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CO_2 storage atlas of the Norwegian Continental shelf: Methods used to evaluate capacity and maturity of the CO_2 storage potential.

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Abstract

A CO_2 storage atlas of different sectors of the Norwegian Continental Shelf has been elaborated by the Norwegian Petroleum Directorate (NPD) in the period 2011 to 2013 and is now compiled into one volume. Main objectives were to facilitate selection of sites which are suited for future CO_2 sequestration projects and to document the total storage capacity of the Norwegian sectors of the North Sea, the Norwegian Sea and the southern Barents Sea. The most attractive aquifers and structures were investigated by geomodelling and reservoir simulation. 5 case studies of different types of aquifers, structures and abandoned fields illustrate how the typical storage options were evaluated. There is a tendency that calculated storage efficiency and storage capacity based on estimates of pore volumes will decrease when the storage assessment units are matured by more detailed studies. The study was based on the assumption of no water production, and it was observed that storage capacity was usually limited by pressure build-up in the investigated aquifers. The case of pressure maintenance by water production has not been studied, but could lead to significantly higher values for storage capacity. The study indicates that CO2 could be used to recover oil from naturally occurring residual oil zones which commonly occur in areas with deep erosion.

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Keywords: CO_2 Storage capacity, aquifer, geomodelling, reservoir simulation

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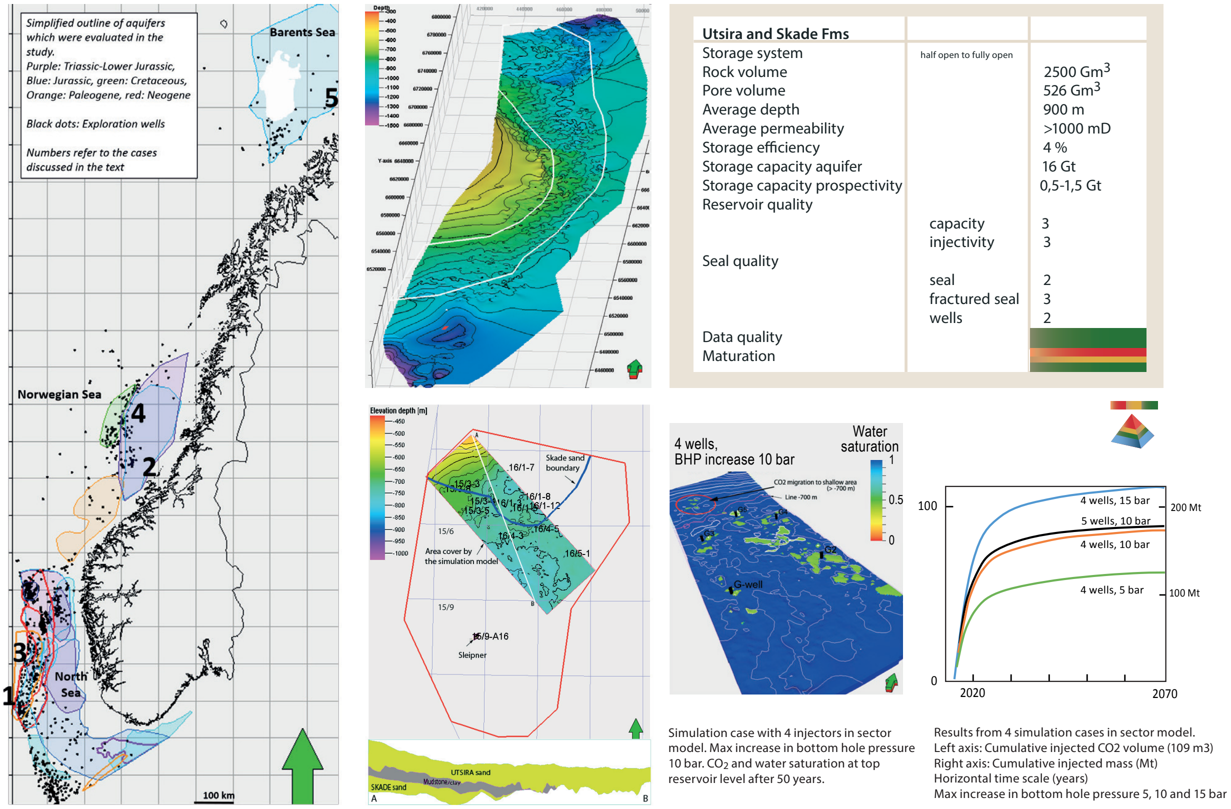
1. Introduction

The CO2 storage potential of the Norwegian North Sea has been evaluated in two different studies, in the GESTCO project [1] and more recently in the CO_2 atlas for the Norwegian Continental Shelf (NCS) [2]. The objective for the Gestco project was to identify all aquifers in the study area and estimate their theoretical CO_2 storage potential, based on aquifer pore volumes and storage efficiency. The results were presented as deterministic estimates.
The storage atlas [2] was elaborated on request from the Norwegian Ministry of Petroleum and Energy and attempted to identify and characterize aquifers and storage sites which can be regarded as available for CO_2 sequestration without interfering with petroleum industry. One objective of the study was to identify locations which could be matured further to be qualified as storage sites. The storage capacities were presented in a pyramid diagram, where the highest level in the pyramid represents the capacity of sites which are already used for CO_2 storage, while the lowest level represents theoretical capacity in poorly known aquifers [2].
Storage options evaluated in the atlas were trapping in closed structures (buoyant trapping, [3]) and trapping in aquifers (mainly residual trapping, [3,4]). Storage capacities were calculated assuming no active pressure management, i.e. CO_2 injection with no water production from the site. With this assumption, injection volumes will commonly be constrained by pressure build-up in the aquifer, and good estimates of pressure build-up are essential.
The atlas is based on new mapping using a large data base of 2D and 3D seismic data and exploration wells (Fig. 1a), as well as revision of existing regional maps. Reservoir simulation studies were performed for the aquifers and structures which were regarded to have the best storage potential in terms of capacity and maturity.



Utsira and Skade Fms		
Storage system	half open to fully open	
Rock volume		2500 Gm^3
Pore volume		526 Gm^3
Average depth		900 m
Average permeability		>1000 mD
Storage efficiency		4 %
Storage capacity aquifer		16 Gt
Storage capacity prospectivity		0,5-1,5 Gt
Reservoir quality		
	capacity	3
	injectivity	3
Seal quality		
	seal	2
	fractured seal	3
	wells	2
Data quality		🟩
Maturation		🟥🟨🟩

Simulation case with 4 injectors in sector model. Max increase in bottom hole pressure 10 bar. CO_2 and water saturation at top reservoir level after 50 years.

Results from 4 simulation cases in sector model.
Left axis: Cumulative injected CO2 volume (109 m3)
Right axis: Cumulative injected mass (Mt)
Horizontal time scale (years)
Max increase in bottom hole pressure 5, 10 and 15 bar

Fig.1(a) Distribution of evaluated aquifers in the NCS. Blue colors Jurassic, orange outline Paleogene, red outline Neogene, dots show released exploration wells. The numbers refer to cases described below. (b) Map of the Utsira Formation, location of the sector model in the southern part of the aquifer and distribution of CO_2 plume in different simulation cases.

Fig.1a gives an overview of the study area and the evaluated aquifers. Compared with the Gestco study, an area has been included in the southern Barents Sea. Some aquifers evaluated by Gestco were screened out. The main reasons to exclude aquifers from evaluation were permeability cutoff and screening out of aquifers with significant ongoing petroleum exploration and production. The Lofoten-Vesterålen region between the Norwegian Sea and the Barents Sea is not opened for exploration drilling and was not evaluated in the study. Aquifers in this area are not indicated in fig.1a.

Fig.1a shows that Jurassic reservoir sandstones form significant aquifers both in the North Sea, the Norwegian Sea and the Barents Sea. Lower, Middle and Upper Jurassic depositional systems have different geographic distribution and are commonly separated by sealing shales where they are in contact. In the North Sea, Paleogene and Neogene sands and sandstones also contribute significantly to the potential storage capacity [2].

2. Storage options

In the NCS two types of aquifers and structures can be distinguished according to their geometry and storage efficiency. The storage potentials of the most promising candidates for CO_2 storage were determined by geological modelling and reservoir simulation studies. The results for 5 cases, one example of each type of aquifer and structure are presented and discussed below.

1. Structured aquifers. In Jurassic aquifers located in major graben areas and salt basins, structural closures are abundant. Most of the larger structures have been drilled, although in areas with low hydrocarbon potential undrilled structures remain. In the Paleogene and Neogene aquifers (Fig.1a), structural and stratigraphical traps were commonly formed by sedimentary processes and soft sediment deformation (Fig. 1b). The main trapping mechanism for injected CO_2 in these aquifers is buoyant trapping in the closed structures and residual trapping in the migration paths of the plumes towards the structural culminations.
2. Monoclinally dipping aquifers. Aquifers located along the coast of Norway were affected by the Neogene and Paleogene uplift of Fennoscandia and typically exhibit regional dips in the order of one degree away from the coast (Fig. 2). Towards the coast they are truncated by the base Quaternary unconformity at shallow depths. With this geometry there is a risk that injected CO_2 can migrate upwards to shallow depths where CO_2 will be in gas phase and could seep further into the sea.

Safe injection of CO_2 can take place in the deeper parts of these aquifers, but most trapping will be residual and trapping by dissolution.

3. Structural closure, abandoned gas fields. Abandoned gas fields are regarded as attractive potential storage sites for several reasons. Their cap rocks are capable to contain a column of methane for long time periods and consequently will also contain CO_2 for more than thousands of years. Most gas fields are produced without pressure support so that their aquifers will be depleted and have a high capacity for CO_2 storage. The main seal risk is considered to be leakage along the paths of old wells where the integrity is poorly documented.
4. Structural closures, drilled and water-bearing. The storage potential was evaluated for several major structural closures which have been tested by exploration drilling and proved to be water bearing. It was investigated if there could be any hydrocarbon potential updip from the exploration well, and whether there was a risk of leaking cap rock. The storage efficiency in a structural closure with buoyant trapping will typically be lower than in a depleted field because the pre-injection pressure is higher. The size of the connected aquifer is important for the storage capacity
5. CO_2 storage with EOR in structures with oil and residual oil. Residual oil is widely distributed in areas which have been exposed to massive Quaternary erosion, in particular in the Barents Sea. Some structures contain residual oil combined with mobile oil.

In all models the volumes of injected CO_2 are constrained by the fracturing pressure. Our estimates of fracturing pressures (Fig. 2) are based on a large data base of leak-off tests and pore pressures in exploration wells. In deeply eroded areas in the Barents Sea the fracturing pressures seem to be somewhat lower.

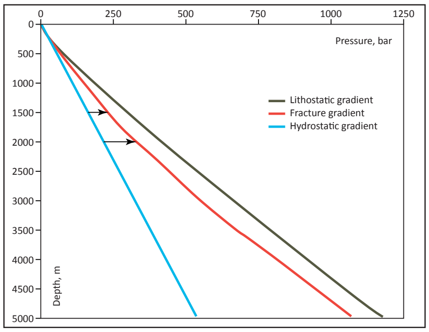


Fig. 2. Pressure gradients obtained from pore pressure data and leak-off tests in wells from the Norwegian Sea Shelf and North Sea at water depths 250 -400 m. The fracture gradient marks the lower boundary of measured leak-off pressures and the upper boundary of measured pore pressures. Arrows show how much pressure can be increased from hydrostatic pressure before it reaches the fracture gradient.

3. Mapping and modelling

3.1. Structured aquifer

The Upper Miocene to Pliocene Utsira Formation is part of a large Neogene aquifer system in the central northern North Sea comprising also the Skade Formation and an unnamed Quaternary sand formation in the Norwegian sector. Fig.1a. In the UK sector, these sands form part of the Oligocene to Quaternary Hutton sand [5]. The excellent reservoir properties of the Utsira Formation have been demonstrated in the Sleipner injection site, where approximately 1 Mt CO_2 has been injected annually since 1996. The upper parts of this system are buried to less than 200 m below the sea floor, and consequently only the deeper parts have a potential for CO_2 storage. At the time of the Gestco study the communication between the different sandy formations was not studied in detail. In order to improve the assessment of storage potential, the NPD performed a regional study based on 3D seismic interpretation and biostratigraphy [5].

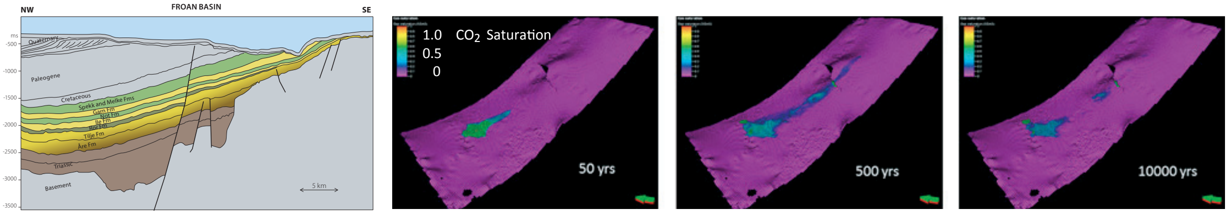
The study documents that the Miocene and Pliocene aquifer is subdivided into four major stratigraphic units which are built out from the Shetland platform to the west. The units are characterized by deltaic deposition in the western, proximal parts and shelf deposits in the eastern, more distal parts. They are vertically connected in the west. The largest pore volumes in the system occur in the Utsira and Skade Formations, which are separated by a Middle Miocene shale formation to the east. There is a regional dip upward towards the west, and consequently there is a risk that injected CO_2 will migrate updip to levels which are too shallow to be accepted for storage. Three areas are assumed to be suitable for CO_2 injection:

1. The southern part of the Utsira Formation below approximately 750 m (Fig. 1b). This area has several structures which could accumulate CO_2 and prevent it from migrating upslope. Large volumes can also be trapped as residual and dissolved CO_2 in the aquifer.
2. A volume in the NE part of the Utsira Formation.
3. The distal part of the Skade Formation where it is sealed by Middle Miocene shale and CO_2 could be trapped within structures formed by clay diapirism.

A reservoir model covering 1600km^2 was built to simulate the long-term behavior of CO_2 injection in the southern part of the Utsira Formation [6]. The area is classified as mature, because it includes the Sleipner injection site, and the geology is similar to this site. Injection was modelled in one segment of the model, with four horizontal wells injecting over 50 years, maximum BHP increase of 10 bars, and no water production. The study illustrates lateral migration of CO_2 and forecasts possible vertical migration of CO_2 from the Skade Formation into the Utsira Formation above. CO_2 injected in the Skade sand may penetrate through an intermediate clay layer into Utsira sand if the clay has permeability from 0.1 mD or higher. Approximately 170 Mt CO_2 can be injected in Utsira-Skade aquifer in the segment model. The CO_2 will be stored in structural traps and by residual trapping. With the assumption that the maximum residual saturation of CO_2 is 0.3, CO_2 trapped by residual mechanisms is 13% of total CO_2 injected after 8000 years. At that time, the dissolved part is nearly 70%. Mineral trapping by geochemical reactions was not considered in the simulation, but will add additional storage capacity. The total storage capacity in the southern area of the Utsira-Skade aquifer was calculated to 0.5-1.5 Gt based on the segment model.

3.2. Monoclinally dipping aquifer. Garn Formation, Froan Basin, Mid Norway

Understanding the timing and extent of long distance CO_2 migration is of importance for evaluation of the storage capacity of monoclinally dipping aquifers, and the aquifers of the Froan Basin are regarded as typical examples.



NW-SE profile showing the geometry of aquifers (yellow) and sealing formations (green) in the simulation model.

Fig.3. (a) Geological profile of the dipping aquifer. The Garn Formation is the uppermost sandstone (yellow). (b) Modelling results after the end of injection (50 y), 500y and 10000 years. The injected volume does not reach the upper shallow part of the aquifer.

A simulation sector model of the Garn, Not and Ile Formations was built covering about 10% of the total expected communicating aquifer volume. The top structure (Garn Formation) depth is about 1800 m in the western area and becomes shallower towards the east, with model cut-off at about 500 m depth. The main storage reservoirs are the Garn and Ile Formations with an average permeability of about 400 mD, separated by tight shales within the Not Formation. The Garn Formation consists of three reservoirs, separated by low permeable shale. The porosity and permeability have been stochastically modelled with both areal and vertical variation. The model layers are fine (<1m) at the top reservoir and underneath the shales to capture the vertical CO_2 saturation distribution. The CO_2 injection well is located down dip, but alternative locations and injection zones have been simulated, with different injection rates. The injection period is 50 years, and the simulation continues for 10,000 years to verify the long term CO_2 migration effects. The main criteria for evaluation of CO_2 storage volumes are the acceptable pressure increase and confinement of CO_2 migration (no migration to eastern model boundary within 10,000 years). CO_2 will continue to migrate upwards as long as it is in a free movable state. Migration stops when CO_2 is permanently bound or trapped, by going into solution with the formation water or by being residually or structurally trapped (mineralogical trapping has not been considered). Vertical sweep of CO_2 can to some extent be controlled by injecting into lower reservoir zones, but it is sensitive to vertical permeability and also zonal permeability distribution in the area near the well. Areal sweep can be achieved through use of several injectors. Fig. 3 b illustrates the development of free CO_2 saturation (green/blue) over 10,000 years.

Based on simulation results (upscaling of sector model), about 400 mill tons CO_2 can be stored in the Garn and Ile aquifer (8 mill tons/year over 50 years). This will require 4 injection wells (2 mill tons/year per well) and yield an acceptable pressure increase (<20bar). After 10,000 years most of the gas will have gone into solution with the formation water or will be residually trapped.

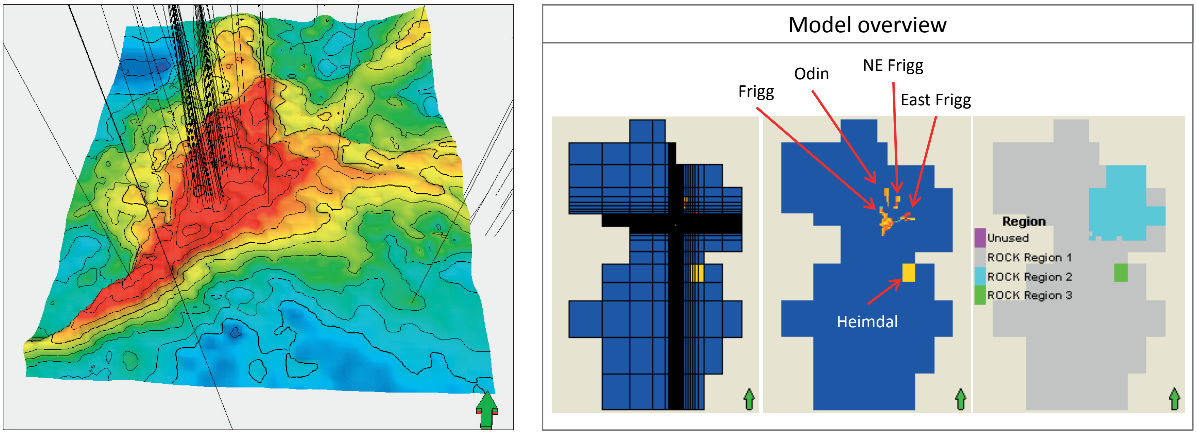


Fig. 4. (a) Top of the Frigg reservoir sandstone with production and exploration wells. (b) Overview of the simulation model for the Paleocene aquifer system.

3.3. Structural closure, the abandoned Frigg field.

The Frigg field is the largest of the abandoned gas fields in the Norwegian Continental Shelf. The initial gas in-place volume was 247 GSm3, of which about 191 GSm3 has been recovered. The volume of remaining producible gas is regarded to be small, but uncertain. A CO_2 injection study was conducted by the NPD in 2010 to see if the abandoned field and its satellites might be a candidate for future CO_2 storage. A reservoir simulation model made by Total for the full field was used and converted to an Eclipse E300 compositional model. The model was matched both with regard to PVT and production history and compared with regional pressure depletion observed in exploration wells. The fluid was described with four component groups: CO_2, N_2+C_1,C_2-C_6 and water. The simulation model included a huge aquifer around the Frigg fields. The model is shown in the lower right figure with grid cells, hydrocarbon accumulation and rock compaction regions. The main cases run were the following:

1. Production of remaining gas together with CO_2 injection (assuming some of the remaining gas is recoverable and not residually trapped)

2 and 3. Injection with no gas production.

In case 1, 10 mill Sm3/d of CO_2 was injected for 55 years from one well in the aquifer, and remaining methane gas was produced from the top of the Frigg field. In cases 2 and 3, CO_2 injection with 10 and 50 mill Sm3/d respectively was applied in an open aquifer. An open aquifer was simulated by producing water in the corners of the aquifer model, thus maintaining a relatively slow pressure increase.

In cases 2 and 3, pressure builds up from about 183 bar in Frigg, which is about 20 bars below initial pressure, to 208 bar in case 2 and 278 bar in case 3. The storage capacity for case 2 is in the order of 400 Mt CO_2. If there is any remaining methane in the structure simulation indicates that it can be produced before it is contaminated by the CO_2 plume

3.4. Structural closures, the Nordland Ridge

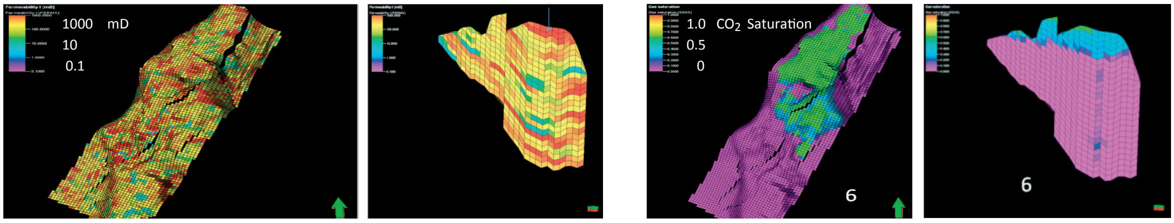


Fig. 5. a) Permeability map at the top of the Åre Formation and in cross-section. b) Distribution of CO2 plume at the top of the structure and in a cross-section after 1000 years in run 6, with a large connected aquifer and high injection volume.

The simulation model of the Nordland Ridge structure (fig. 5 a, for location see fig. 1a) was built for the purpose of assessing its CO_2 storage potential within the Lower Jurassic Åre Formation . The modelled structure has two dome-shaped culminations. Segment 3 is the deepest dome, and segments 1 and 2 combined represent the shallowest dome. There is a possibility for down flank aquifer communication to areas outside of the model. The depth of the top reservoir (Åre Formation) in the two main storage domes is between 1000 m and 1150 m. Generally the thickness of the Åre Fm varies between 300 and 500 m, with a maximum thickness of 780 m in the eastern part of the Halten Terrace (Heidrun area).

The Åre Formation consists of heterogeneous fluvial deposited sand channels. The connectivity between channels is uncertain. The average sand permeability within channels is about 500 mD. The porosity and permeability have been stochastically modelled with both lateral and vertical variation (fig. 5 a). One CO_2 injection well is located in segment 3. Different injection rates and volumes have been simulated (fig. 5 b). The figures illustrate CO_2 saturation (green/blue) after 1000 years. The main simulation case injects 2 mill Sm^3 CO_2/day (daily rate of 1/5000 of total volume) for 28 years with acceptable pressure increase and CO_2 plume spreading. CO_2 will continue to migrate upwards as long as it is in a free movable state.

Migration ends when CO_2 is permanently bounded or trapped, by going into solution with the formation water or by being residually trapped (mineralogical trapping has not been considered). Structural trapping is the main storage mechanism in the simulation model of the Nordland Ridge.

Applying a safety factor of 2 to the acceptable pressure increase, shows that 18.7 Mt of CO_2 can safely be stored in the Nordland Ridge within the Åre Formation.

3.5. Storage related to EOR projects

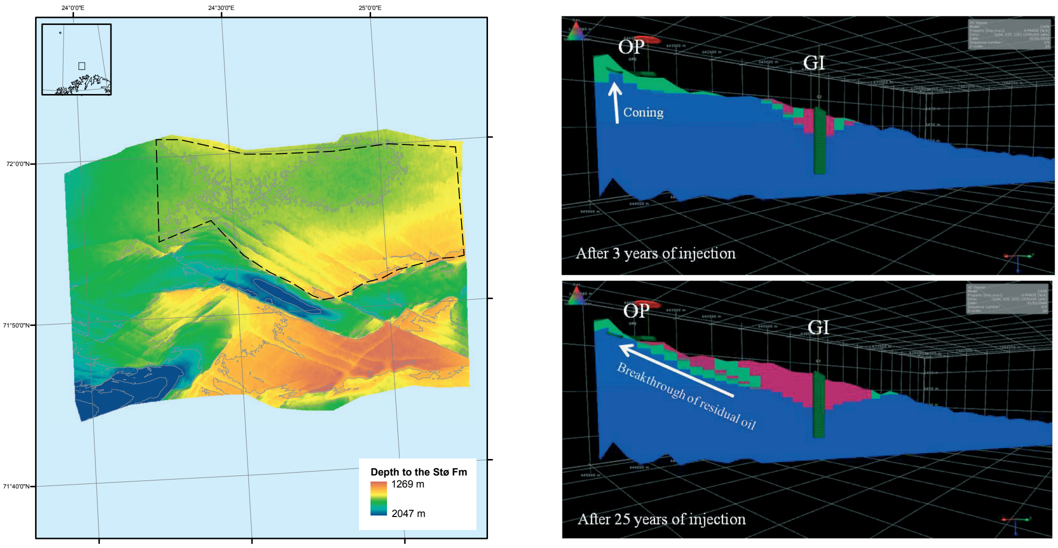


Fig. 6 a) Structural map of the top reservoir sand in the study area, location marked by 5 in fig. 1 a. b)Profile showing locations of CO_2 injector and oil producer. CO_2 is colored red, oil green and water blue.

CO_2 flooding will usually be a tertiary process with recovery from residual oil zones after water flooding. Some discoveries have residual oil below the main oil zone down to a paleo-oil contact. A simulation study was performed on a structure with residual oil in the southernmost Bjarmeland Platform in the Barents Sea to investigate if some of the residual oil could be produced. Data was obtained from the wells 7125/1-1 and 7125/4-1 (fig. 6 a). The main oil zone was 1-1,5 m thick in well 7125/1-1 with a 32,5 m residual oil zone below. The study indicated that the main oil zone could be up to 30 m thick in average. Simulation cases were run both on a thin and a thick oil zone. The oil was produced (well OP fig. 6 b) from the main oil zone while CO_2 was injected in the residual oil zone with an injection period of 30 years (well GI fig. 6 b).

The effect of CO_2 injection was modelled for different strategies of oil drainage and CO_2 injection. The sector model with a thick oil zone gave a recovery of 6.3 mill Sm3 including the residual zone. That means a total recovery of 18 %. For the thin oil case the recovery was 4.5 % including the residual zone. It was not easy to distinguish between the main zone and the residual zone recovery in the model. The stored CO_2 in the two cases was 40 and 30 mill tons respectively. The recovery of oil is to a large degree dependent on the amount of CO_2 injected.

4. Observations and conclusions

The evaluation of the storage potential of the Norwegian Continental shelf was initiated in 2003 with the GESTCO study, where the theoretical potential for all known aquifers was estimated. The next step in the evaluation was to elaborate the CO_2 storage atlas which required more in-depth geological mapping and reservoir modelling of the most promising aquifers and traps. In this process, some aquifers and structures were matured and some were screened out. As would be expected, the matured potential is lower than the theoretical potential of the initial study. Some of the experience from this study believed to be of general interest is summarized below.

Significance of geological mapping: For the evaluation in the Gestco project [1], it was assumed that the Utsira Formation and Skade Formation represented separate aquifers. A more detailed investigation showed that these formations were connected in a large aquifer system. Significant parts of the aquifer are not available for injection because of shallow burial. In general, detailed subsurface data, geological modelling and reservoir simulation studies are needed in order to mature the storage potential of an aquifer from a potential based mainly on pore volumes to a potential which can be used for planning and CO_2 strategy.

Storage efficiencies: In the storage atlas [2], the storage efficiency in cases with no pressure management by water production is typically assumed to be 1 % for closed aquifers and 4-5 % for partly open aquifers. In a simulation study several cases will be run in order to investigate the probability distribution of the capacity and storage efficiency. Efficiencies estimated through reservoir simulation tend to be lower than typical values for storage efficiency based mainly on pore volumes. The study was based on the assumption of no water production, and it was observed that storage capacity was usually limited by pressure build-up in the investigated aquifers. The case of pressure management by water production has not been studied, but could lead to significantly higher values for storage capacity.

In an offshore situation where injection wells are expensive, storage efficiencies for residual trapping based on reservoir simulation of plume migration tend to be lower than in the methodology suggested by [3], because the lateral and vertical sweep of CO_2 through the aquifer will not be perfect.

Injectivity and pressure control in heterogeneous reservoirs is a large uncertainty in an offshore situation where wells are expensive. Theoretically, storage efficiency in a heterogeneous reservoir will be good because CO_2 may be trapped below many internal seals, but in a simulation case there is a risk of low connectivity and rapid pressure build-up at the injection site.

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References

[1] Christensen, N.P. and Holloway, S. 2003. The GESTCO project Summary Report. *http://www.geus.dk/program-areas/energy/denmark/co2/GESTCO_summary_report_2ed.pdf*

[2] Halland, E. et al. 2014. CO2 storage Atlas, Norwegian Continental Shelf. *http://www.npd.no/en/Publications/Reports/Compiled-CO2-atlas/*

[3] Blondes, M.S. et al. 2013. National assessment of geologic carbon dioxide storage resources – Methodology implementation: U.S. geological Survey Open-File Report 2013-1055; 26p. *http://pubs.usgs.gov/of/2013/1055/*

[4] Heidug, W. 2013. Methods to assess geologic CO2 storage capacity: status and best practice. IEA Publications, OECD/IEA 2013.

[5] Eidvin, T. Riis, F. and Rasmussen, E. and Rundberg, Y. 2013. Investigation of Oligocene to Lower Pliocene deposits in the Nordic offshore area and onshore Denmark. *http://www.npd.no/engelsk/cwi/pbl/NPD_papers/Hyperlink-NPD-Bulletin-10.pdf*

[6] Pham VTH, et al., 2013: Assessment of CO2 injection into the south Utsira-Skade aquifer, the North Sea, Norway, Energy (2013), *http://dx.doi.org/10.1016/j.energy.2013.03.026*