close to Norway. Reservoir parameters in the Danish wells and predicted in the pseudo well are shown.

A sequence stratigraphic approach has been used to predict the reservoir facies/parameters for the sandstones of the Gassum and Haldager formations and to develop a likely geological model including the area closer to Norwegian coast. The reservoir facies for the Gassum Formation are predicted assuming a depositional model where the sediments are sourced from north. The thickness of the Gassum Formation is predicted using thicknesses from seismic data and a pseudo-well is generated about 50 km north of existing Danish well (Figure 4b, 5). Erosion of highstand sandstones was assumed at each cycle when sea level fell during a low (Figure 6). The eroded sediments thickness was compensated by assuming deposition of fine-grained transgressive system tracts sediments, which are not included in the reservoir thickness. Assuming 0%, 25%, 50%, and 75% thickness erosion of highstand sandstones resulted into N/G = 0.66, 0.50, 0.33, 0.17 respectively. Good reservoir porosities (~20%) were found in the reservoirs penetrated by wells in the southern part of the study area. The porosity values towards north are expected to be higher related to shallower burial depth. The sealing properties of the transgressive shales overlying the low-stand sandstones are crucial for local sealing and lateral distribution of injected

CO_2. Well-defined depositional models from the Danish part of the basin justify the assumption of internal seals. Furthermore, the potential intercalation of shaly units and permeability heterogeneities developed in prograding sand systems may provide additional trapping capacity to the reservoir; this has been shown from closely spaced well Danish sections in the eastern central part of the basin [17].

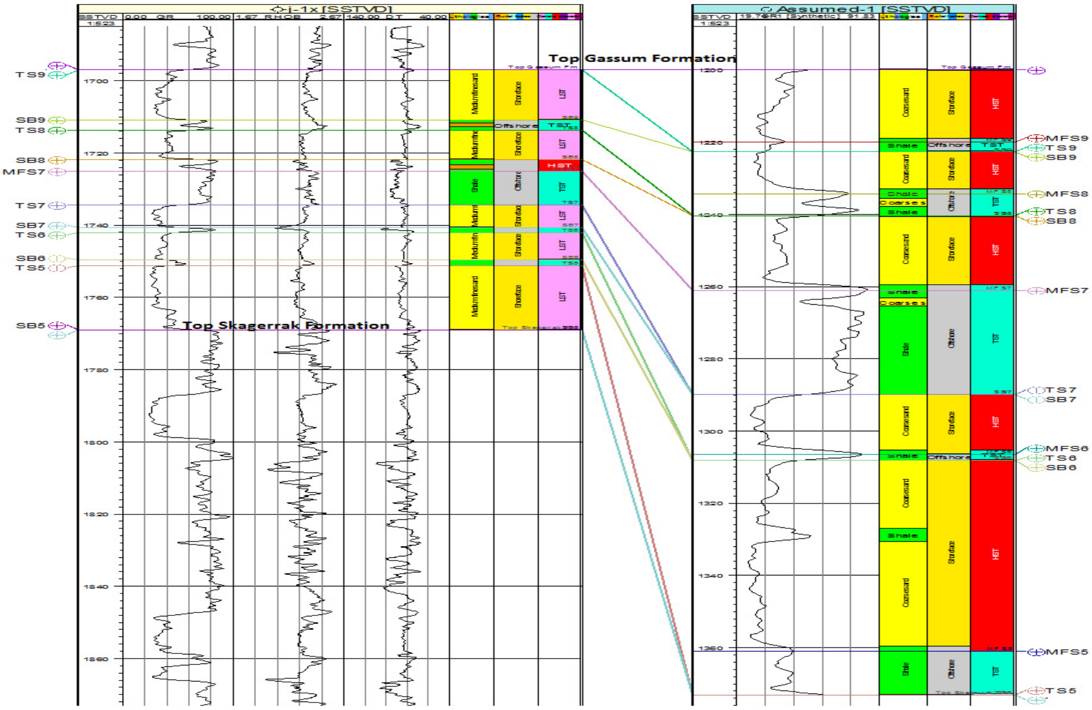


Figure 5. South to North cross section from J-1x well to the pseudo-well "Assumed-1". The facies in the pseudo-well were predicted on the basis of sequence stratigraphic considerations.

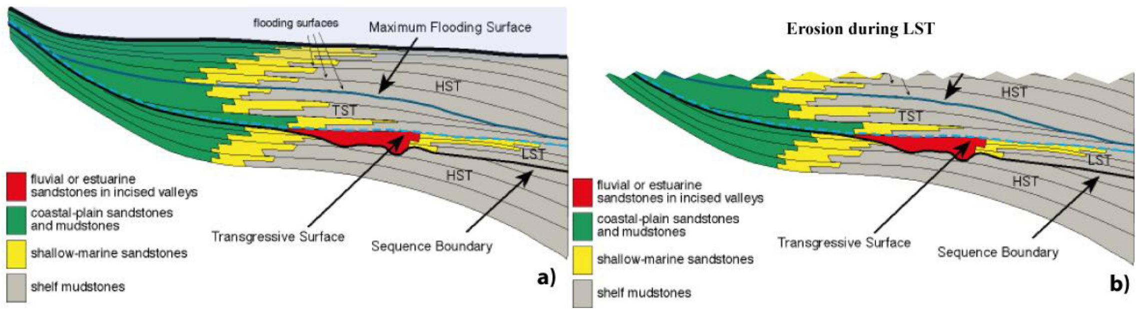


Figure 6 a) Generalized sequence stratigraphy: Depositional sequences and system tracts, b) During lowstand tract (LST) the upper part of prograding HST sands may get eroded preserving only the bottom part below the next cycle modified after.[18].

Based on the present study, several injection sites were proposed both in the Norwegian and Danish sectors. The Norwegian case is based on injection some 50 km south of Kristiansand, Norway. The open/semi-closed dipping aquifer is 40 km long and 0 to 360 m thick with net reservoir thickness of 52 m. The depths at proposed injection site for the sandstone reservoirs of the Haldager and Gassum formations are approximately 1580 m and 1960 mbsl respectively. The Haldager and Gassum reservoirs are truncating below ~117 m thick Quaternary sediments in the north approximately 38 km away from the position of the proposed injection well (Figure 7).

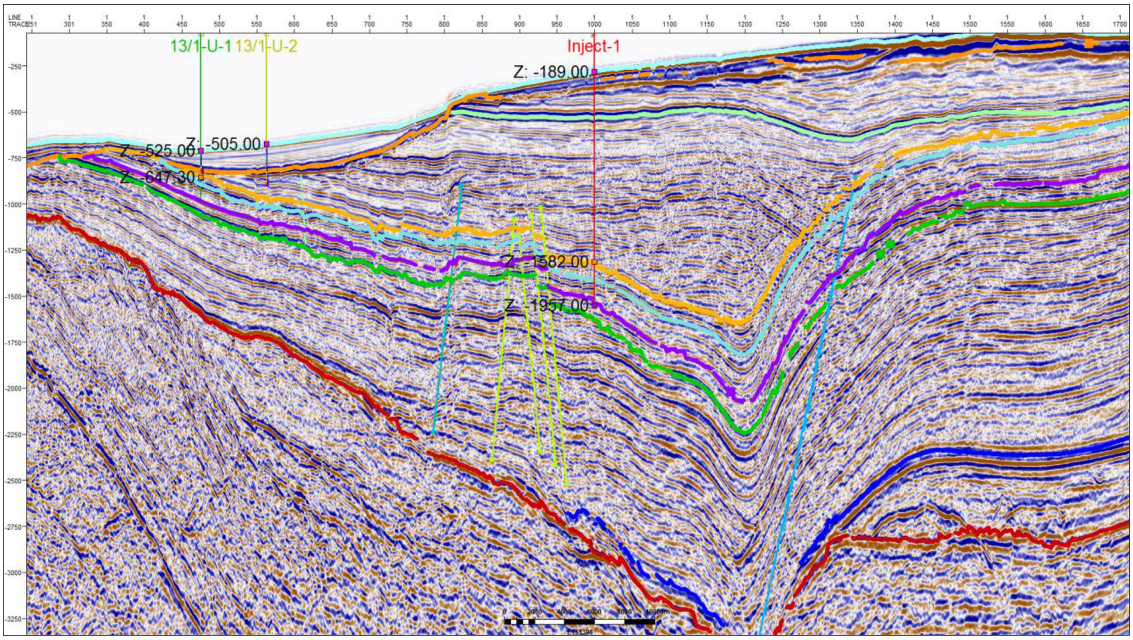


Figure 7. North to south seismic line (red line in Figure 2) showing depths of Haldager and Gassum formations at the location of the proposed injection well. Light Blue line marks top of Gassum Formation and orange line marks top of Haldager Formation.

1.5. Reservoir simulations

Reservoir simulations on two open/semi-closed dipping aquifer (Model1, Model2) and one dome structure (Hanstholm) model (Model3) have been made (Figure 8).

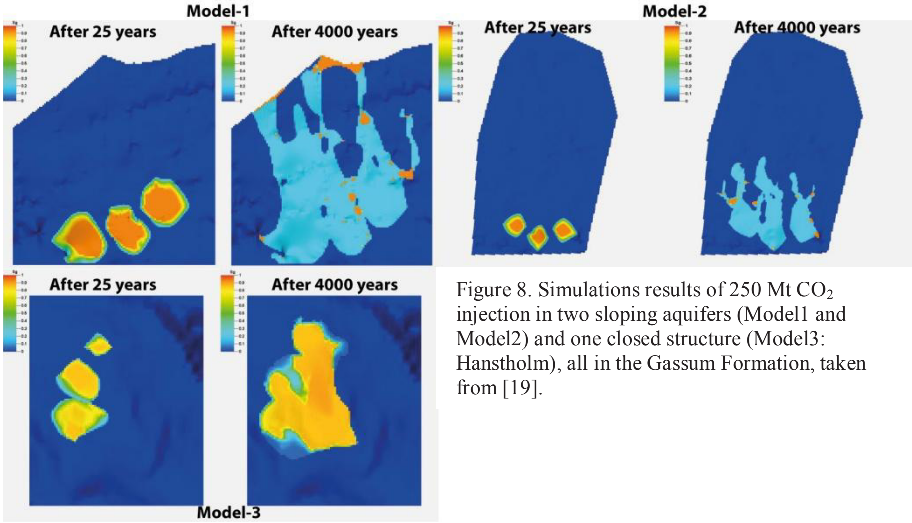


Figure 8. Simulations results of 250 Mt CO_2 injection in two sloping aquifers (Model1 and Model2) and one closed structure (Model3: Hanstholm), all in the Gassum Formation, taken from [19].

Model1 is located south of Kristiansand with injection 60 km offshore and approximately 2000 m below seabed, Model2 northwest of Jutland on Danish sector (Figure 2). Initial hydrostatic conditions were assumed, with open/semi-closed boundaries up-dip towards northwest (Model1) and northeast (Model2). For grid specification, reservoir parameters, temperature model and other boundary conditions, see the work of [19]. Injection of 10 million ton CO_2 per year for 25 years gave the following storage budget after 4000 years: Model1: 74.5 % capillary trapped, 18 % dissolved in formation water, and 7.5 % may have escaped; Model2: 76 % capillary trapped and 24 % dissolved; Model3: 87.5 structurally/capillary trapped and 12.5 % dissolved.

2. Conclusion

This geologic model is one of several possible scenarios that favour Gassum Formation as a potential CO_2 storage reservoir in Skagerrak area. Therefore, an evaluation of the reservoir properties using other possible scenarios is necessary. Ongoing work will use the depositional model framework of Nielsen (2003) to derive at a more realistic reservoir model. The sandstones of the Gassum and Haldager formations with their high net/gross ratios and good porosity/permeability provide promising aquifers for storing CO_2 in the Skagerrak area. The present study indicates that at least three aquifers structures should be able to accommodate 250 Mt CO_2 each.

References

[1]. Benson, S., Cook, P., Anderson, J., Bachu, S., Nimir, H., Basu, B., Bradshaw, J., Deguchi, G., Gale, J., and von Goerne, G., (2005). Underground geological storage. IPCC special report on carbon dioxide capture and storage: 195-276.
[2]. Faleide, J. I., Morisbak Jarsve, E., Aagaard, P., Thyberg, B., Heeremans, M., Jahren, J. S., and Gabrielsen, R. H., (2010). Possibilities of CO_2 storage in eastern North Sea, Skagerrak, Kattegat and onshore Denmark. Phase 1 Report Work Package 1: Geology and Geophysics, submitted to TEL-TEK Gassnova project "Muligheter for lagring av CO_2 i Skagerrak og østlige Nordsjø, og på land i Danmark"
[3]. Smelror, M., Jacobsen, T., Rokoengen, K., Bakke, S., BØ, R., Goll, R. M., Lippard, S. J., Mørk, A., Rise, L., Os Vigran, J., Wiess, H. M., and Århus, N., (1989). Shallow drilling Farsund Subbasin: Main Report. IKU report 21.3460.00/04/89.
[4]. Haugen, H. A., Aagaard, P., Thyberg, B., Kjärstad, J., Langlet, D., Melaaen, M. C., Liljemark, S., Bergmo, P., Skagestad, R., Mathisen, A., Jarsve, E. M., Faleide, J. I., and Bjørnsen, D., (2011). CCS in the Skagerrak/Kattegat area. Energy Procedia, 4(0): 2324-2331.
[5]. Heeremans, M. and Faleide, J. I., (2004). Late Carboniferous-Permian tectonics and magmatic activity in the Skagerrak, Kattegat and the North Sea. 223: 157-176.
[6]. Mogensen, T. E., (1994). Palaeozoic structural development along the Tornquist Zone, Kattegat area, Denmark. Tectonophysics, 240(1-4): 191-214.
[7]. Mogensen, T. E., (1995). Triassic and Jurassic structural development along the Tornquist Zone, Denmark. Tectonophysics, 252(1-4): 197-220.
[8]. Pegrum, R. M., (1984). The extension of the Tornquist zone in the Norwegian North Sea. Norsk Geologisk Tidsskrift, 64(1): 39-68.
[9]. Ro, H. E., Stuevold, L. M., Faleide, J. I., and Myhre, A. M., (1990). Skagerrak Graben-the offshore continuation of the Oslo Graben. Tectonophysics, 178(1): 1-10.
[10]. Liboriussen, J., Ashton, P., and Tygesen, T., (1987). The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics, 137(1-4): 21-29.
[11]. Heeremans, M., Timmerman, M. J., Kirstein, L. A., and Faleide, J. I., (2004). New constraints on the timing of late Carboniferous-early Permian volcanism in the central North Sea. 223: 177-194.
[12]. Frederiksen, S., Nielsen, S. B., and Balling, N., (2001). A numerical dynamic model for the Norwegian-Danish Basin. Tectonophysics, 343(3-4): 165-183.
[13]. Christensen, J. E. and Korstgard, J. A., (1994). The Fjerritslev Fault offshore Denmark - salt and fault interactions. First Break, 12(1): 31-42.

[14]. Hospers, J., Rathore, J. S., Jianhua, F., Finnstrøm, E. G., and Holthe, J., (1988). Salt tectonics in the Norwegian-Danish Basin. Tectonophysics, 149(1-2): 35-60.
[15]. Jensen, L. N. and Schmidt, B. J., (1992). Late Tertiary uplift and erosion in the Skagerrak area: magnitude and consequences. Norsk Geologisk Tidsskrift, 72(3): 275-279.
[16]. Nielsen, L. H., Weibel, R., Kristensen, L., Dybkjær, K., Japsen, P., Olivarius, M., Bidstrup, T. and Mathiesen, A., (2011). Contribution to prediction of stratigraphy and reservoir properties in the Eastern Norwegian-Danish Basin. Report to Universitet i Oslo, UiO. Geological Survey of Denmark and Greenland Report 2011/95.
[17]. Nielsen, L. H., (2003). Late Triassic–Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, 1: 459-526.
[18]. Holland, S. M., (1999). An Online Guide to Sequence Stratigraphy.Retrieved from http://www.uga.edu/~strata/sequence/seqStrat.html
[19]. Bergmo, P. E. S., Pham, V. T. H., Nielsen, L. H., Kristensen, L., Fawad, M., Faleide, J. I., and Aagaard, P., (2011). A potential CO_2 storage play in Skagerrak– Injection strategy and capacity of the Gassum formation. Poster presentation, TCCS-6, Trondheim, Norway.