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CO_2 Capture, Transport and Storage

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STORAGE RESOURCES FOR FUTURE EUROPEAN CCS DEPLOYMENT; A ROADMAP FOR A HORDA CO_2 STORAGE HUB, OFFSHORE NORWAY

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Abstract

Deployment of Carbon Capture and Storage (CCS) at large scale will be necessary to be able to fulfil the goal from the Paris Agreement to keep the global mean temperature in year 2100 well below two degrees Celsius above pre-industrial levels. Consequently, it is anticipated that there will be a significant increase in demand for CO_2 storage capacity. Offshore areas, such as the North Sea part of the Norwegian Continental Shelf, are prime candidates to provide this storage capacity. Given that the development of a storage site can take five years or more, it is of major importance to start the planning of expandable storage hubs. Anticipating and planning of additional stores will give industry clusters and power producers confidence that there will be sufficient operative storage capacity available for the expected increasing supply of captured CO_2. In this study, which is part of the ALIGN-CCUS project, we outline how an expansion in annual storage capacity of a CO_2 storage hub offshore the west coast of Norway can be achieved. Simulation of CO_2 storage and capacity estimates show that the Horda Platform study area has at least four potential storage sites with capacities in million tonnes (Mt) or thousand million tonnes (Gt) CO_2 as follows: 1) Aurora structure, in the Johansen Formation, south-east of the Troll Gas Field (120–293 Mt); 2) Alpha structure, in the Sognefjord Formation, northern Smeaheia area (40–50 Mt); 3) Gamma structure, in the Sognefjord Formation, southern Smeaheia area (0.15–3 Gt) and 4) Troll Field, Sognefjord Formation, after cessation of gas production (3–5 Gt). We sketch a timeline for which possible sites could be used for the development of the industrial-scale Horda CO_2 Storage Hub over the next thirty years. The annual storage capacity is matched to the estimated CO_2 supply rates (million tonnes per year) from sources in Norway, Sweden and Northern Europe. These estimates indicate cumulative totals of CO_2 stored in range of 810 Mt by 2050, and 1.85 Gt by 2065.

Keywords: *Horda CO_2 Storage Hub, road map, deployment*

1. Introduction

In the ERA-ACT ALIGN-CCUS project several European industrial Carbon Capture and Storage (CCS) clusters are described, with sources, transport solutions and linked geological storage. The development of such clusters will facilitate a rapid deployment of CCS and thereby contribute to the urgently needed reduction in emissions of CO_2 to the atmosphere.

The present paper discusses possible storage options on the Norwegian Continental Shelf (NCS), expanding from the storage solution for the Norwegian full-scale CCS demonstration project [1] [2]. This demonstration project plan to capture CO_2 at industrial sources in Oslo and Brevik, transport the CO_2 by ship to Øygarden west of Bergen, and from there transport the CO_2 via a pipeline to a permanent geological storage site south-west of the Troll Gas Field. The joint venture project 'Northern Lights', with partners Equinor, Total and Shell, is at present developing the storage solution for the demonstration project [3][4].

In the pre-feasibility study for the demonstration project [2] the outlined project would at most inject 1.25 million tonnes of CO_2 per year for 25 years. The required storage capacity of maximum 31 million tonnes would be met by the eastern part of the late Jurassic Sognefjord Formation which had at the time been subject to several modelling and simulation studies. A storage site prospect named 'Smeaheia Alpha' was believed to have a storage capacity of 100 million tonnes within a structural trap. The wider Smeaheia area, consisting of the Sognefjord Formation east of the Vette Fault, was believed to have a storage capacity of at least 500 million tonnes, based on earlier studies.

The giant Troll Field has its reservoir in the Sognefjord Formation in several fault blocks west of the Vette Fault. Production of gas from the field is believed to be influencing the pore pressure in the Sognefjord Formation in the whole region. The effect east of the Vette Fault at present is uncertain, but on the long term the pressure depletion effect is believed to be significant also in the Smeaheia Alpha prospect [5][6][7][9][10]. The resulting uncertainty in the density of the CO_2 and the risk of spill-over of expanding CO_2 into the Øygarden Fault complex has led the Northern Lights project to shift the focus for developing a CO_2 storage site to the south-western part of the early Jurassic Johansen Formation. A storage site prospect called 'Aurora' has been identified in the Johansen Formation, based on earlier studies [11][12]. These studies and others [13][14] have indicated a storage capacity in the Johansen Formation of at least 160 million tonnes.

The Smeaheia area, the Johansen Formation and the Troll Field all lie in the wider Horda Platform. Fig. 1 shows the location of the Horda Platform in relation to the west coast of Norway. Earlier simulation studies have investigated several possible injection locations for CO_2 in this area. Eigestad et al. [13] simulated injection of 3.5 million tonnes per year for 110 years in the southern part of the Johansen Formation. Bergmo et al. [14] simulated injection of 3 million tonnes per year for 110 years in the western part of the Johansen Formation. Bergmo et al. [15] also investigated the effect of extracting formation brine for pressure control in simulations of up to 540 million tonnes CO_2 injected into the western part of the Johansen Formation over a 50-year period.

Lauritsen et al. [10] simulated injection into the Smeaheia Alpha structure during depletion from the Troll Field gas production and found that the maximum injected amount should be kept below 40 million tonnes to avoid spill-over into the Øygarden Fault complex. Nazarian et al. [9] investigated, in addition to studies of the long-term expansion of the CO_2 plume at Smeaheia Alpha, a larger scenario with injection of massive amounts of CO_2 into the 'Smeaheia Gamma' structure further south in the Sognefjord Formation. Scenarios with as much as 100 million tonnes CO_2 injection per year over a period of 30 years was tested. Results show that if the injection rate is increased significantly this can counteract the pressure depletion caused by the gas production at the Troll Field, and the injected CO_2 will remain in a dense state and have a smaller final footprint.

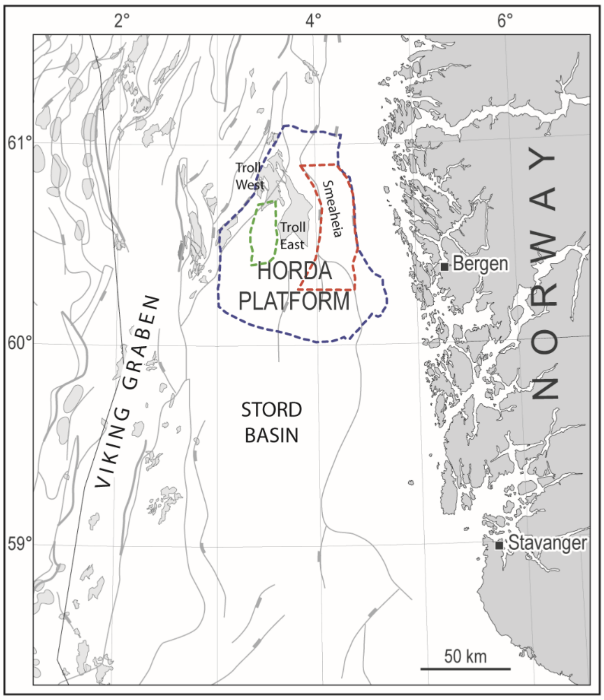

Fig. 1. The location of the Horda Platform area, offshore Norway. Blue outline show area for pressure simulations in [7], green online show outline of Aurora simulation model, and red Smeaheia reservoir model. Modified from [8].

Lothe et al. [7] investigated the effect of various assumptions for the transmissibility of the faults in the region (see Fig. 1, blue outline) and particularly Vette Fault with two fault ramps near the Smeaheia area (Fig. 2). Simulation results show that the final extent of the CO_2 plume at Smeaheia Alpha is much smaller if low transmissibility of the fault is assumed, since the higher local pressure will give a smaller occupied pore volume.

The prospective storage sites in the Smeaheia area and the Johansen Formation represents a potential storage capacity much larger than what is needed for the Norwegian full-scale demonstration project. The sites are located within an area of about 50 x 50 km. It is therefore interesting to consider development of a CO_2 storage hub in the area, combining the individual storage sites into a larger infrastructure that can receive and store an increasing annual amount of CO_2 from sources in Norway and other parts of Northern Europe.

The practical CO_2 storage capacity of a storage site is dependent on several factors like connected pore volume, permeability, depth, structural trapping and the boundary conditions (open/semi-open/closed). In this paper we investigate in more detail how the storage prospects will respond to CO_2 injection at increasing annual rates, and how the capacity can be matched to the requirement for storage from various CO_2 sources.

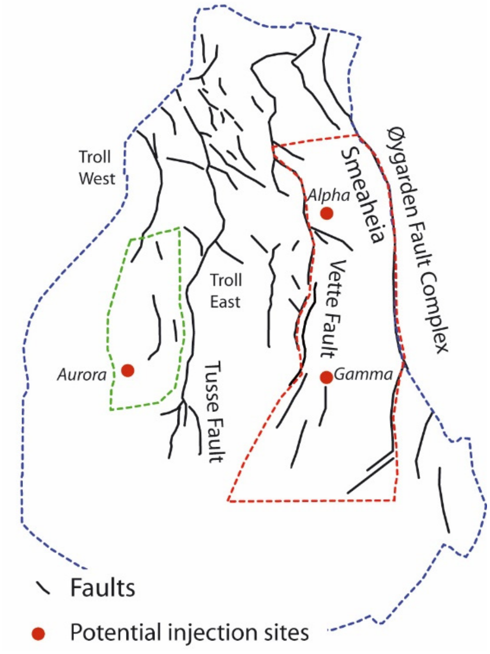

Fig. 2. Major fault systems and storage prospects in the Horda Platform area. The red and green outlined areas show, respectively, the outline of the Smeaheia reservoir simulation model and the Aurora simulation model. Modified from [8].

2. Geological setting

The study area covers the Horda Platform and the northern part of the Stord Basin in the northern North Sea (Fig. 1). The Smeaheia prospect is located on the eastern margin of the Horda Platform, approximately 20 to 35 km offshore Western Norway. The giant Troll Field (1310 x 10^9 Sm^3 recoverable gas) within a thick sandstone reservoir, is located west of Smeaheia. The Aurora prospect is located in the western part of the Horda Platform, south-west of the Troll Field (Fig. 2).

The northern North Sea has experienced three main extensional rift episodes in the Devonian, Permian-to-Early Triassic, and Middle Jurassic to Early Cretaceous (e.g. [16]). The present-day rift structure being predominantly a result of reactivation of the Permian structures during Middle Jurassic to Early Cretaceous (see e.g. [17]). During these rift episodes the structural inventory of the area was developed. The fault pattern of the Horda Platform is dominated by three North-South striking basement-involved faults, named from east to west the Øygarden, Vette and Tusse Fault Complex (Fig. 2). The Tusse Fault Complex divides the Troll Field into the Troll West and Troll East. These three main faults dip toward the west, bounding major half-graben basins, with the basement displaced across these faults by a maximum of around 4 kilometres. Depth conversion of seismic lines indicates the faults have dip values of approximately 40° where they separate Permian-Triassic sediments from crystalline basement and steepen upward to roughly 55° where they offset Jurassic and Cretaceous stratigraphy [18]. In addition to the northerly trending large faults, there are smaller structures observed in the area. Duffy et al. [19] mapped smaller North-West trending faults 2 to 10 kilometres in length with displacements of less than 100 metres.

2.1 Major storage options

The main possible CO_2 storage reservoir units in the Horda Platform area are the Middle to Upper Jurassic Sognefjord, Fensfjord and Krossfjord formations and the deeper Lower Jurassic Johansen Formation.

The Sognefjord Formation (Upper Jurassic, Oxfordian to Kimmeridge), the Fensfjord Formation (Upper Middle Jurassic, Callovian) and Krossfjord Formation (Upper Middle Jurassic, Bathonian) represents three coastal shallow-marine sandstones in the Viking Group that interfinger with the shaly Heather Formation on the Horda Platform (Fig. 3). The total thickness of the three formations is around 400 to 500 metres [20].

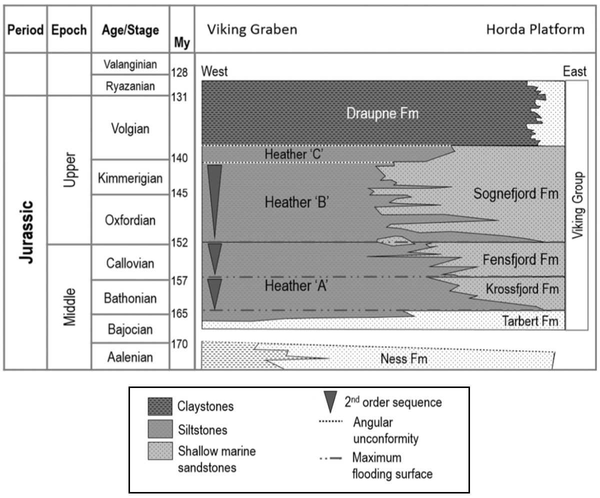

Fig. 3. Middle to Upper Jurassic chronostratigraphic framework for the Viking Graben and Horda Platform. The shallow marine Sognefjord, Fensfjord and Krossfjord formations build out from the east. From [21].

The Early Jurassic Johansen Formation and Cook Formation sandstones of the Dunlin Group (Fig. 4) are deposited on the Horda Platform area, with the Amundsen Formation mudstones separating the formations, in part of the study area (northern part of the Horda Platform). The whole of the parent Dunlin Group has a thickness in order of 320 metres, with Johansen Formation approximately 120 metres thick. The top-Johansen surface is buried between 2- and 3-kilometres depth, with gentle tilting towards north (approximately 0.6°).

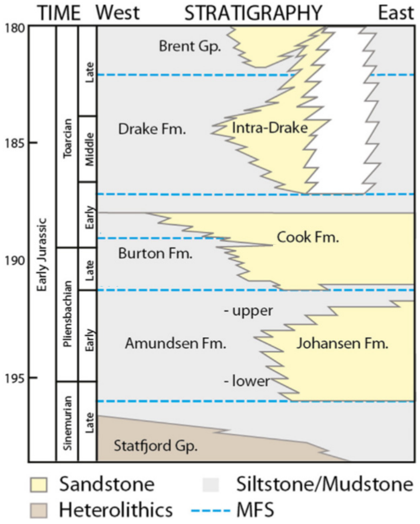

Fig. 4 Stratigraphy for the Early Jurassic Dunlin Group, with Johansen and Cook formations marked. Slightly modified from [11] with references therein.

2.1 Sognefjord, Fensfjord and Krossfjord Formations

The Oxfordian to Kimmeridgian Sognefjord Formation consists of sands and sandstones, grey-brown in colour, medium to coarse-grained, well sorted and friable to unconsolidated. It is the main reservoir in the Troll Field with a thickness of 100–170 m and individual target sands are in the order 3 to 45 metres thick with permeability values ranging from 1 to 20 Darcy. Porosities at the Troll Field range between 19 % and 34 %. These sands alternate with more fine-grained micaceous units. In addition, calcite cemented zones can be found in both Sognefjord and Fensfjord formations typically being in the order of a couple of metres thick and with a lateral extent between tens of meters to a few kilometres [22]. Gibbson et al. [22] using petrographical analysis, showed that early diagenetic, near-surface cementation has occurred in connection with maximum flooding surfaces and sequence boundaries at the Troll Field. These cemented horizons have a large impact on the oil production strategy in the field [23]. Patruno et al [24] show in detail, how the shallow-marine clinoform sets to the Sognefjord Formation has prograded in the Troll field area. Internally, in the Sognefjord Formation, there are four stratigraphic series mapped, bounded by regional maximum flooding surfaces, each corresponding to a westward dipping clinoforms.

The Fensfjord and Krossfjord formations compromise sandstone, around 195 m thick in the Troll Field area, that is sourced from the Norwegian mainland to the east. Six facies have been mapped, representing wave- and tide-dominated deltaic, shoreline and shelf deposits. Coastal plain facies are absent, indicating that the strata of the Troll Field were deposited in a fully subaqueous environment [21]. Four bio-stratigraphically distinctive, regional maximum flooding surfaces are recognized in cored wells. The series, bounded by maximum flooding surfaces have relatively uniform thickness, that indicates little tectonic influence [21].

2.2 Johansen and Cook formations

The Lower Jurassic Johansen Formation sandstones (Dunlin Group) represents shallow-marine deposits at the Horda Platform [25]. The sandstone consists of E-W prograding delta front deposits, with clinoforms building out into deep waters, associated with delta front and pro-delta turbidites. During an aggradation stage, thick NNW-SSE oriented spit bar facies were deposited down-current. The sandstones, deposited in the proximal delta top and shallow shore-face environments of the delta front have high porosity and permeability [11][12].

Several interlayers of mudstone and siltstone with low porosities are observed within the Johansen Formation [12] that are associated with flooding events. They are rather thin (a few metres) but are observed laterally over a kilometre scale. Carbonate layers i.e. calcite cemented sandstone, usually <1 m thick, are frequent in the Johansen Formation [11].

The sandy Early Jurassic Cook Formation lies stratigraphically above the Johansen Formation. In part of the study area, it directly overlay the Johansen Formation. In other areas, they are separated by the shaly Amundsen Formation. The Cook Formation is commonly erosionally based [26]. In the Horda Platform area, the Cook Formation is described as progradation shoreface sand deposits, locally influenced by tidal processes (Sundal et al. [11] and references therein).

3. Methodology and model set up

For storage sites in the Sognefjord Formation the pressure depletion caused by gas production at the Troll Field has been an important part of the boundary conditions of the simulations. The site-specific modelling issues are discussed in the following subsections.

3.1 Sognefjord and Fensfjord Formation reservoir model

For the model setup, seismic horizons and faults interpreted on high quality 3D seismic data by the Norwegian Petroleum Directorate (NPD) is used [5][6]. The reservoir model built by NPD, consists of data from Sognefjord Formation and Fensfjord Formation. The model is set up for a large area, and effect of pressure depletion were simulated for the whole region (Lothe et al. [7]). However, to be able to simulate capacity of CO_2 injection in the Smeaheia area, a detailed model has been set up east of the Vette Fault (see the red model outline in Fig. 2). The heterogeneous flow properties in the model is guided by a reservoir model released by Equinor for use in the Pre-ACT and ALIGN projects.

3.1.1 Boundary condition with pressure depletion from the Troll Field

The boundary conditions, and effect of pressure depletion from Troll area are taken from Lothe et al. [7]. In that study pressure depletion from Troll Field were simulated varying the influence of faults (effect of fault transmissibilites), and the effect of open and closed relay zones along the Vette Fault (Fig. 5).

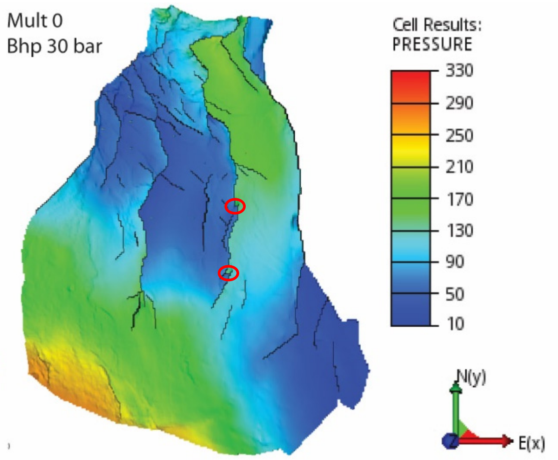

Fig. 5. Map with modelled pressure in year 2072 with two extended faults in the relay zones along the Vette Fault (marked with red), using sealing (mult 0.0) faults. Pressures in bar Modified from [7].

In that study it was assumed to be no-flow boundary conditions in all directions and the model is initialised with only water at hydrostatic conditions. To represent the production and future pressure depletion in the Troll Field, 10 water production wells are evenly distributed between the Troll West and Troll East. The water production wells are set to produce at a desired bottom-hole pressure (BHP). The base case was set up assuming a constant pressure depletion rate in the Troll Field from 1995 till 2022, with 2.66 bar depletion every year (see also Eiken et al. [27]). This is done by reducing the controlling BHP in the production wells by 8 bar every third year. From year 2022 until 2072 we assume a constant pressure depletion rate down to a final controlling BHP in the production wells equal to 30 bar in 2072.

3.1.2 Upscaling of sedimentary heterogeneities

In the original NPD model for the Sognefjord and Fensfjord formations, four layers (three in Sognefjord and one from Fensfjord to top Brent) were modelled. In the southern part of the study area, a deltaic lobe and associated channel structures were defined for the Fensfjord Formation The channels were correlated with ancient valley systems routed from the Norwegian mainland [5]. The porosity values in the model were varied between 15 and 35 %. The vertical permeability varies between 0–1760 mD, with a mean permeability of 31 mD. The horizontal permeability varies between 0.25–22 000 mD, with a mean permeability of 456 mD.

To model the dynamic behaviour of injected CO_2 a new refined simulation model is required. A smaller more refined model (400 m by 400 m grid) east of the Vette Fault has been constructed with the objective to refine the model in the vertical direction. The resulting model has 27 layers (Fig. 6). In the new model three intra sand shale layers have been constructed in the Sognefjord formation in addition to the shale layers (maximum flooding surfaces) between Sognefjord and Fensfjord and between Fensfjord and Krossfjord formations. For the base case a stochastic distribution of properties is assumed where the shale layers are not continuous but have localized zones of high permeabilities (green patches in Fig. 6a). The shale layers within and between the Sognefjord and Fensfjord formations have an average permeability of 1 mD, while the sand "holes" are in range of 1 Darcy (Fig. 6b).

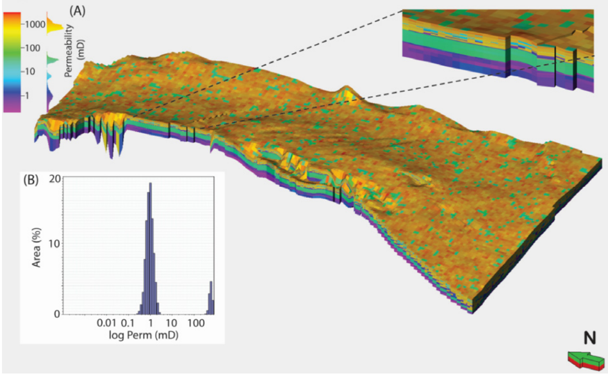

Fig. 6 a) Smeaheia Reservoir model set up with permeability distribution for Sognefjord, Fensfjord and Krossfjord formations east of Vette Fault, b) Logarithmic base case permeability (mD) versus area (%) distribution for the clay-rich layers, with sand patches. Modified from [8].

3.1.3 Simulation set-up

For the simulations, it is assumed that constant depletion from the Troll Field will affect the CO_2 injection in the Smeaheia area. We use the simulated pressure history from Lothe et al. [7], with extended faults in the two relay zones along the Vette Fault, and fault transmissibility set to 0, as boundary conditions for the model. The dynamic boundary conditions are imposed on the model by use of five water production wells along the boundary. The CO_2 is injected at a constant injection rate of 3 million tonnes per year over 50 years (total 150 Mt). The injection well is located close to the Alpha structure (Fig. 1) and the simulations are run for a total period of 1000 years.

3.2 Johansen and Cook Formation reservoir model

The reservoir model used for the simulations was defined by Gassnova [28] and Sundal et al.[11], covering an area of 475 km^2 south of the Troll Field (green model outline in Fig. 2). The model resolution is 250 by 250 metres laterally, with 120 layers vertically, incorporating the Johansen and Cook Formations. The porosity is calculated from interpreted acoustic impedance in the GN10M1 3D seismic volume [28]. The horizontal permeability is calculated form porosity based on core measurements [11]. The vertical to horizontal permeability anisotropy is set to 0.1, which is a common assumption for low-energy clastic deposits (see e.g. [29],[11]). Sundal et al. [11] assume ordinary transmissibility calculation of non-neighbour connections across the faults, i.e., no transmissibility modifier for faults. Large faults to west and east, Tusse and Vette faults, are assumed to be sealing. The full connected volume of the Johansen and Cook formations is modelled through the use of pore volume multiplicators on the northern boundary of the model. The southern boundary, as well as the boundaries to the east and west are closed.

4. Results from reservoir simulations

4.1 Smeaheia Alpha structure

For the Smeaheia Alpha simulation studies the effect of various assumptions for the reservoir heterogeneity is tested. This serves to further illuminate the potential storage capacity of the structure, which in previous work has varied from 40 Mt to several hundred Mt. The pressure depletion effect from the Troll Gas Field is modelled using "pseudo-wells" in the southern boundary of the model. The drawdown schedule in these wells is determined from simulations of the regional pressure development in the Sognefjord Formation during production from the Troll Field. See Lothe et al. [7] for details. Long-term simulations are run for a period of 1000 years.

4.1.1 Effect of pressure depletion

The effect of pressure depletion from the Troll Field was studied by Lothe et al. [8] for several assumptions on the sealing properties of the faults in the larger study area. Using boundary conditions based on the pressure modelling from Lothe et al. [7], the effect on injected CO_2 in the Smeaheia was modelled. The CO_2 injection rate used was 3 million tonnes per year over a period of 50 years from 2022 to 2072. Rapid migration into the eastern Øygarden Fault Zone was observed in all three scenarios. This behaviour is mainly controlled by the topography of the top layer and shows that this injected amount (150 Mt) is probably larger than the storage capacity of the Smeaheia Alpha structure. With this CO_2 injection rates the effect of Troll gas production on the pressure depletion in the area is temporarily counteracted, in particular for the cases with low fault transmissibility. Still, the CO_2 density decreases rapidly after the injection period, and the largest reduction is seen using the open fault assumption, that gives a large depletion from Troll Field. Pressure depletion on the long term is significant even with closed faults, due to pressure communication in the southern part of the Sognefjord Formation, where the faults die out.

4.1.2 Effect of facies heterogeneities

It is known from other studies that heterogeneities like calcite layers or clay layers may have a major impact on the storage capacity. Lothe et al. [8] also studied the effect of different sealing properties of the shale layers in three simulation scenarios. The base case (a) is as described in the geology section above. In a low-permeability case (b) the permeability in the shales layers is multiplied by 0.001. In a third case (c) a constant permeability of 0.1 mD is assigned to the shale layers, with no holes or weak zones. The CO_2 injection rate also in these simulations was 3 Mt/year over 50 years. The injection well is, however, a horizontal well placed somewhat deeper in the model. The simulation results showed that the shales layers have a large impact on the saturation distribution during and directly after the injection, with a larger CO_2 footprint in the deeper layers when shale layers have lower permeability. All simulations show some migration of CO_2 into the Øygarden Fault Zone and the main difference is the amount of residually trapped CO_2 close to the injection well. The larger footprint of CO_2 around the injection well will also result in more CO_2 dissolving into the water phase.

4.1.3 Lower injection rate – 1 million tonnes per year

To give an estimate of the practical storage capacity of the Alpha structure new simulations are performed for this paper, with the injection rate reduced to 1 million tonnes per year for the same injection period of 50 years. This gives a total injection of 50 Mt CO_2. The injection site is also moved 800 metres westward compared to the simulations in Lothe et al. [8], to increase the distance to the spill point of the Alpha structure. The other parameters of the model are kept constant. The simulation is run for 1000 years from the start of the simulation. In this simulation the main amount of the injected CO_2 migrates westwards and to the north, while only a small volume migrates east to the Øygarden Fault Zone (Fig. 7). From these simulations, we estimate that a total of 50 Mt CO_2 can be stored in the Alpha structure, with minor migration into the Øygarden Fault Zone.

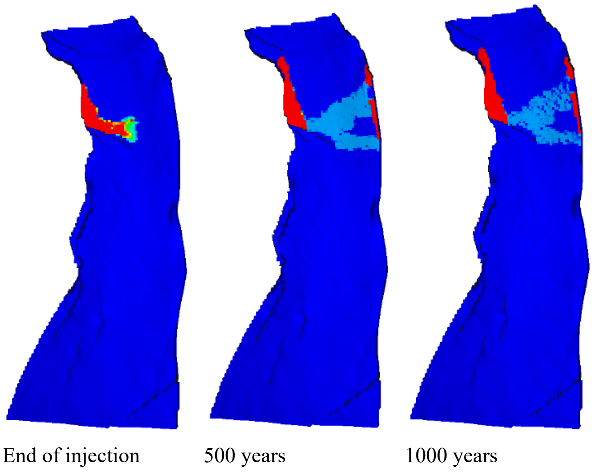

Fig. 7. Maps of simulated CO_2 injection at a rate of 1 Mtpa for 50 years in a vertical well in the Smeaheia Alpha structure. Red colours indicate high gas saturations, while blue indicate low gas saturation at left; end of injection, middle figure 500 years and right 1000 years.

4.2 Smeaheia Gamma Structure

Simulations have been carried out injecting CO_2 into the Gamma structure in the southern part of the Smeaheia area. We assume injection in one vertical well (located down-flank of the structure) with injection rate of 3 million tonnes per year over 50 years, and otherwise the same model setup as earlier described in Section 3.1.1. Pressure depletion from the Troll Field is incorporated into the model assuming sealing faults. The simulation has been run for 1000 years. The shale layers are assumed to have "holes" as described in the base case, Section 3.1.2.

Fig. 8 show the CO_2 saturation at the end of injection (50 years), where the gas fills the Gamma structure. After 500 years, some of the CO_2 have migrated into the Øygarden Fault Zone, and finally after 1000 years, more of the gas have migrated northwards along the Øygarden Fault Zone.

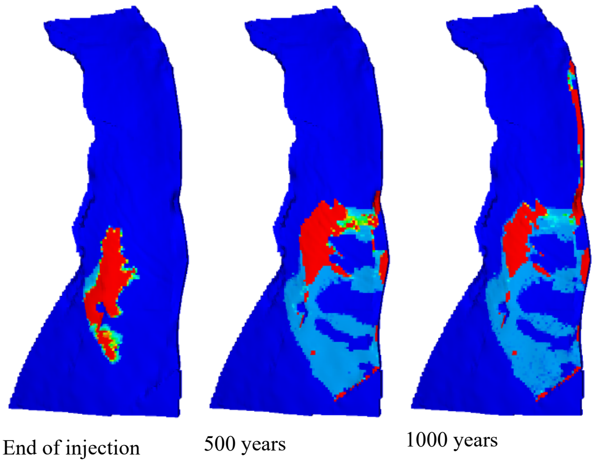

Fig. 8. Map view of CO_2 gas saturation from injection into one vertical well situated in the Smeaheia Gamma Structure. Colours as in Fig. 7.

4.3 Aurora Structure

For the Johansen Formation the goal was to simulate CO_2 injection with gradually increasing rate, matching a CO_2 supply scenario where new sources are added to the full-scale demonstration project after an initial period with only the sources defined in the full-scale project. When the total annual rate exceeds the capacity of a single well (assumed to be 3 million tonnes per year) a new well is drilled and added to the set of injection wells. The number of injection wells is increased further for each 3 million tonne rate increase, up to a maximum of 6 injection wells (with a total rate of 18 million tonnes per year). After a slower increase in annual rates in the first five years the annual rate is increased by 1.5 million tonnes per year. This means that a new injection well is drilled every second year. The locations of the wells in the simulation model are shown in Fig. 9.

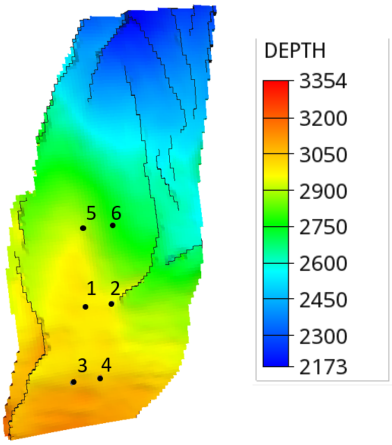

Fig. 9. Depth map in metres of the top Johansen Formation used for the detailed reservoir model of the Aurora site. Injection well locations (1 to 6) used in this work is shown. The distance between the wells in each pair is 2 km.

The injection schedule is shown in Fig. 10. Sensitivity cases are simulated with one and two injection wells. Fig. 11 shows the CO_2 footprint injecting CO_2 from the years 2023 to 2050 (27 years) using a) one well, b) two wells and c) six wells. For the two and six well cases, a ramp-up of the injection rate shown in Fig. 10 is used. The one well case injects 3 Mtpa from the start. Total injected amount of CO_2 in the shown cases are a) 81 Mt, b) 136

Mt and c) 322 Mt. The wells in the model are vertical wells and penetrate the top of the model at depths between 2700 and 3000 m below sea level. The minimum distance between wells is 2 km, with the reasoning that two slightly deviated wells can be drilled from the same template with distance of 2 km between the wells at reservoir depth.

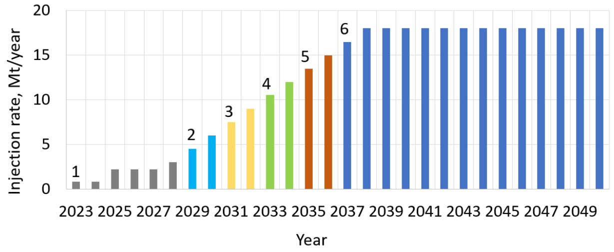

Fig. 10. Annual CO_2 injection rate schedule 2023 to 2050 in the simulations for the Aurora case with 6 injection wells. The numbers above the bars, and the colours indicate when a new well is added to the pool of active wells.

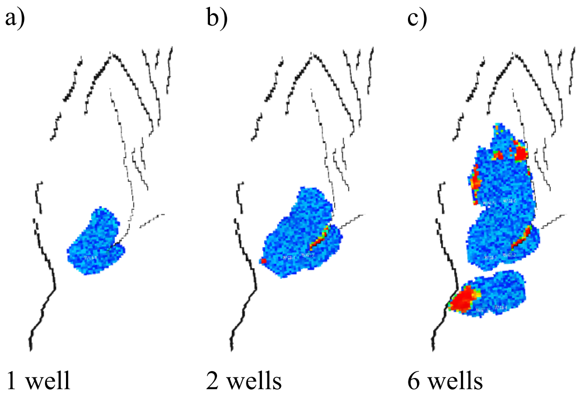

Fig. 11. Maps showing grid cells with CO_2 gas saturations and the major faults in the model area for the Aurora storage prospect. For well placement, see Fig. 9, for colour scale see Fig. 13.

4.3.1 Total pore volume

Sensitivities have been run on the assumed total pore volume in pressure communication with the Aurora storage site. In the Norwegian CO_2 Storage Atlas [20] the pore volume of the combined Johansen and Cook Formations is given at 90 Gm^3. This includes the part of the Johansen Formation east of the Tusse Fault. The simulations in Fig. 11 have been run with pore volume multipliers along the northern model edge that give the model a total pore volume of 280 Gm^3. This case assumes that a larger pore volume is in connection with the Johansen and Cook formations. A sensitivity case has also been run with a smaller multiplier giving a total model pore volume of 50 Gm^3 representing only the Johansen and Cook formations west of the Tusse Fault. The individual injection rates for the different wells are kept constant for the first 20 years, thereafter, reduced for the low case, see Fig. 12a) and b) for comparison. The size of the connected pore volume for the Aurora structure is uncertain and a more precise estimate of pore volume can only be assessed after several years of injection, by monitoring and modelling the injection pressure. The simulated cases should be considered upper and lower estimates for pore volume.

Simulation results show that the smaller model volume impacts the injection rate of the wells, which are all bottom-hole pressure restricted at 1.5 times the initial hydrostatic pressure at the top of the model at the position of each well. Fig. 13 shows in map view, that smaller pore volume, reduces the distribution on the CO_2 slightly. The reduction in injection rate at the end of the injection period leads to injection of a total of 293 Mt CO_2, compared to 322 Mt for the base case with larger pore volume.

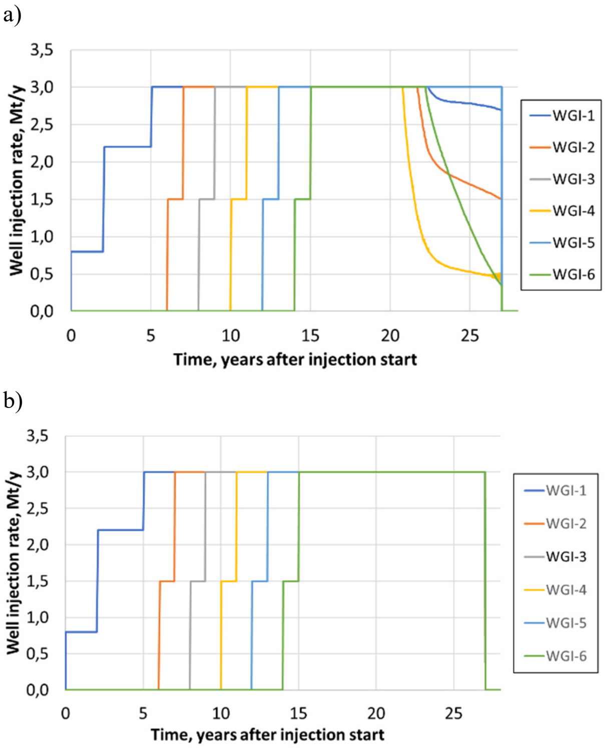

Fig. 12. Individual injection rates per well in the a) 50 Gm^3 and b) 280 Gm^3 pore volume cases.

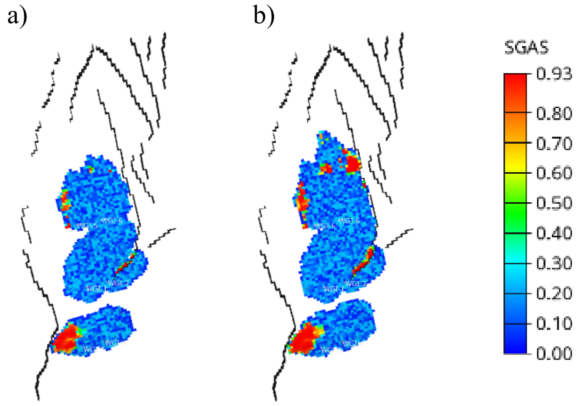

Fig. 13. CO_2 footprint at the end of the injection period for two cases with different total pore volume of a) 50 Gm^3 and b) 280 Gm^3. The case with pore volume 50 Gm^3 has slightly smaller total injected CO_2 amount due to pressure constraints in the injection wells towards the end of the simulation period.

5. Discussion

From earlier studies and from ongoing research, four potential storage sites at the Horda Platform have been identified (Fig. 14):

(1) Aurora structure: For the deeper Johansen Formation, several studies have been carried out over the last years at different locations. Eigestad et al. [13] simulated CO_2 storage of 3.5 Mt per year over 110 years at the southern end of the Tusse Fault. Bergmo et al. [14] simulated CO_2-storage with injection of 3 Mt per year over 110 years in one well further north in the formation, west of the Tusse Fault. They showed a promising storage site, with permanent storage, although in a worst-case scenario, the injected CO_2 would migrate to the Troll Field after 150 years of injection. Sundal et al. [11] simulated injection in the western part of the formation, about half-way between the injection site of [13] and [14]. Sundal et al. [11] targeted a section of the formation where seismic attribute analysis indicated high porosity. They used a single vertical well perforated in the lower half of the Johansen Formation (location as in the present study), with injection of 3.2 Mt per year over 50 years (160 Mt). Their study also tested the impact of geological heterogeneities and its effect on residual trapping and up-dip migration of CO_2.

In the present work we have modelled the full pore volume for the Johansen Formation. Several injection wells have been progressively introduced, with increasing rate of CO_2 supply. Assuming an injection rate of 3 Mt per year for each well, up to six wells were introduced. The total injected volumes of CO_2 simulated for a period of 27 years, from 2023 to 2050, by number of injection wells are: injecting in only one well stores 81 Mt; ramping up to two wells stores 136 Mt; injecting at six well sites store 322 Mt. These simulation results indicate that Johansen Formation seem very promising for CO_2 storage.

(2) Alpha structure: For the Alpha structure at Smeaheia, Lauritsen et al. [10] simulated injection in one well, with an injection point deep in the Viking Group, assuming strong pressure influence from nearby fields. The modelled storage capacity was up to 40 Mt CO_2, above which CO_2 would spill from Alpha to the more uncertain Beta structure and to the Øygarden Fault Complex. Lothe et al. [7] on the other hand simulated storage of 3 million tonnes per year over 50 years with no spill to Beta. However, in this work a coarse gridding of the Sognefjord Formation was used, with low resolution at the top of the structure, which is well suited for single-phase pressure modelling, but less valid for CO_2-injection modelling.

Whether the Øygarden Fault Zone is sealing or not for CO_2 storage, is not clear with the present knowledge of the area, but recent literature indicate that caution is required. Ksienzyk et al. [30] documents several episodes of deformation in the Bergen area, just onshore the Øygarden Fault Zone. The Øygarden Fault Complex represents the eastern boundary of the Mesozoic rift, and thereby control the reactivation of this major structure. As shown in the modelling, the storage capacity for the Alpha structure is in the range of 50 Mt CO_2, using an injection rate of 1 Mt per year for 50 years. This indicates that a storage potential in the range 40–50 Mt, given a conservative approach, without migration eastwards into the Øygarden Fault Zone.

(3) Gamma structure: For the Gamma Structure in the southern part of the Smeaheia area, [9] simulated storage of between 600 Mt and 3 Gt CO_2, even under continuous pressure depletion from the Troll Field. In this work, we simulate storage in range of 150 Mt, using injection in one well with 3 Mt per year for 50 years, which is on a smaller scale than in Nazarian et al. [9] simulation results. However, [9] have simulated three injection sites and, most importantly, we anticipate that Equinor have access to newer data. New interpretation of the top Sognefjord Formation surface would provide better representation of the structural traps in the area than those available for the present work.

(4) Troll Field: The fourth potential site for large-scale CO_2 storage is the giant Troll Gas Field itself. The field will stay in production for several decades, perhaps until the year 2060. However, it represents a vast potential for CO_2 storage that can be phased in as the other large storage sites comprising a CO_2 storage hub, i.e. Johansen Formation and Smeaheia Formation Gamma structure, become filled. Simple mass-balance calculations based on recoverable gas reserves, the initial formation volume factor for gas and the initial pressure show a CO_2 storage capacity of 5 Gt. Influx of water from the regional Sognefjord Formation will reduce the practical storage capacity, but even at two-thirds of the mass balance estimate the storage capacity will be several thousand million tonnes.

6. CO_2 supply

The Norwegian process industry has issued a roadmap for reduction of CO_2 emissions [31]. Their vision is to reduce CO_2 emissions to zero by 2050 while maintaining value creation, increasing production, and developing new processes and products. CCS is identified as an important tool to fulfil this vision. The roadmap from Norsk Industri gives a possible timeline for implementation of the various CO_2 reduction technologies [31]. In the presented scenario the annual amount of CO_2 captured in 2030 is about 1.8 million tonnes, and in 2050 about 5.5 million tonnes.

CO_2 can also be collected from other Scandinavian sources and from Northern Europe and transported to the onshore CO_2 transport hub near Bergen. The need for emissions reductions is large, and even in Northern Europe the amount that needs to be captured annually by 2030 is much larger than a single storage hub can accommodate. Several demonstration projects with specific sources and sinks are in development, as shown by the other ALIGN cluster studies and also by other ERA-Net ACT projects. These other clusters represent a joint effort to demonstrate that CO_2 storage can be managed in a safe and cost-efficient manner.

The effort of the Northern Lights project to secure additional CO_2 sources to fill the first pipeline to capacity could be met by first movers in the European industry and energy production sectors. Individual possible sources have not been identified in this work, except for the refinery at Lysekil. Cross-border transport is still a big unknown factor, which could delay implementation of CO_2 transport form Sweden or any of the other European countries with large point sources of CO_2.

7. Roadmap for a Horda CO_2 Storage Hub

Published studies, in addition to simulations of CO_2 storage in the Sognefjord and Johansen formations in this work, show the large potential for rapid increase in the annual storage capacity in the Horda Platform area to match an expected increasing storage demand from CO_2 sources in Norway and in Northern Europe. Fig. 15 shows a scenario for tie-in time and amount for storage sites in a Horda Storage Hub. The figure shows a sketch of how the potential storage units in the Horda Platform area can match CO_2 supply rate from sources in Norway, Sweden and northern Europe. In the roadmap we suggest to commence injection in the Johansen Formation Aurora site in 2023 with continuous injection till 2050, assuming injection in up to six injection wells. We estimate the total capacity of Aurora to be 293 Mt CO_2, using the lower limit pore volume (e.g. 50 Gm^3). Thereafter, injection into the Sognefjord Fm. Alpha structure could be started in 2032, and the possible commencement of CO_2 storage operations in the Gamma structure in the south of the Horda Platform in 2034 (Fig. 15).

However, the timing of the different CO_2 storage sites is tentative. For instance, the availability of (3) Smeaheia Gamma structure is dependent on the outcome of future oil and gas exploration in the area and may be either postponed or never be carried out. Equinor will drill a hydrocarbon exploration well (Gladsheim in the Gamma structure) in near future, and the outcome of that well will most likely influence the interest to use this structure for CO_2 storage. Also, the order of (1) and (2), is still very open, and will be decided by the Northern Lights project and Gassnova in the coming years.

In long-term context it is also interesting to consider including the Troll Gas Field into the development plans for the storage hub. The field will be in production for several decades, possibly until year 2060. However, it represents a large potential for CO_2 storage that can be phased in as the other large storage sites in the hub are getting filled. In Fig. 15, we have anticipated that CO_2 injection can start in 2055.

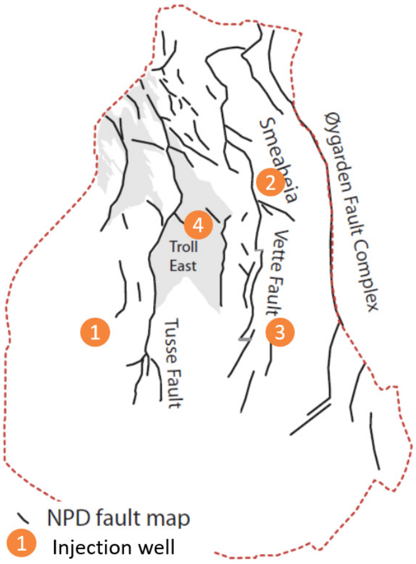

Fig. 14 Location of potential storage sites in the Horda CO_2 Storage Hub. (1) Aurora structure, (2) Alpha structure, (3) Gamma structure and (4) Troll Field. See Fig. 15 for timing for the storage sites.

All sites have been mapped with seismic surveys and have been subjected to several desktop studies, including the simulations in this work. However, the geological horizons and fault descriptions used have not been consistent from one study to the next. Likewise, the representation of petrophysical heterogeneities varies considerably. There are, therefore, still large uncertainties in the simulated storage capacities. The situation can be expected to improve when additional data have been obtained and interpreted. The results from two new exploration wells, in the Smeaheia Formation Gamma structure and Johansen Formation Aurora structure, are anticipated towards the end of year 2019-early 2020.

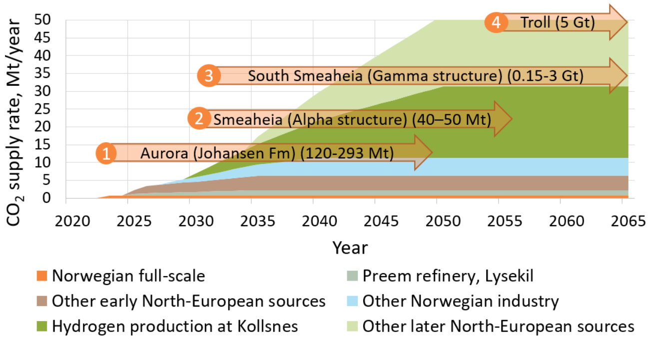

Fig. 15. Horda CO_2 Storage Hub deployment for CO_2 supply (million tonnes per year) from sources in Norway, Sweden and Northern Europe. A possible schedule for tie-in of the prospective storage sites linked to a Horda CO_2 Storage Hub, as discussed in this paper, is marked with arrows. The arrows show possible starting dates and estimated potential storage capacity. For location see Fig. 14.

8. Conclusions

In this work, which is part of the ALIGN-CCUS project we have evaluated the potential of using the Horda Platform, offshore western Norway as a European industrial CCS Cluster, with the focus and investigation of the storage potential and options. The effect of large-scale depletion due to the gas production at the Troll Field, has been considered in the simulation approaches.

The simulation and resulting range of CO_2 capacity estimates show that the study area has at least four potential storage sites: the

1) The Aurora structure, southeast of Troll in the Johansen Formation (120- 293 Mt),

2) The Smeaheia Alpha structure, in the northern part of the Sognefjord Formation (40-50 Mt),

3) The Smeaheia Gamma structure (Sognefjord Formation) (0.15-3 Gt) and

4) Troll Field, after cessation of gas production in the Sognefjord Formation (3-5 Gt).

We sketch an annually rate and timeline for which possible sites could be used for the development of the industrial-scale Horda CO_2 Storage Hub over the next thirty years. Possible CO_2 supply rates (million tonnes per year) from sources in Norway, Sweden and Northern Europe is used as input. These estimates show potentially totally CO_2 stored by 2050 in range of 810 Mt, and 1.85 Gt in 2065.

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