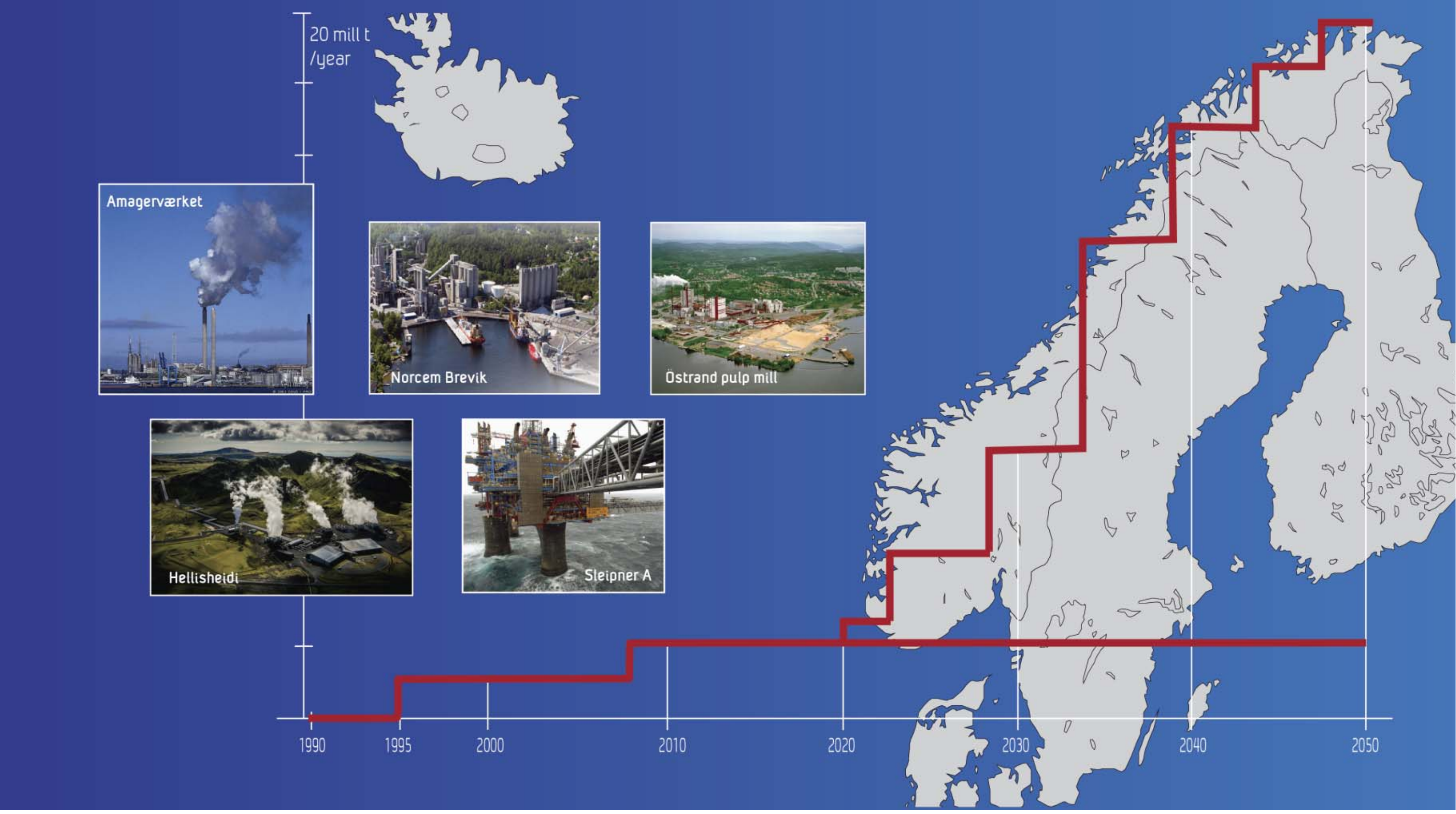

CO_2 storage modelling and capacity estimation for the Trøndelag Platform, offshore Norway - using a basin modelling approach

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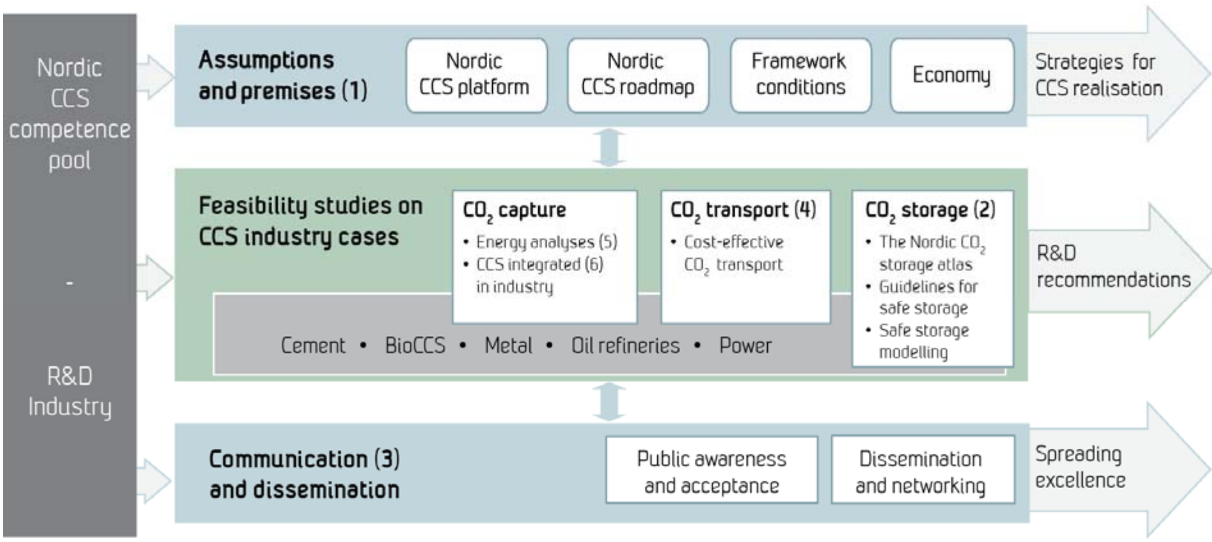

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Summary

There are several approaches to estimate possible storage capacities for aquifers and traps in sedimentary basins, this paper used a modified version of the basin modelling software SEMI which applies a ray tracing technique to migrate CO_2 within a carrier bed below a sealing cap-rock. A modelling strategy for a systematic modelling of maximum trap storage capacities and a mapping of possible "safe" injection localities for a storage unit were used.

Simulations were carried out for the Trøndelag Platform, offshore Norway covering an area of ca. 15,000 km^2. The Middle Jurassic Garn Formation is considered as a good candidate for CO_2 storage. Two simulation approaches were tested. First, injection in the Garn Fm. over the whole study area were simulated, to get the maximum total trap storage capacity. Secondly, simulations were carried out with 38 CO_2 injection sites. From these, the injection sites which caused migration out of the study area where removed. Finally, 7 sites with very low probability for migration out of the area were selected. These "safe" injection sites were mainly mapped in the centre of the Trøndelag Platform where only a few faults are mapped.

Keywords Storage capacity, modelling, CO_2 injection, Trøndelag Platform

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Date October 2014

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About NORDICCS

Nordic CCS Competence Centre, NORDICCS, is a networking platform for increased CCS deployment in the Nordic countries. NORDICCS has 10 research partners and six industry partners, is led by SINTEF Energy Research, and is supported by Nordic Innovation through the Top-level Research Initiative.

CO_2 storage modelling and capacity estimation for the Trøndelag Platform, offshore Norway - using a basin modelling approach

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During the last years, several projects have been mapping and modelled CO_2 storage in the Trøndelag Platform area, offshore Mid-Norway (e.g. Rinna et al. 2013, Halland et al. 2011). The mid Jurassic Garn Formation seems like a promising reservoir for CO_2 storage activities. The north-westwards dipping structure is characterised by a high sand content only moderately buried (< 2 km). Consequently porosity and permeability are excellent for CO_2 storage purposes. Formation thickness has been estimated at between 100 and 150 m, and the number of faults is low on the Platform. In addition, the Garn Formation is overlaid by thick shale sequences further reducing fault leakage risk and also suggesting a low risk for cap rock leakage.

A basin modelling tool named SEMI (Sylta 2004), originally developed for hydrocarbon migration modelling will be used for the CO_2 storage modelling for the Trøndelag Platform. SEMI uses a ray-tracing (flow path) technique to migrate oil, gas and CO_2 or other compounds within a carrier bed below a sealing cap-rock. The technique uses the dip of the carrier to determine pathway directions. In order to model CO_2 migration and entrapment the tool has been adapted with respect to time steps suitable for CCS and physiochemical behaviour of the CO_2 phase (Rinna et al. 2012, Grøver et al. 2013). Secondary migration losses are computed during the ray-tracing according to volumes lost in dead-ends and micro traps, in addition to the required saturation of the pore space of the migration stringers. This saturation requirement can be computed from Darcy permeability grids and relative permeability relationships.

In 2011 the Nordic Top-level Research Initiative funded a Nordic centre of excellence for CCS, named NORDICCS, where a web-based Nordic CO_2 storage atlas is to be released in 2015 and also prospective CO_2 sites in the Nordic region will be selected (Anthonsen et al. 2014). As a part of this project further modelling of the storage in the Trøndelag Platform will be carried out. This modelling will include multi-storage approach, with many injection sites (10-20 sites) modelled for the same storage unit and period. Also storage in two reservoir units e.g. Ile and Garn Formation should be tested. The overall aim with this work is to quantify the storage potential in this area, and to map the storage migration path ways, and also the storage traps for the Trøndelag Platform.

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CO_2 storage modelling and capacity estimation for the Trøndelag Platform, offshore Norway - using a basin modelling approach

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Abstract

There are several approaches to estimate possible storage capacities for aquifers and traps in sedimentary basins, ranging from static theoretical capacities estimates to more detailed methods involving dynamic modelling. In this paper, we used a modified version of the basin modelling software SEMI [1, 2] which applies a ray tracing technique to migrate CO_2 within a carrier bed below a sealing cap-rock. We present a modelling strategy for a systematic modelling of maximum trap storage capacities and a mapping of possible "safe" injection localities for a storage unit. Two end-member models regarding the influence of faults were tested. The basin modelling results are compared and validated with results obtained from an reservoir simulation software.

Simulations were carried out for the Trøndelag Platform, offshore Norway covering an area of ca. 15,000 km^2. The slightly north-westwards dipping Middle Jurassic Garn Formation (Fm.) is considered as a good candidate for CO_2 storage. It is widely deposited at the Trøndelag Platform, with a thickness around 120 m and shallow buried (<2 km). It is overlain by a thick shale-mudstone sequence (the Middle Jurassic Viking Group), and thick Cretaceous shales favouring a low risk for caprock leakage.

Two simulation approaches were tested. First, injection in the Garn Fm. over the whole study area were simulated, to get the maximum total trap storage capacity. The modelling showed a storage capacity of 2.0 Gt with no faults and 5.2 Gt using interpreted faults at top Garn Fm. level as input to the simulations. Secondly, simulations were carried out with 38 CO_2 injection sites. From these, the injection sites which caused migration out of the study area (e.g. upward to the rim of the storage unit, with only Quaternary coverage), where removed. Finally, 7 sites with very low probability for migration out of the area were selected. These "safe" injection sites were mainly mapped in the centre of the Trøndelag Platform where only a few faults are mapped.

Keywords: CO_2 storage; basin modelling; Trøndelag Platform; migration pathways

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1. Introduction

One feasible option to reduce CO_2 emission into the atmosphere is carbon capture and storage in aquifers and traps within sedimentary basins [e.g., 3, 4]. Offshore Norway CO_2 injection on industrial scale has been ongoing in the Sleipner field in the North Sea since 1996 [5], and in the Snøhvit area during the last years [6].

The possibilities to monitor in-situ CO_2 behaviour, e.g., by repeated 3D seismic surveys [7], or in-situ measurements are very costly and time-consuming. Thus, the safety and capacity evaluation of potential storage units and injections sites relies to a high degree on mathematical and numerical models [8]. Many simulators which solve multi- component and phase equations to model CO_2 behaviour under reservoir conditions are available [e.g. 9]. However, such models require extensive computational power, very good data-coverage as well as a detailed geological knowledge of the working area. If geological CO_2 storage will become an industrial standard, it will be necessary to test different geological scenarios and map reliable injection sites especially during a first evaluation phase in an underexplored area. For such a purpose, fast simulations covering large areas are required. Migration and trapping behaviour of supercritical CO_2 is similar to hydrocarbons and thus basin modelling approaches coming from gas modelling might be suitable to evaluate carbon storage problems. The Trøndelag Platform, offshore Mid-Norway (Figure 1) has been subject of several CO_2 related research projects such as the Gestco [10], CO_2STORE [11], SiteChar [12] projects. Previous studies covering parts of the area indicate that the Jurassic units are well suited for industry scale CO_2 storage [10, 12, 13].

In this contribution we use an updated version of SEMI [1, 2], a basin modelling software usually applied to simulate migration and trapping of hydrocarbons in sedimentary basins. We test a systematic modelling approach on the mid Jurassic Garn Fm. whereby in particular the effects of fault permeability are studied. We aim to estimate maximum trap storage capacities as well as migration path ways, and to map "safe" CO_2 injection sites.

2. Geological setting

The Trøndelag Platform, offshore Norway covers an area of more than 50,000 km^2 (Figure 1). It is roughly rhomboid in shape and is situated between 63ºN - 65º50'N and 6º20'E - 12ºE [14]. The platform has been a large stable area since the Jurassic and it is covered by relatively flat-lying and mostly parallel-bedded strata that dip gently towards the north-west. The investigated central Platform is confined to the Halten Terrace in the west by the Bremstein Fault Complex, to the Helgeland Basin in the north by the Ylvingen Fault Zone, to the Froan Basin the south-east by the Vingleia Fault complex, and bounded to the east by Caledonian crystalline basement (Figure 1). Both the Helgeland and the Froan Basin have been recognized as subsidiary elements of the Trøndelag Platform.

During the last two decades the Halten Terrace, west of the Trøndelag Platform area has become a rather mature exploration area for the oil and gas industry with currently 16 fields under production [15]. Data from the area is available from the Norwegian Petroleum Directorate homepage [www.npd.no].

The Garn Fm. has been interpreted as homogenous sandstone, with a lateral extent of 10's of km. However, Gjelberg et al. [16] demonstrat a facies diachroneity of the formation on regional scale, and Corfield et al. [17] support this view on a local scale (Smørbukk area). The Garn Fm. consists of medium to coarse grained, moderately to well-sorted sandstones [18]. Mica-rich zones are also represented. The Garn Fm. is deposited in a near shore, shallow marine environment, with an assumed N-S trending paleo-coastline [19]. In the Halten Terrace area the Garn Fm. has a measured porosity of 25-34% at a depth of 2.2 km [20]. In well 6407/6-6 (Mikkel South) a permeability of 700 mD is measured.

Above the Garn Fm, the caprock unit is predominantly the Viking Group with Melke and Spekk formations that are totally dominated by mudstones and shales (Figure 1c). Thin beds of carbonate and scattered sandstone stringers are minor constituents. The Viking Group are post-rift deposits. Thick sequences of Cretaceous and Tertiary fine-grained sedimentary deposits and Quaternary glacial deposits overlie the Viking Group. Due to Neogene uplift the Mesozoic and Early Cenozoic succession crop out at the seafloor beneath Quaternary deposits close to the Norwegian coast. That is why it is important to study possible migration routes.

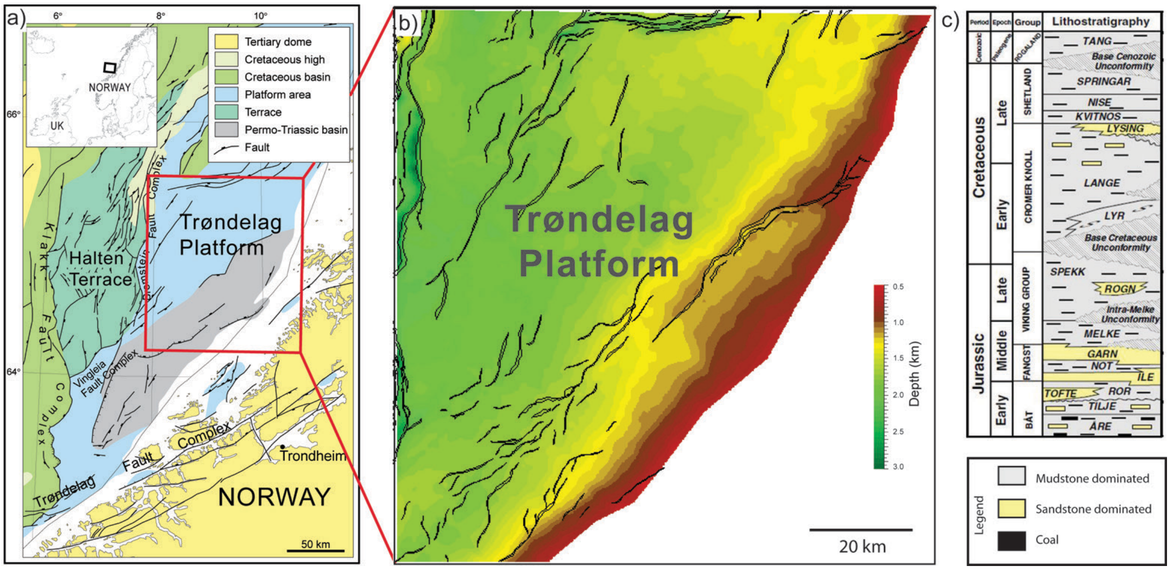

Fig. 1. (a) Main structural elements offshore Mid-Norway. The working area within the Trøndelag Platform is marked by the red box [modified from 14, 21]. (b) Depth map (km) of the top Garn Fm. (c) Lithostratigraphy of Mid-Norway with interpreted input horizons marked [from 18].

3. Methodology

In order to test a basin modeling approach we used an updated version of the SEMI software [1, 2] and compared final results to outcome of the commercial reservoir simulation software ECLIPSE 100.

3.1 Basin Modelling - SEMI

The basin modelling tool SEMI has been developed to model quantitative hydrocarbon migration and exploration risk [1]. It includes all ‘standard’ migration processes and can handle multi-carrier secondary migration and entrapment on geological time scales. It uses a ray-tracing technique to migrate CO_2 within a carrier bed just below a sealing cap-rock. This carrier unit can also act as a storage unit. The technique uses the dip of the carrier to determine pathway directions (Figure 2). The phase pressure, volume, and temperature properties are computed as properties for each trap during simulations. Secondary migration losses are computed during the ray-tracing according to volumes lost in dead-ends and micro traps, in addition to the required saturation of the pore space of the migration stringers. This saturation requirement can be computed from Darcy permeability grids and relative permeability relationships.

The methodology for SEMI adapted as a tool for CO_2 storage simulations was presented in Grøver et al. [2], where two loss mechanisms were introduced: (i) Migration loss (trapping of CO_2 along migration pathway) (ii) Dissolution of CO_2 at gas-water-contact within trap entities. Gas is here referring to the CO_2 phase independent of its supercritical or not supercritical state.

CO_2 dissolution is modelled mainly at the gas-water phase contact within a trap. In our implementation the dissolution by convective mixing is assumed to be the dominant term, and for simplicity, the only term included. After onset of convection, dimensional analysis and numerical flow simulations suggest that this rate of dissolution by convective mixing (C_c) at the gas water contact (in [*m/s*]) is given by equation (1):

$$C_c = \frac{k_v}{\mu_w} \Delta\rho_{dis} g \psi(\zeta) \tag{1}$$

Thereby, k_v is the vertical permeability ratio, μ_w is the viscosity of water, $\Delta\rho_{dis}$ is the water density change during CO_2 dissolution, g is gravity and ψ (ζ) is a dimensionless intrinsic function estimated in flow simulations [22]. The ζ is proportional to the permeability ratio (k_v/k_h) [23]. In the software we have introduced a CO_2 dissrate-factor as the inverse value of the intrinsic function.

The simulator workflow starts with finding every migration path within the carrier unit and correspondently identifies all drainage areas (each with a distinct trap structure). The injected CO_2 will then be migrated towards its nearest trap structure along the identified paths. If the CO_2 volume is greater than the trap structure capacity, the surplus volume of CO_2 will be spilled along a distinct spill path towards neighbouring trap structure. These steps are performed until there is no more CO_2 volume left to migrate.

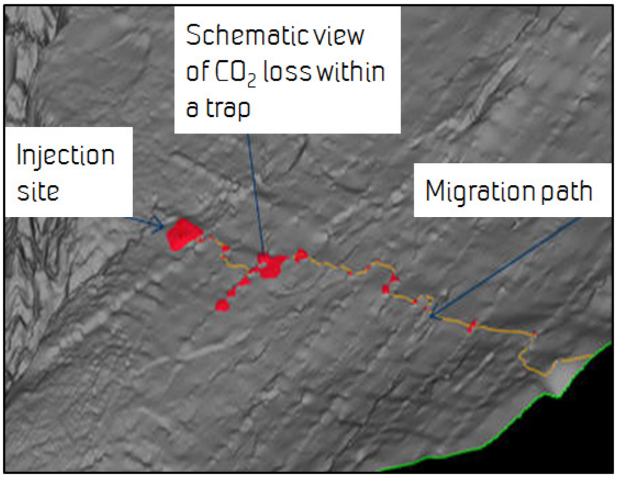

Fig. 2. Schematic overview of how CO_2 will migrate from injection site to traps and maybe also out of the reservoir (orange and green line).

3.2 Reservoir Modelling – ECLIPSE

Dynamic modelling of CO_2 injection into deep saline aquifers is performed using the industry standard reservoir simulator ECLIPSE 100 from Schlumberger. ECLIPSE 100 is a fully-implicit, three phase, three dimensional, general purpose black oil simulator which accounts for all trapping mechanisms involved in CO_2 storage except mineral trapping.

3.3. Input parameter and data used

For the basin modelling approach, an interpreted seismic horizon at top Garn Fm., the today's seabed and an interpreted fault map at top Garn Fm are used as input. The parameters are set as shown in Table 1.

A 3D reservoir model of the Trøndelag platform has been constructed based on data from well logs and interpretation of top Garn Fm. from seismic. Porosity and permeability was estimated to vary between 15-40 % and 0.5-10 D (Table 1). Salinity was set to 3 wt% TDS and a uniform temperature gradient of 40 °C/km and surface temperature of 4 °C were assumed.

Table 1. Input parameters used in the simulations.

Parameters	SEMI model	ECLIPSE 100
Thermal gradient	40 [ºC/km]	40 [ºC/km]
Entry pressure	5000 [Pa]	
Water depth	Present day seabed [m]	Present day seabed [m]
Pressure	Hydrostatic conditions [MPa]	Hydrostatic conditions [MPa]
Average net permeability	1 [D]	0.5-10 D, a log linear relation between porosity and permeability
CO_2-diss-rate factor	Variable [dimensionless]	
Total injection	Variable [Mt]	700 Mt
Porosity	Compaction curve from [24] calibrated vs. data from [20].	15-41% (depth dependent); [20] with cut-off at 41%
Thickness maps*	Garn Fm. 127 m	Garn Fm. 127 m
Top reservoir map	Interpreted top Garn Fm. seismic map (surface)	Interpreted top Garn Fm. seismic map (surface)
Fault map	Interpreted fault map at top Garn Formation	

*Well data from six wells: 6407/6-3, 6407/6-5, 6407/6-4, 6407/6-1, 6407/9-7 and 6408/4-1

3.4. Basin modelling set up

The horizontal grid dimension is set to 200 m x 200 m. Two set-ups are used for the basin modeling approach. To estimate the total trap storage capacity a "pseudo" CO_2 layer below the reservoir layer where introduced (Figure 3a). Secondly, injections were carried out in 38 injection sites distributed over the whole working area (Figure 3b).

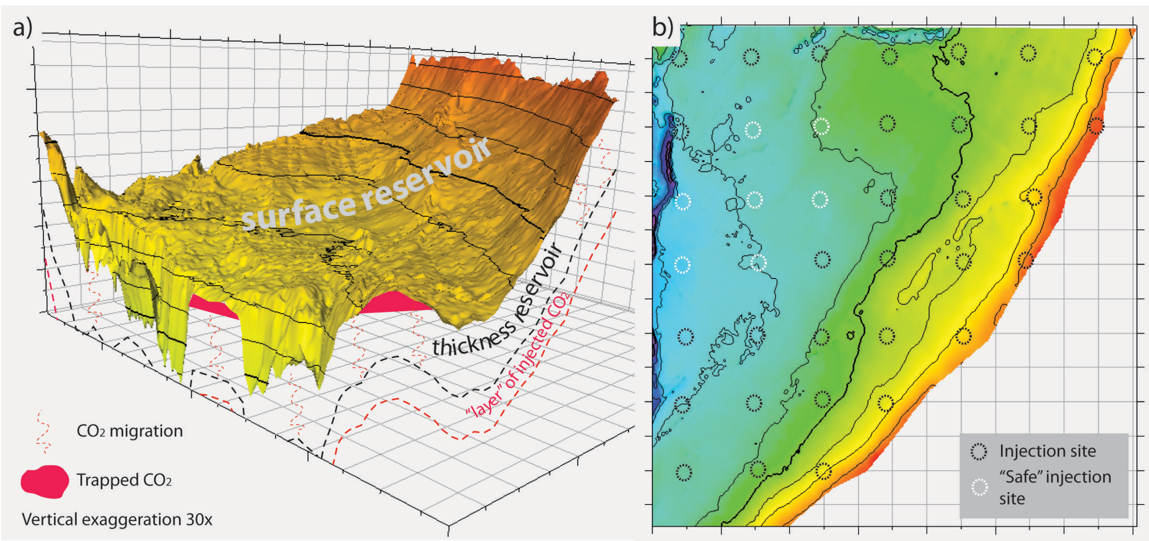

Fig. 3. Concept for the basin modelling approach. (a) At first, the total trap storage capacity was estimated by flooding the reservoir with CO_2. This is technically done by adding a "layer" of CO_2 under the reservoir unit. (b) Secondly, simulations were carried out using 38 CO_2 injection sites. The simulations showed that injection into 7 sites did not cause migration out of the Garn Fm., shown as "safe" injection sites.

3.5. The reservoir model set up

The grid dimension is set to 500 m x 500 m. Vertical grid layer thickness is refined below the top. Average vertical layer thickness is 16 m. Faults are implemented as geometrical features, but with no transmissibility modifications. Net-to-gross values are set to 1-0.85 with a random assigned algorithm for the reservoir layer.

4. Results

4.1. Modelling of total trap storage capacity for the Garn Formation

The total trap-storage capacity was estimated assuming the parameters given in Table 1 and using the modelling set-up described in section 3.4. An important assumption is that the whole platform is overlain by sealing layers. An infinite amount of CO_2 was "injected" into the carrier unit, migration loss and dissolution in the traps was disabled. Two scenarios were tested (a) no faults or open faults (b) all faults are sealing (Figure 4). The modelling results suggest a total maximum trap storage capacity of ca. 2.0 Gt for the no faults scenario and a significantly higher value of 5.2 Gt if sealing faults were taken into account (Figure 4).

Some traps show significant differences for the two scenarios, e.g., trap 1 does not exist if faults are neglected whereas up to 716 Mt of CO_2 can be stored in the trap if all faults are sealing. In general, the traps in the faulted northern part of the working area give higher capacities for the fault scenario (e.g., traps 1, 2, 3). In contrast, traps located in the center of the working area show similar results for both scenarios (e.g., traps 4, 5, 7).

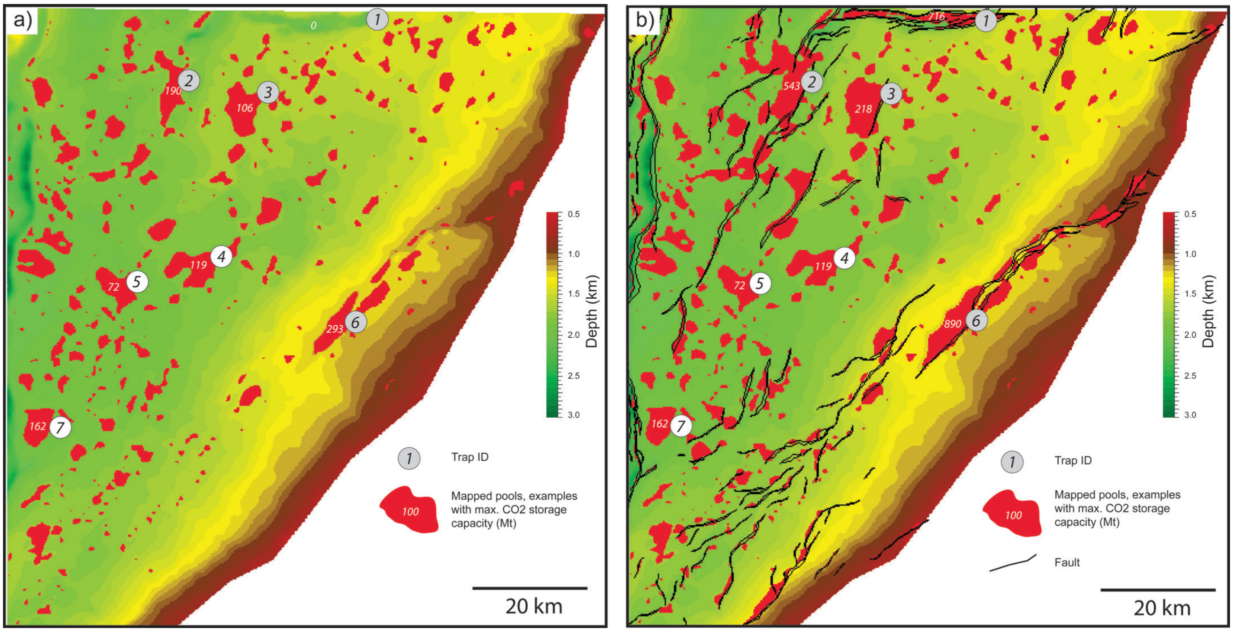

Fig. 4. Modelled CO_2 accumulations projected onto the Garn Fm. depth map using the basin modelling approach. In order to estimate a total trap-storage capacity for the Garn Fm. the whole area was "flooded" with CO_2 and all traps were filled to a maximum. CO_2 dissolution during migration and within the trap entities was disabled. (a) For the scenario without faults a total trap storage capacity of ca. 2.0 Gt was modelled. (b) The second scenario assuming sealing faults gave a total trap storage capacity of ca. 5.2 Gt.

4.2. Varying the CO_2 dissolution rate factor

The CO_2 dissrate-factor was varied for a base case with open faults, multi injection sites and with a total injection of 1000 Mt CO_2. The amount of dissolved CO_2 was dependent on the dissrate-factor (Figure 5). The factor was calibrated versus migration distance simulated by reservoir models for Gassum Formation, Skagerrak area [25] and core measurement of residual CO_2 saturation (ca. 25 %) from the unconsolidated Utsira Sand at the Sleipner CO_2 injection site [26]. From this calibration, a dissrate-factor of 250 was used further in the basin modelling approach.

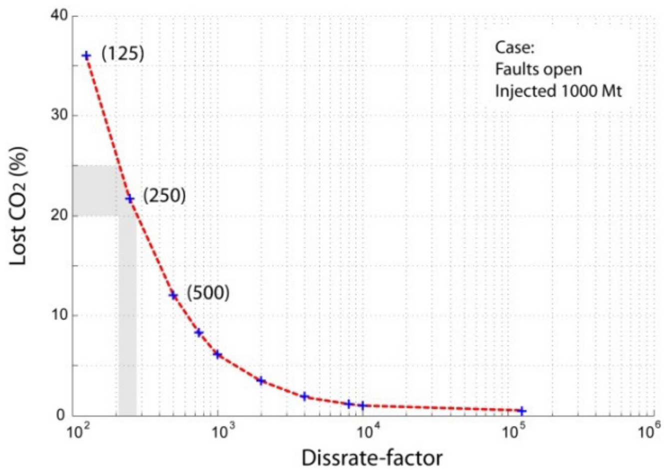

Fig. 5. Scatter plots highlighting the impact of the CO_2 dissolution rate-factor on SEMI modelling results. Assuming high CO_2 dissolution at gas-water-contact has a significant impact on the calculated total CO_2 loss in the SEMI software. Grey shaded area depicts the most realistic values for our models.

4.3. Mapping possible injection sites for the Garn Formation

In a second approach SEMI was used for a systematic mapping of possible "safe" injection sites. At first, 38 CO_2 injection sites with constant plume radii's of ca. 1.6 km were distributed with equal spacing (ca. 20 km) over the area of interest (Figure 2). Thereby, very high amounts of CO_2 (up to 3.8 Gt) were injected over a period of 100 year assuming a CO_2 dissrate-factor of 250 (Figure 5) for a no faults scenario and a sealing fault scenario. Subsequently, injection sites which caused CO_2 migration out of the boundary of the working area were excluded. Our modelling results indicate 7 injection sites which fulfil the criteria for safe CO_2 storage (Figures 2, 6).

The final 7 injection sites were used as input to the reservoir model and a simulation injecting a total of 700 Mt CO_2 over 100 years was performed. Simulating CO_2 loss over 3000 years took approximately 23 hours (CPU-time) on a standard desktop single processor. A total of 35 % of the injected CO_2 was dissolved after 3000 years and the remaining CO_2-phase was capillary trapped below the sealing cap rock or as residual phase in the pores. CO_2 saturation after 3000 years is shown in Figure 6c.

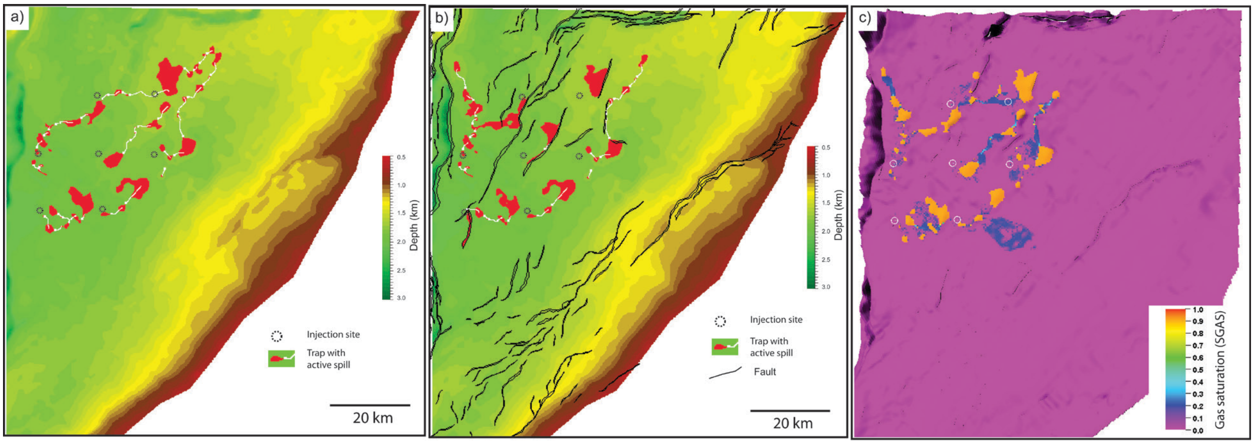

Fig. 6. Basin modelling results of the systematic mapping for "safe" CO_2 injection sites compared with reservoir modelling results. Map view of the top Garn Fm. horizon with pools of CO_2 accumulations and active spill paths 100 yrs after the injection. (a) For the no faults scenario a total trap storage capacity of ca. 447 Mt was modelled. (b) For the simulations taking sealing faults into account a total trap storage capacity of ca. 477 Mt was estimated. (c) CO_2 saturation below the top of the storage unit in the reservoir model after 3000 years.

5. Discussion

The method used to simulate the total trap storage capacity, with a pseudo CO_2 layer below the storage unit, is a very simplified approach. However, it gives a maximum estimate of how much CO_2 can be trapped if all the traps are filled. The simulation results show a large range from 2.0 Gt with no faults to 5.2 Gt with faults included (Figure 4). A reservoir model for the Garn/Ile aquifer by Halland et al. [19] gave a maximum storage capacity of up to 8 Gt CO_2 assuming a half open system (contact with a larger aquifer). In a second model set-up they used a closed system which indicates a drastic lower storage capacity of only 0.4 Gt.

In a trap-scale the basin modelling approach can give a rapid overview of which structures might be good candidates for planning CO_2 injection. For example, traps 4 and 7 (Figure 4), can store large volumes both with and without sealing faults. Other traps like 2 and 3 show significant differences in the storage capacity of CO_2 e.g., trap 2 with a capacity of 543 Mt taking sealing faults into account and a significantly lower capacity of 190 Mt without faults.

These modelling results illustrate the significance of the chosen model assumptions on the final storage capacities.

5.1. CO_2-dissrate factor

CO_2 storage capacity estimate in the SEMI approach focus on reservoir capacities and thus the CO_2 dissolution is modelled mainly at the gas-water phase contact within a trap. By running several simulations, varying the dissrate-factor from minimum 125 to 10000 (Figure 5), the corresponding loss of CO_2 can be evaluated. The simulations show that SEMI's migration and storage estimates strongly correlate with the dissrate-factor (Figure 5). The equation (1) illustrates the strong dependency of the dissrate-factor. In principle, this factor represents the lateral and vertical heterogeneous lithologies within the trap, and its impact on the dissolution rate [23]. Unfortunately, for the Garn Fm. lithological variations are not mapped and thus a homogenous sediment model was applied. Core measurement of residual CO_2 saturation from the unconsolidated Utsira Sand at the Sleipner CO_2 injection site gave values of CO_2 loss of ca. 25 % [26]. Applied to our modelling area, such a value would indicate a dissrate-factor of ca. 250 which was applied in the final model for the 7 selected injection sites.

5.2. Effect of fault on migration pathways and traps

In a brittle undeformed, homogeneous sedimentary strata overlaying by a sealing unit, buoyancy forces would cause CO_2 migration from the bottom towards the top of the layer and finally migrating along the top towards the highest points. Faults interrupt this general migration path and can cause deflection from the estimated migration paths depending on their properties and spatial distribution. In our approach the faults were modelled as an open conduit per se [27] or as sealing. For all modelled cases with sealing faults the regional fault distribution has a significant influence on the lateral migration pathways and on the trap capacities (Figures 4, 6). Here we only presented end-member models for sealing or open faults which visualised the drastic impact on final trap storage capacities. In nature, fault permeability's will vary substantially and a rigorous testing is necessary for CO_2 storage estimates. This might be achieved by using Monte Carlo simulation testing various fault models.

5.3. Mapping of "safe" injection sites

In the mapping of "safe" injection sites, we followed strict limitations such as that no migration out of the storage unit should occur, for both scenarios (with and without faults). Finally, 7 sites showed no migration spill out of the Garn Fm.

For the selected 7 injection sites two fault scenarios (with or without faults), were modelled injecting a total amount of 700 Mt CO_2 and applying a dissrate-factor of 250 (Figure 6). The selected injection sites are mainly located in the center of the working area following an SW-NE trending axis. Our model results indicate that the spatial distribution of sealing faults has a significant influence on CO_2 storage capacities. For both cases the injected CO_2 remains in the working area but migration pathways and CO_2 accumulations in traps differ significantly. For the no fault scenario the spill paths follow a general SE-NW trend (Figure 6a). In contrast assuming sealing faults would deflect some of the spill path in an S-N trend following the strike of the faults (Figure 6b). Moreover, total CO_2 as well as migration losses are with ca. 30 Mt and 1.9 Mt lower than in the non-fault case (40 Mt and 3.1 Mt). The general low migration losses point to the main weakness of the basin modelling approach. SEMI simulates migration using the ray-tracing (flow path) technique and migration loss is spatially very limited. In a proper reservoir simulator software CO_2 flows along a migration front and covers a larger area. This gives more reliable results on the migration loss and migration paths. The results for the reservoir models show a similar distribution for the CO_2 saturation in the working area (Figure 6a-c). However, the reservoir model gives more realistic estimates for the total CO_2 loss (ca. 35 % or 245 Mt; 3000 years after injection).

6. Conclusion

According to our modelling estimates the Garn Fm. of the Trøndelag Platform has in structural closures, a total trap storage capacity in the range of 2.0 Gt for the non-fault scenario and 5.2 Gt with faults included. This estimate is made assuming no migration loss and a very low dissolution rate in the traps and can be interpreted as a maximum estimate. Seven locations for "safe" CO_2 injection have been mapped and results are validated by an ECLIPSE reservoir model. Compared to conventional reservoir simulators, the basin modelling approach allows fast simulations (minutes instead hours/days) which can be utilized for testing several scenarios in a short time-period. Thus, this approach offers a possibility for a rigorous statistical testing of different parameters.

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