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Storage potential for CO₂ in the
Froan Basin area of the
Trøndelag Platform, Mid-Norway

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<p>Summary:</p> <p>The sedimentary sequence in the subsurface of the Trøndelag Platform (Mid-Norway) has been assessed with regard to its suitability for long-term storage of CO₂. This study is part of the EU-funded CO2STORE project and was stimulated by the geographical proximity of the Trøndelag Platform to planned CO₂ point sources in Mid Norway.</p> <p>The sedimentary succession has been interpreted from seismic data and by analogy to the geology in the nearby Haltenbanken hydrocarbon province. Key seismic horizons have been mapped on seismic and depth-converted. Since no hydrocarbon exploration wells have been drilled in the Froan Basin area, the properties of the sedimentary formations are not known. In analogy to the sedimentary succession in hydrocarbon fields nearby, three formations of Jurassic age are likely to have properties suitable for CO₂ injection: the Tilje, Ile and Garn Formations. These formations dip to northwest. It was assumed that the conformable seal of these formations is tight, while the Quaternary overlying their subcrop is not sealing. Small anticlinal traps and fault-bounded traps exist locally in these formations.</p> <p>A digital subsurface geology model has been generated based on the mapped horizons. Petrophysical properties of the potential reservoir formations are only tentatively known from nearby fields. Therefore several cases with variable reservoir properties have been simulated. The simulations are for simplicity restricted to the Garn Formation. They assume injection at the base of this formation, approximately 60 km (trap case) and 55 km (no-trap case) from its subcrop below the Quaternary, at a depth of approximately 1.9 km. None of the simulations with up to 100 Mtonnes injected CO₂ resulted in any leakage largely because most of the CO₂ was trapped in subtle structural traps. Dissolution of the CO₂ into formation water and trapping as residual gas will aid local fixation of the CO₂.</p> <p>The simulations utilised only one of three formations and only a small areal fraction of the Trøndelag Platform (southeasternmost part of the Froan Basin area). The overall storage potential of the Jurassic formations of the Trøndelag Platform is thus estimated to be of the order of several 1000 Mtonnes. A more detailed study is proposed to derive a more precise estimate of the storage capacity and to evaluate the seal quality above the reservoir formations.</p>					
Keywords: Aquifer		CO ₂		Carbon dioxide storage	
Reservoir simulation		Numerical modelling		Trøndelag platform	
Leakage rate		Storage capacity		Jurassic	

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1. EXECUTIVE SUMMARY

Plans for a combined heat and power plant (CHP) in Skogn in the inner part of the Trondheimsfjord (Mid-Norway) include options to capture CO₂ from the flue gas stream. At Tjeldbergodden in Mid-Norway, a methanol plant emits at present approximately 450 000 tonnes of CO₂ per year, and plans exist to build an additional methanol plant there with a similar CO₂ emission and a gas-fired power plant which would emit approximately 2 100 000 tonnes of CO₂ per year. In order to reduce anthropogenic greenhouse gas emissions, several potential sites for underground storage of CO₂ are investigated as part of the EU- and industry-funded project CO₂STORE. One of the potential storage sites offshore Mid-Norway is the Trøndelag Platform. The Beitstadfjord Basin close to the CHP in Skogn has been assessed in an earlier study (Polak et al. 2004a) which concluded that that basin was not suitable for long-term CO₂ storage. The Frohavet Basin close to the coast has also been studied (Polak et al. 2004b) and a restricted storage potential has been identified. The present report documents the results of an assessment of the subsurface sedimentary succession of the Froan Basin area of the Trøndelag Platform with regard to its suitability for long-term storage of CO₂.

The objective of the assessment is to predict if CO₂ injected at the typical emission rate from a CHP of approximately 2 000 000 tonnes per year would stay in the subsurface and would leak - if at all - at a rate acceptable to reach long-term goals for maximum atmospheric CO₂ concentrations.

The geometry and sedimentary content of the southeastern Trøndelag Platform have been interpreted from a dense network of seismic data. The sedimentary rocks of the platform dip towards northwest (Figure 1.21, Figure 1.2). The relevant part of the Trøndelag Platform has not been drilled but information about the age and lithology of its geological formations is available from some wells at its margins and from hydrocarbon wells in the Haltenbanken area.

Three main formations with a high likelihood to possess favourable reservoir properties have been identified: these are the Lower to Middle Jurassic Tilje, Ile and Garn Formations, which contain relatively coarse-grained clastic deposits. These formations are overlain by a sequence of up to 1650 m thickness consisting largely of low-permeable clastic rocks which are assumed here to constitute a seal. The potential reservoir formations subcrop in the east below the Quaternary. The Quaternary is here assumed to be not sealing.

The reservoir formations are locally dissected by faults. However, these faults die out rapidly upwards above the Garn Formation and should thus not constitute efficient leakage pathways. In contrast, they may define local structural traps. Some anticlinal or domal traps exist but their volume is small.

A digital subsurface geology model has been generated based on the mapped horizons. Since the petrophysical properties of the potential reservoir formations are not known due to the lack of wellbore data, they had to be estimated based on data from the nearby hydrocarbon fields. The implicit uncertainty was addressed by simulation of a range of cases with varying reservoir properties (porosity, horizontal permeability, k_v/k_h ratio, NTG).

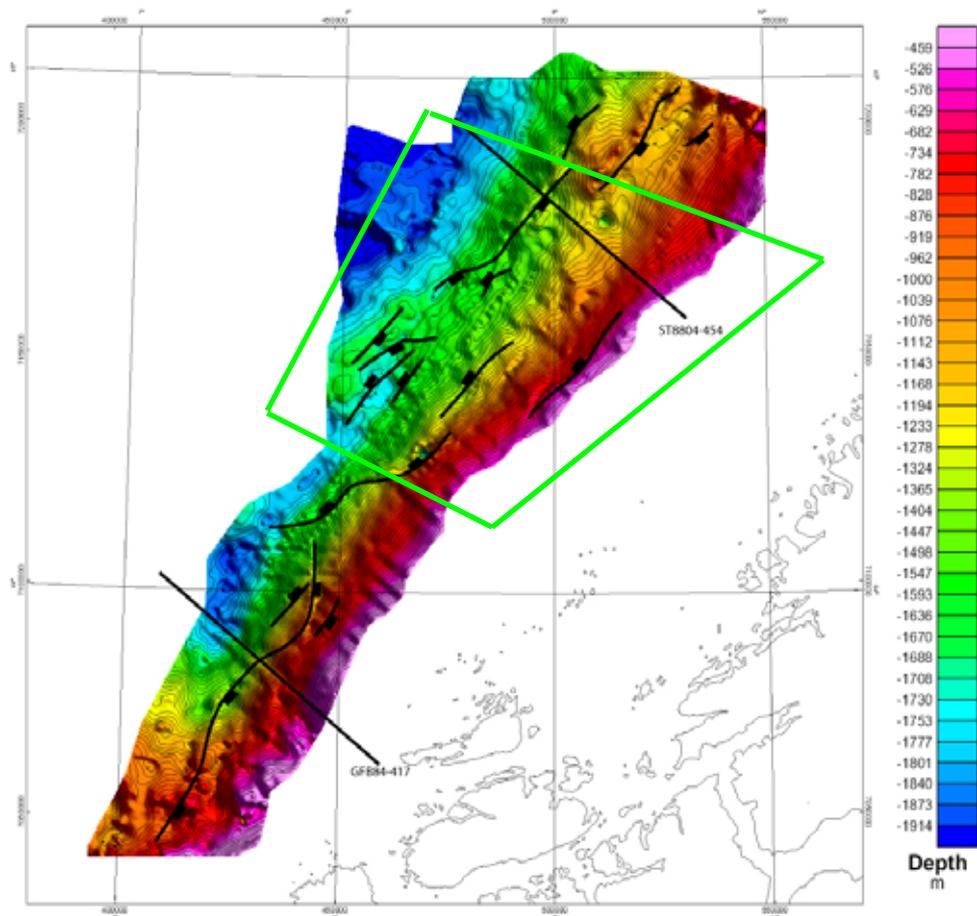


Figure 1.1 Structural map in depth (m) of the Base Upper Jurassic horizon (top Garn Formation). Green lines indicate the part of the Trøndelag Platform which was selected for reservoir simulation investigation. From this part of the reservoir two NW-SE-trending segments were chosen for simulation runs.

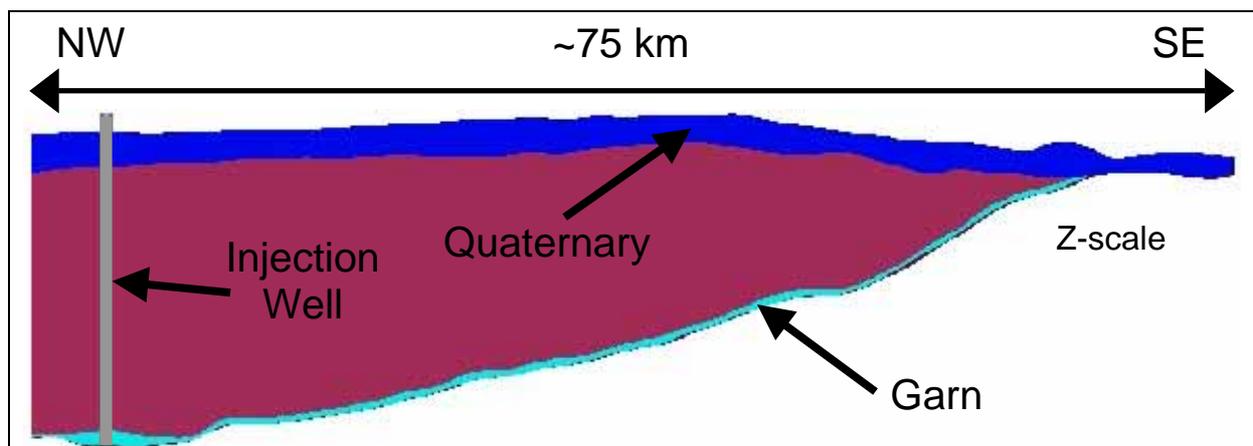


Figure 1.2 Schematic cross-section through the northeastern one of the two reservoir models of the Trøndelag Platform that were used in simulations. Note that the z-scale is exaggerated ten times.

Simulation of the subsurface behaviour of injected CO₂ was carried out with the commercial black-oil simulator Eclipse 100. For simplicity, only two segments of the Trøndelag Platform of approximately 2250 km² (trap case) and 1450 km² (no-trap case) were simulated and the simulations were restricted to the Garn Formation. The simulations assume injection at the base of this formation, at a depth of approximately 1900 m b.s.l. approximately 60 km (trap case) and 55 km (no-trap case) km from its subcrop below the Quaternary. The simulated injection rate was 2 million tonnes per year over a period of 25 years. For comparison, cases were also simulated with the same injection rate but injection time extended to 50 years.

At the probable pressure and temperature conditions in the Trøndelag Platform, CO₂ will have a relatively high density of approximately 600 to 800 kg/m³ below a depth of about 500 m b.s.l. This is lower than the density of the formation water. The main process expected to occur in case of CO₂-injection here is buoyancy-driven upward migration within the Garn Formation until the CO₂ reaches an impermeable seal. It will fill available structural traps at this level and then migrate upwards along the top of the reservoir formation until it escapes into the sea water. Some CO₂ will be trapped in the pore space as residual gas. Some additional CO₂ will be dissolved into formation water in the reservoir unit, but this process is slow, operating over a time scale of 1000s of years.

Simulations were carried out for two scenarios: injection below a local domal trap and injection at a position likely to result in fast migration towards the subcrop. For none of the simulations any leakage occurred. The general feature of all simulations is that CO₂ migrates upwards along the base of the seal towards the subcrop. In most cases, all CO₂ is trapped in structural traps which it reaches on its way. However, all CO₂ that is not trapped locally in structural traps is dissolved into the formation water before it could come into the proximity of the subcrop. Dissolution into the formation water entails an immobilization of the CO₂. In fact, formation water with dissolved CO₂ has a higher density than pristine formation water and it is likely to migrate downwards within the reservoir.

The overall conclusion is thus that the Froan Basin area of the Trøndelag Platform seems to be suitable for underground long-term CO₂ storage.

The simulations carried out so far utilised only one of three potential formations and only a small areal fraction of the Trøndelag Platform. The overall storage potential of the Jurassic formations of the Trøndelag Platform is thus estimated to be of the order of several 1000 Mtonnes. This estimate requires the validity of at least one of two assumptions: (a) that sufficient structural traps are present everywhere in the basin, or (b) that CO₂ dissolution appears fast enough to inhibit far migration of free CO₂. A more detailed study is proposed to derive a more precise estimate of the storage capacity and to evaluate the seal quality above the reservoir formations.

Effects of pressure increase have not been assessed in detail. A distribution of pressure increase due to injected CO₂ over large parts of the basin is likely, which will keep the overall increase small. Injection at high rates at several places in the basin may however lead to pressure increases, which should be studied in a comprehensive model for the whole basin.

2. INTRODUCTION

Industrikraft Midt-Norge (IMN) is planning to build a combined heat and power plant (CHP) at Fiborgtangen in Skogn (Figure 2.1) in the inner part of the Trondheimsfjord. The plant will utilize natural gas from Haltenbanken, off Mid-Norway. In the EU-funded GESTCO-project, the total storage capacity for CO₂ in aquifers offshore Mid-Norway was estimated to be ca. 30 000 Mt, assuming a storage efficiency of 2% for the aquifers (Bøe et al. 2002). A significant portion of this storage capacity is on the southeastern part of the Trøndelag Platform (Froan Basin area, east and south of the major hydrocarbon province on the Halten Terrace/Nordland Ridge). CO₂ storage in oil and gas fields on the Halten Terrace will not be possible in the next ten to twenty years (except for enhanced oil recovery) due to probable conflicts with the hydrocarbon exploitation. The alternative is thus to store CO₂ in aquifers east and south of the major hydrocarbon province, an area which has previously not been mapped in detail for the purpose of CO₂ storage. This area has the advantage of being closer to onshore CO₂ point sources, which will require shorter pipelines.

With this background, it was decided to participate in the partly EU-funded project CO2STORE, which runs from 2003 to 2005 and which aims to prepare the ground for widespread underground storage of CO₂. The project shall investigate how lessons learned from previous projects, e.g. SACS, GESTCO and NASCENT, can be implemented for CO₂ storage in European aquifers offshore and on land. The project is organized in the following four work packages:

- WP1, Transfer of technology to four other potential demonstration projects (Feasibility Case Studies).
- WP2, Long-term behaviour of injected CO₂
- WP3, Monitoring
- WP4, Management

As part of WP1, Feasibility Case Study Mid-Norway is carried out in cooperation between the Geological Survey of Norway (NGU), SINTEF Petroleum Research, Industrikraft Midt-Norge (IMN) and Statoil. The objectives of this feasibility case study are to:

- Identify suitable saline aquifers for underground CO₂ storage on the southeastern part of the Trøndelag Platform and in fjords along the coast of Mid-Norway.
- Determine storage capacity by regional mapping, reservoir parameter quantification, and simulation of migration and underground behavior of CO₂ in these aquifers.
- Investigate and evaluate stability of CO₂ storage in the study area. The risk for, mechanism behind and effect of potential leakages from the storage formations will be studied.
- Suggest further investigations of prospective aquifers.

In this report, the results of the mapping, reservoir parameter quantification and migration simulation for the Froan Basin area of the Trøndelag Platform are summarized, and the storage capacity is evaluated. Similar studies have been performed for the Beitstadfjord and Frohavet basins (Polak et al. 2004a, 2004b) earlier in the project.

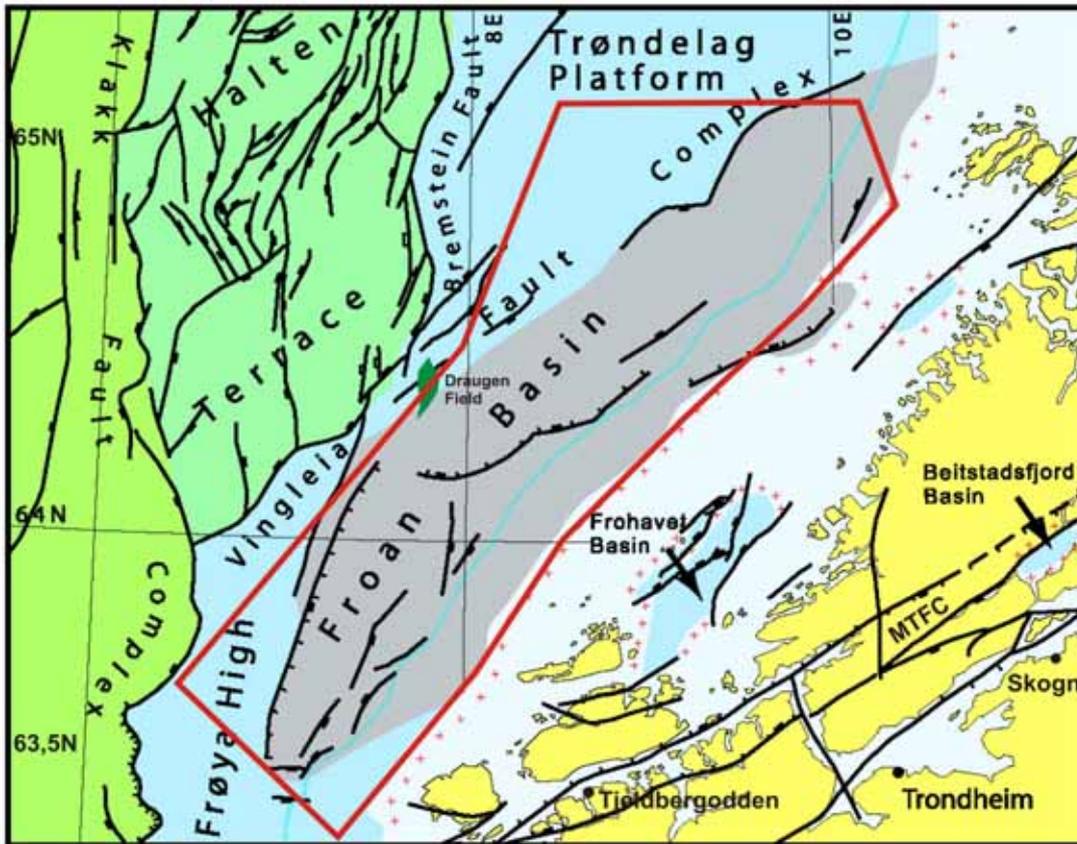


Figure 2.1 Geological map of Mid-Norway showing the main structural provinces. The location of Skogn and the Trøndelag Platform (which includes the Frøya High and the Froan Basin) are shown. Modified from Blystad et al. (1995). The study area is outlined in red. MTFC: Møre-Trøndelag Fault Complex.

3. GEOLOGY OF THE TRØNDELAG PLATFORM

The Trøndelag Platform (Figure 2.1) covers an area of more than 50 000 km². It is roughly rhomboid in shape and is situated between 63°N - 65°50'N and 6°20'E - 12°E (Blystad et al. 1995). This has been a large stable area since the Jurassic and the platform is covered by relatively flat-lying and mostly parallel-bedded strata that usually dip gently northwestwards.

The Trøndelag Platform is one of the major structural elements off central Norway and includes several subsidiary elements like the Nordland Ridge, Frøya High and Froan Basin. The Platform is bounded to the east by outcropping Caledonian crystalline basement. The Møre-Trøndelag Fault Complex forms the southeastern boundary. The southern part of the Trøndelag Platform, investigated in this project, is separated from the Halten Terrace to the west by the Bremstein Fault Complex. In its southwestern corner, it meets the Jan Mayen Lineament and the Møre Basin, from which it is separated by the southern part of the Klakk Fault Complex (Figure 2.1)

Most of the scattered NE- to NNE-trending normal faults on the platform have minor displacement. Cretaceous strata are thin and partly absent over the southern part of the platform, but both Lower and Upper Cretaceous strata occur (Blystad et al. 1995). The platform surface (base of the Cretaceous) is underlain by a uniform thickness of Jurassic deposits overlying deep basins filled by Triassic and Upper Palaeozoic sedimentary rocks. The pre-Jurassic rocks are arranged in NE-SW trending, en-echelon basins which contain a profound unconformity of probable Middle Permian age that separates an early period of intense block faulting from the tectonically quieter Late Permian and Triassic. The Froan Basin (Figure 2.1) is the southernmost of these pre-Jurassic basins. The Vingleia Fault Complex forms the northwestern boundary of the basin and was reactivated in both Jurassic and Cretaceous times. Towards the south the Froan Basin becomes progressively shallower, as a result of a combination of an original thinning of the basin sequences and a later uplift and erosion in late Mid- to Late Jurassic times (Blystad et al. 1995).

The Trøndelag Platform was initiated during the late Middle Jurassic-Early Cretaceous rift episode when the Nordland Ridge and the Frøya High became uplifted. The Frøya High must have been a basement high at least from Late Permian times (Brekke 2000). All the elevated areas were deeply eroded in the Late Jurassic, and a peneplain developed across the Trøndelag Platform. The Nordland Ridge experienced further uplift and faulting during the Late Cretaceous and in the Tertiary. The western margin areas of the Trøndelag Platform can be considered an uplifted footwall.

The area was also tectonically active during earlier episodes, in Carboniferous to late Early Permian and Middle to Late Triassic times. Some minor Early Jurassic normal faulting occurred in parts of the platform area (Blystad et al. 1995). The only currently active fault zone cutting through the Trøndelag Platform is the Cretaceous Ylvingen Fault Zone located further north on the platform.

3.1 Seismic database

The Trøndelag Platform is covered by several 2D multichannel seismic surveys. A selection of seismic profiles from five surveys (ST8804, FRDE90, GFB84, MND84 and ST8707) was

used for the interpretation in this project. The seismic profiles cover an area of the Trøndelag Platform between latitudes 63°N and 65°N and the study area was limited westward by the Bremstein, Vingleia and Klakk Fault Complexes (Figure 2.1). Seismic profiles ST8707-483 and ST8804-472-A were used for correlation between our interpretations and those of Blystad et al. (1995) and Brekke (2000) (Figure 3.1, Figure 3.2 and Figure 3.3).

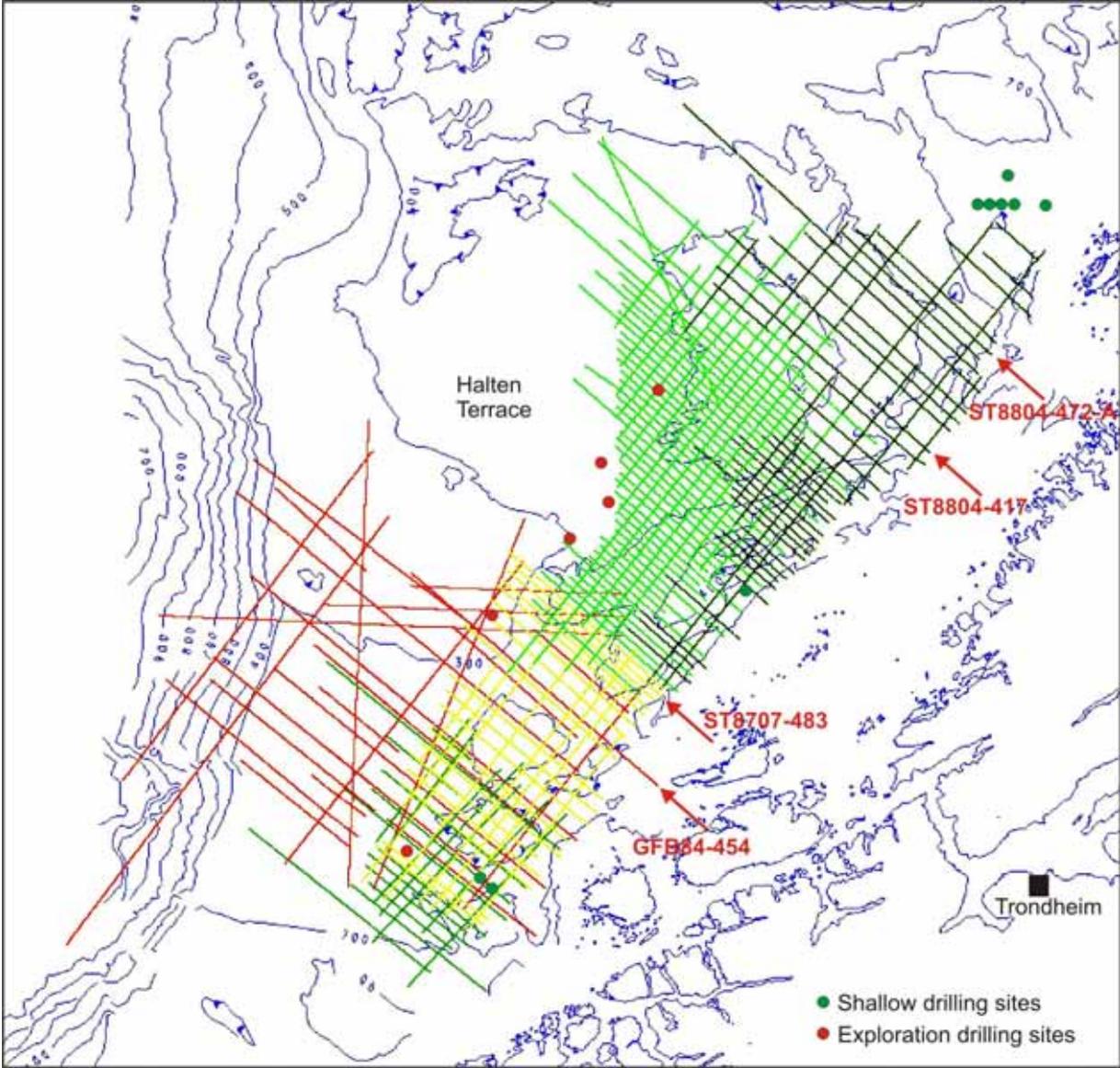


Figure 3.1 Seismic database. 100-m depth contours are shown for the shelf area. The location of interpreted seismic lines used as figure examples, and exploration drill holes used for depth conversion are also shown.

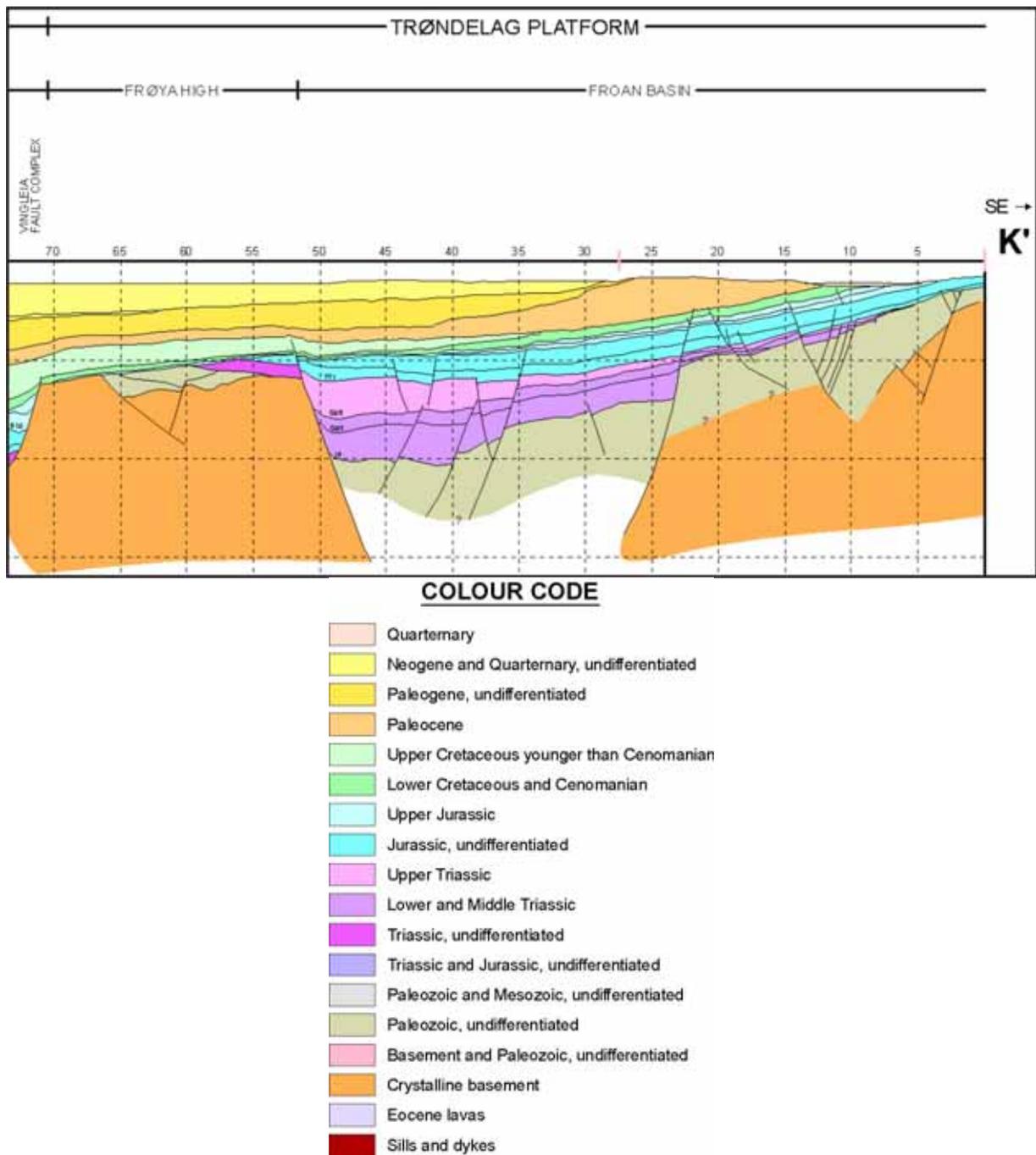


Figure 3.2 *Interpreted geoseismic section K partly based on seismic line ST8707-483 (from Blystad et al. 1995). See Figure 3.1 for location.*

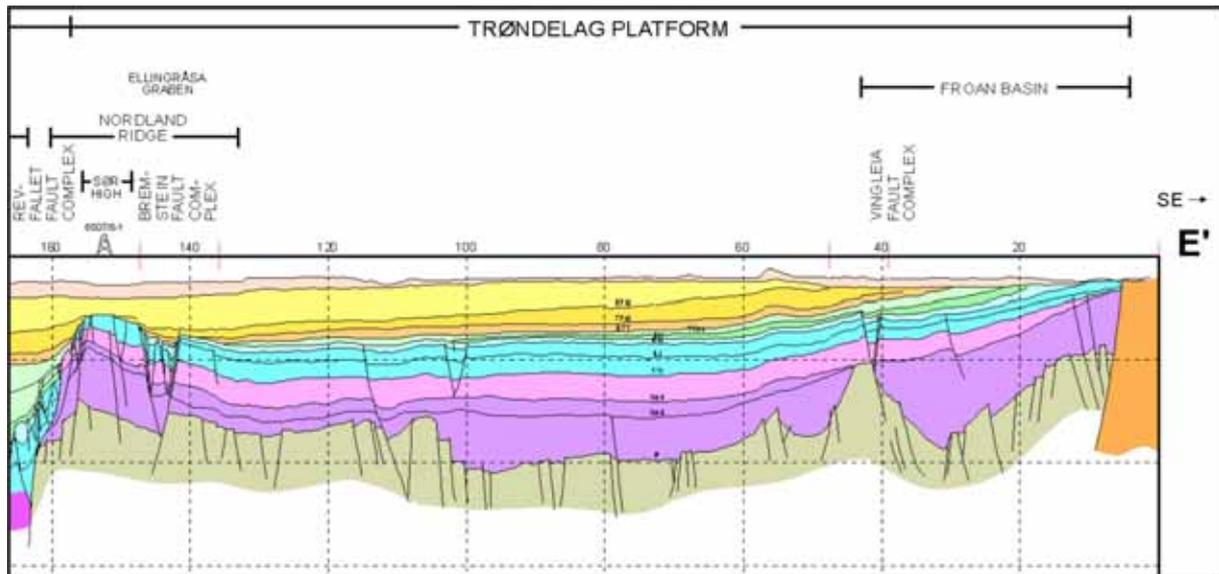


Figure 3.3 Interpreted geoseismic section E partly based on seismic line ST8804-472-A (from Blystad et al. 1995). See Figure 3.1 for location and Figure 3.2 for colour legend.

3.2 Bathymetry

The water depth on the investigated part of the Trøndelag Platform varies strongly. Bank areas such as Haltenbanken and Frøyabanken have water depths locally shallower than 200 m, while the depth in the intervening glacial troughs (Sklinnadjupet, Suladjupet, Breisunddjupet) are 400-500 m (Figure 3.1 and Figure 3.4). At the shelf edge in the west, the water depth increases rapidly to more than 800 m. In the southwest, the headwall of the Storegga Slide defines the shelf edge.

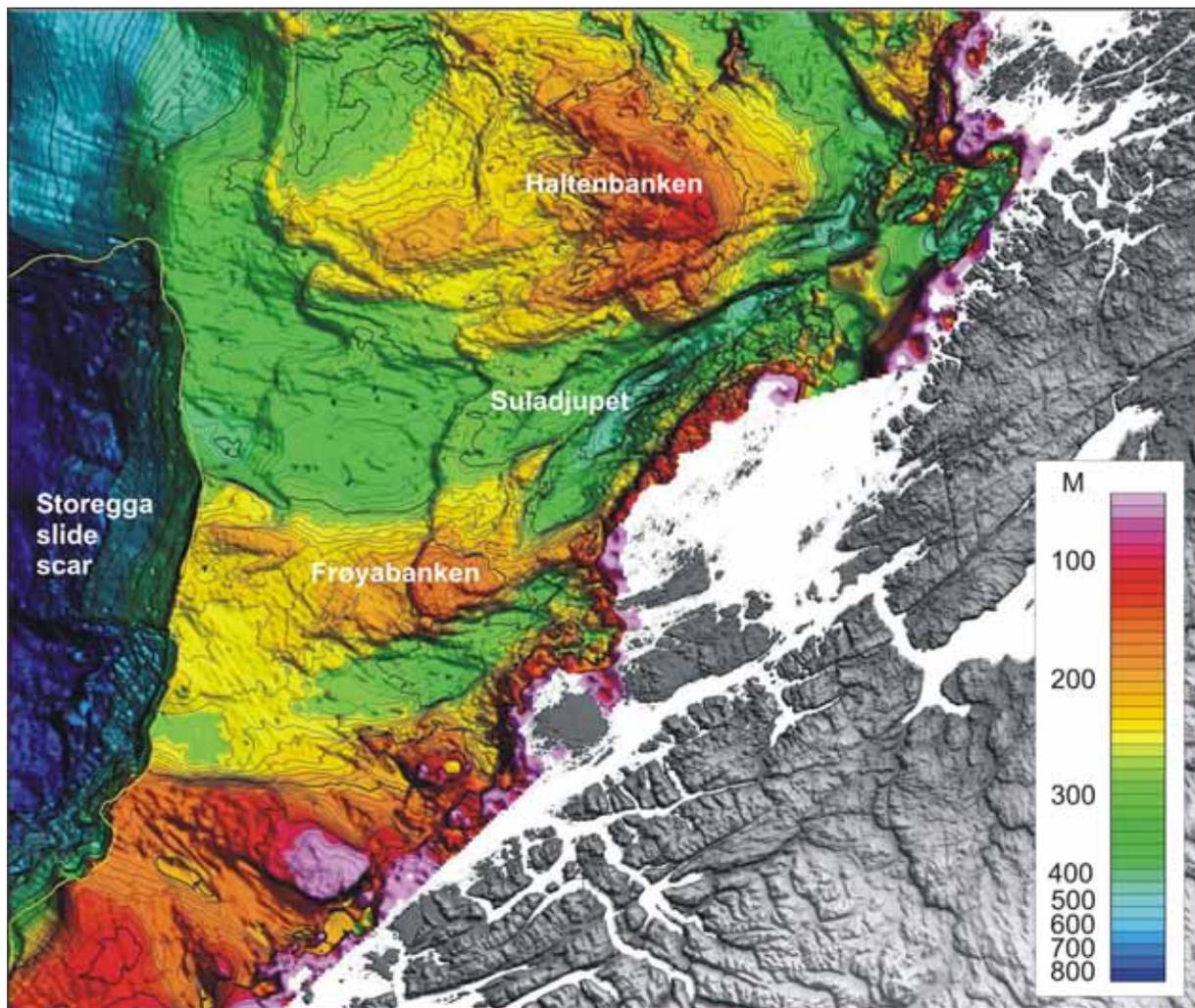


Figure 3.4 Bathymetry of the area of the Trøndelag Platform between latitudes 63°N and 65°N (modified from Ottesen et al. 2002). Yellow line shows the headwall of the Storegga Slide.

3.3 Stratigraphy

On the Trøndelag Platform, Triassic and older rocks have very low porosities and permeabilities (Bugge et al. 1984). They are thus probably unsuitable for CO₂-storage and have not been further considered in this study. The reservoir rocks with the largest theoretical storage potential are of Early to Middle Jurassic age (Bøe et al. 2002). Younger rock units are mostly fine-grained and/or glacial tills. They are thus considered as cap rocks on top of the Jurassic sandy formations. A description of the Mesozoic and Cenozoic lithostratigraphic succession offshore Mid-Norway was provided by Dalland et al. (1988). No deep hydrocarbon exploration wells have been drilled in the Froan Basin area of the Trøndelag Platform.

3.3.1 Jurassic reservoir rocks

On the southeastern Trøndelag Platform, the formations with assumed storage potential are the Åre, Tilje, Ile, and Garn Formations (Figure 3.5). These are separated by the shale-dominated Ror and Not Formations.

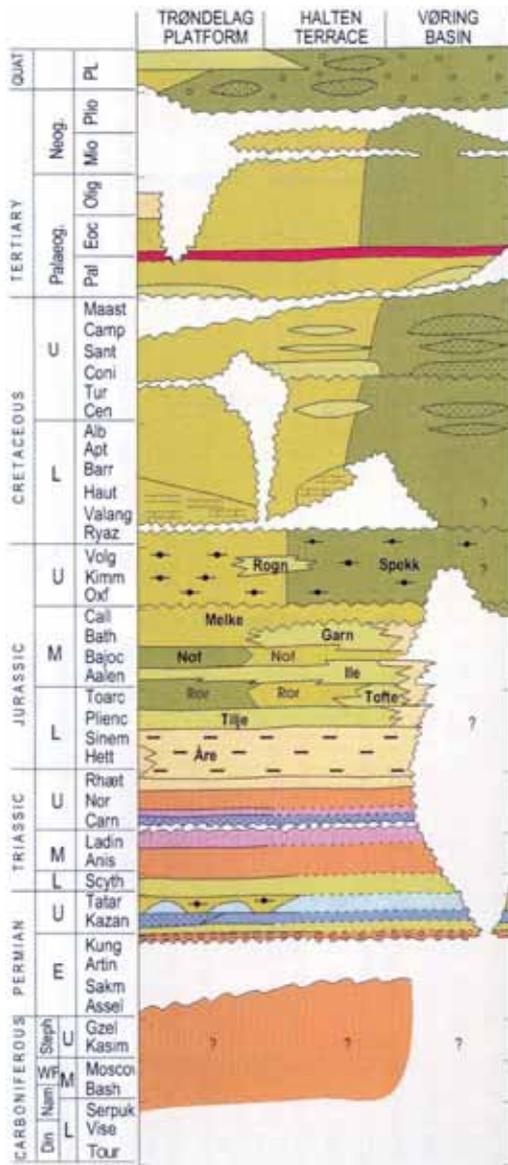
The reservoir interval considered for CO₂ storage in this study is located between two regional seismic reflectors interpreted as Intra Lower Jurassic (ILJ) and Base Upper Jurassic (BUJ). These reflectors can be traced throughout the investigated area, but are locally offset by normal faults.

If we assume that the ILJ is located in the uppermost part of the Åre Formation, the formations relevant for CO₂ storage would be the Tilje, Ile and Garn. The only stratigraphic wells that have drilled Jurassic sequences in the Froan Basin area are those belonging to the IKU B85 sampling program, located along the southeastern margin of the Trøndelag Platform (Bugge et al. 1984, Figure 3.1). Samples were collected with electric rock core drilling and vibrocore, which limited the core lengths to 5.5 m and 6 m respectively. A large number of exploration wells have drilled the Jurassic successions on the Haltenbanken Terrace. Table 3.1 contains aquifer parameters for the Tilje, Ile and Garn Formations (Figure 3.5) in Haltenbanken. These parameters are assumed to be representative also for the Jurassic deposits on the more landward part of the Trøndelag Platform.

Tilje Formation: In Haltenbanken, the Tilje Formation comprises fine to coarse-grained sandstones interbedded with shales and siltstones (Figure 3.5, Table 3.1, Dalland et al. 1988, Martinius 2001). The sandstones are commonly moderately sorted, have high clay content, and most beds are bioturbated. Shale clasts and coaly plant remains are common. Pure shale beds are rare; most of the finer grained interbeds are silty or sandy. Shallow drilling close to the coast (Bugge et al. 1984) indicates time equivalent deposits dominated by coarse-grained clastics. The formation was deposited in nearshore marine to intertidal environments (Martinius et al. 2001). Subcrops near the coast indicate a gradual transition to continental environments eastwards (Bugge et al. 1984).

Ile Formation: In Haltenbanken, fine to medium and occasionally coarse-grained sandstones with varying sorting are interbedded with thinly laminated siltstones and shales (Figure 3.5, Table 3.1, Dalland et al. 1988). Mica-rich intervals are common. Thin carbonate-cemented stringers occur, particularly in the lower parts of the unit. The formation represents various tidal-influenced delta or coastline settings. Sandstone-dominated successions of similar age have been located by sea-bottom sampling and shallow drilling on the eastern part of the Trøndelag Platform (Bugge et al. 1984).

Garn Formation: In Haltenbanken, the Garn Formation consists of medium to coarse-grained, moderately to well-sorted sandstones (Figure 3.5, Table 3.1, Dalland et al. 1988). Mica-rich zones are present. The sandstone is occasionally carbonate-cemented. The Garn Formation may represent progradations of braided delta lobes. Delta top and delta front facies with active fluvial and wave-influenced processes are recognized. Time-equivalent deposits have been mapped in the Frohavet and Beitstadfjord Basins further east (Sommaruga & Bøe 2002).



LEGEND

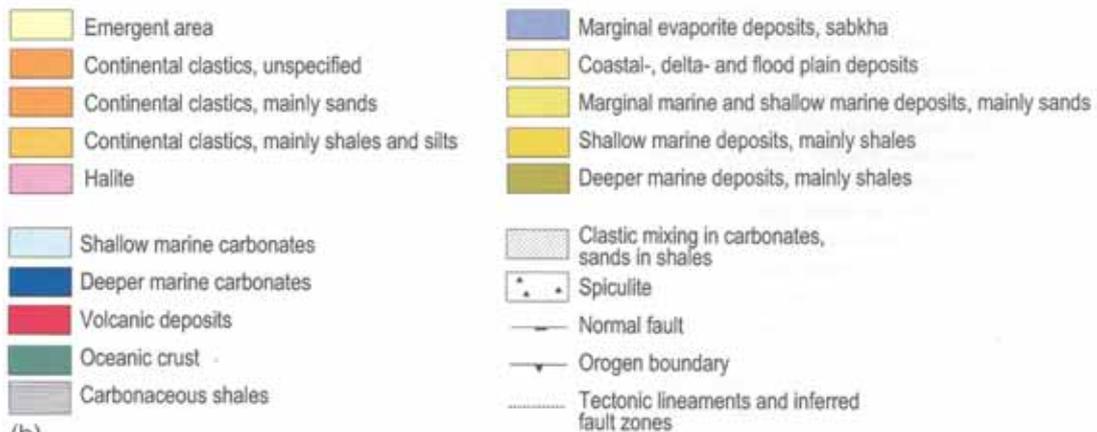


Figure 3.5 Stratigraphy on the Mid-Norwegian shelf. The stratigraphy on the Trøndelag Platform has been interpreted from seismic data correlated with wells in the Halten Terrace. Modified from Brekke et al. (2001).

Table 3.1 Estimated reservoir parameters for a maximum burial depth of 2.0-3.0 km. Values for porosity, permeability and net/gross are from published data on fields in Haltenbanken.

Formation	Aquifer thickness (m)	Porosity 2 km depth	Porosity 3 km depth	Permeability 2 km depth (mD)	Permeability 3 km depth (mD)	Net/Gross 2 km	Net/Gross 3 km
Garn	50	30%	20%	5000	1000	1	0.9
Ile	50	28%	21%	5000	650	0.85	0.65
Tilje	100	25%	20%	1000	500	0.85	0.65

On the southern part of the Trøndelag Platform, southeast of the Draugen Field (Figure 2.1), the succession between the ILJ and BUJ reflectors is several hundred metres thick. According to the Norwegian Petroleum Directorate, the thickness of the Tilje Formation alone reaches 450 m (Bøe et al. 2002). Towards the northeast there is a thinning of the accumulated succession to around 200 m. From various published descriptions (e.g. Blystad et al. 1995, Brekke 2000), we have estimated that of the total reservoir interval (ILJ-BUJ) thickness on the Trøndelag Platform, the distribution is as in Table 3.2.

Table 3.2 Thickness distribution in ILJ-BUJ interval.

Formation	Thickness distribution
Garn	27%
Not	5%
Ile	14%
Ror	27%
Tilje	27%

The strata generally dip gently towards the northwest. Along the coast, the dip may locally be as large as 5%, but on the central parts of the Trøndelag Platform the strata are subhorizontal.

3.3.2 Upper Jurassic, Cretaceous and Cenozoic cap rocks

The Jurassic reservoir rocks on the southeastern Trøndelag Platform are overlain by a thick succession of cap rocks (Figure 3.2 and Figure 3.3), and are interbedded with the claystone-dominated Ror and Not formations (between the Tilje and Ile formations and between the Ile and Garn formations, respectively). The Viking Group (Melke and Spekk formations, Figure 3.5), which occurs above the Garn Formation, is totally dominated by shales and mudstones. Thin beds of carbonate and scattered sandstone stringers are minor constituents. Only in the Draugen Field is sandstone (Rogn Formation) a significant component. The group extends to the basin margin on the eastern part of the Trøndelag Platform where it has been sampled just beneath the sea-floor at several locations (Bugge et al. 1984). The Viking Group is again overlain by thick successions of Cretaceous and Tertiary fine-grained sedimentary rocks and by Quaternary glacial deposits.

Due to Neogene uplift of the Norwegian mainland, the Mesozoic and Early Cenozoic successions typically subcrop at the seabed or beneath thin Quaternary deposits, in the southeast (Figure 3.2, Figure 3.3, Figure 3.6 and Figure 3.7). The subcropping strata along the coast have no top seal, but local fault seals may be present. Further west on the Trøndelag Platform, the Cretaceous succession provides a good top seal.

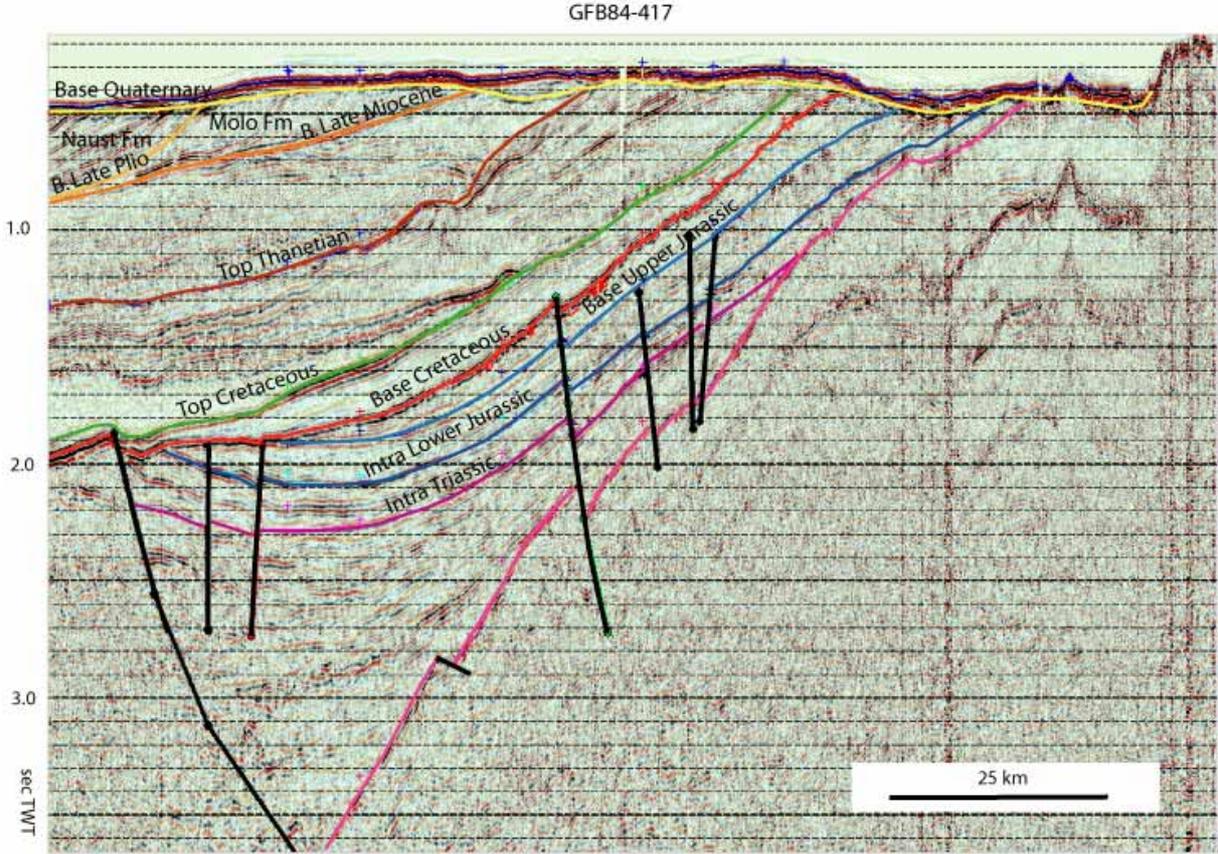


Figure 3.6 Seismic profile GFB84-417. See Figure 3.1 for location. SE is to the right.

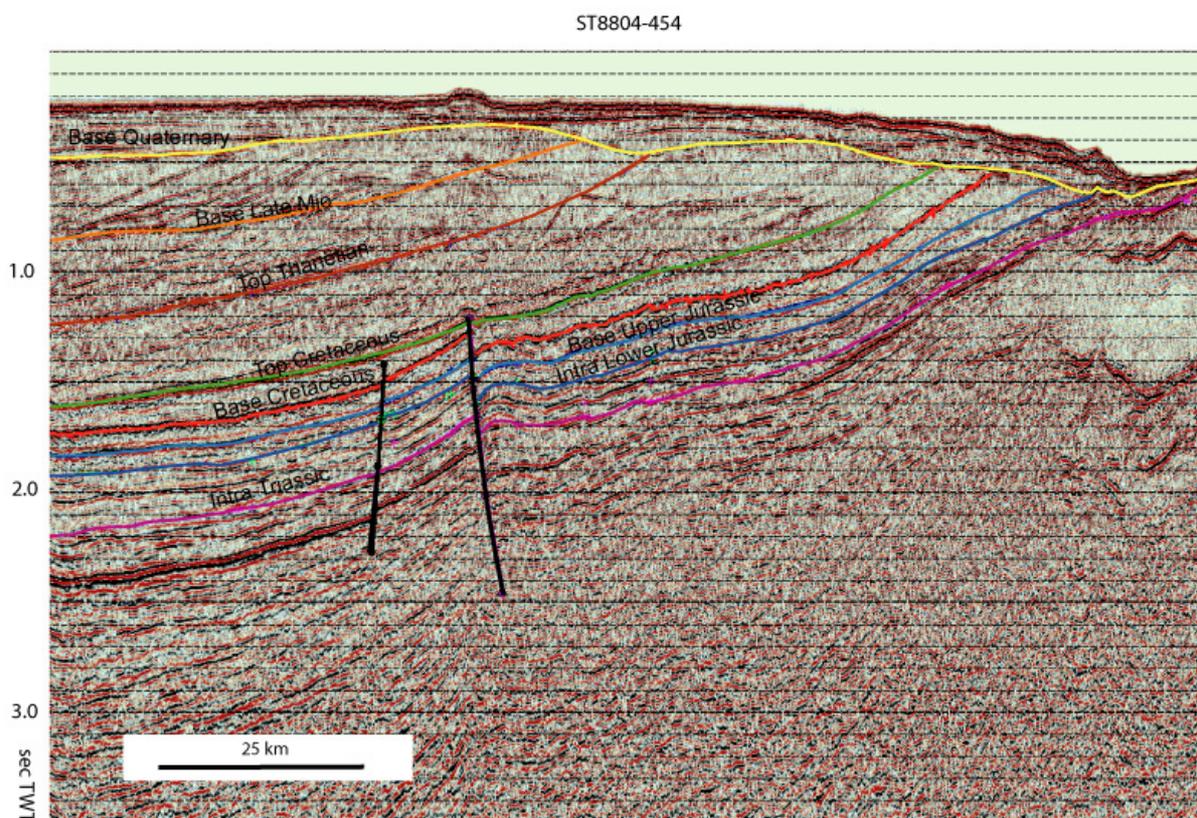


Figure 3.7 Seismic profile ST8804-454. See Figure 3.1 for location. SE is to the right.

3.4 Geological structure of the Froan Basin area of the Trøndelag Platform

3.4.1 Structural geology

Overall, the study area can be characterized as a northwest dipping monocline (Figure 3.8). This dip relates to a combination of the area being located along the basin edge, and to Neogene tilting. Neogene tilting was caused by uplift of the mainland and subsidence offshore. Erosion at wave base resulted in the observed subcrop pattern.

In the south, a syncline is present against the Frøya High and its development can be related to footwall uplift of the Frøya High along the Klakk Fault Complex. A limited portion of the study area covers the western flank of the syncline, which rises westward against the Frøya High. However, the majority of the area rises eastward towards the coast.

By and large, fault activity along the Klakk Fault Complex took place in Late Jurassic time. The faults in the study area are of Late Jurassic and Early Cretaceous age. At greater depth, the main bounding faults to the Froan Basin are of Permo-Triassic age.

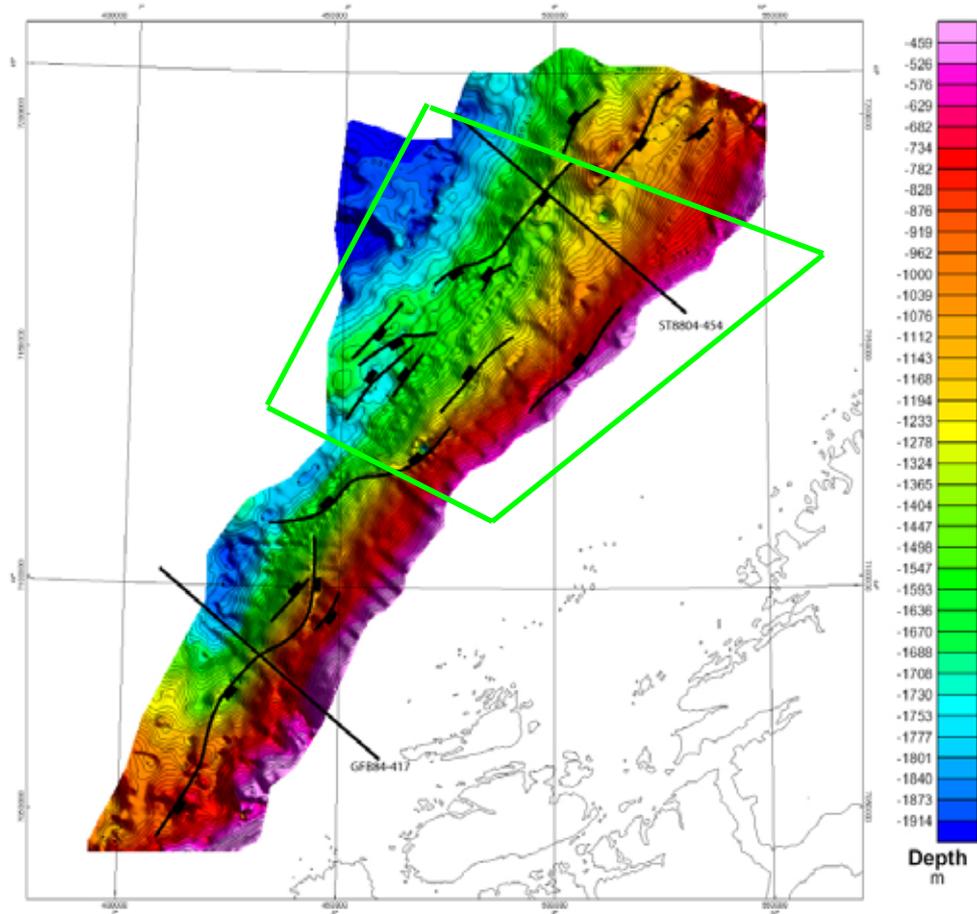


Figure 3.8 Structural map in depth (m) of the Base Upper Jurassic horizon (top Garn Formation). The location of seismic profiles GFB84-417 (Figure 3.6) and ST8804-454 (Figure 3.7) are shown as black lines. Green lines indicate the part of the Trøndelag Platform which was selected for reservoir simulation investigation. From this part of the reservoir two segments were chosen for simulation runs (see Figure 4.1).

3.4.2 Fault pattern

Overall, the study area is characterized by NE-trending, coast-parallel, normal faults (Figure 3.6 – Figure 3.9). The faults dip both landward and basinward and displacement is mainly less than ca. 150 milliseconds. The faults do not compartmentalize the area significantly. Thus, even if the faults were perfectly sealing they cannot be expected to form large structural traps.

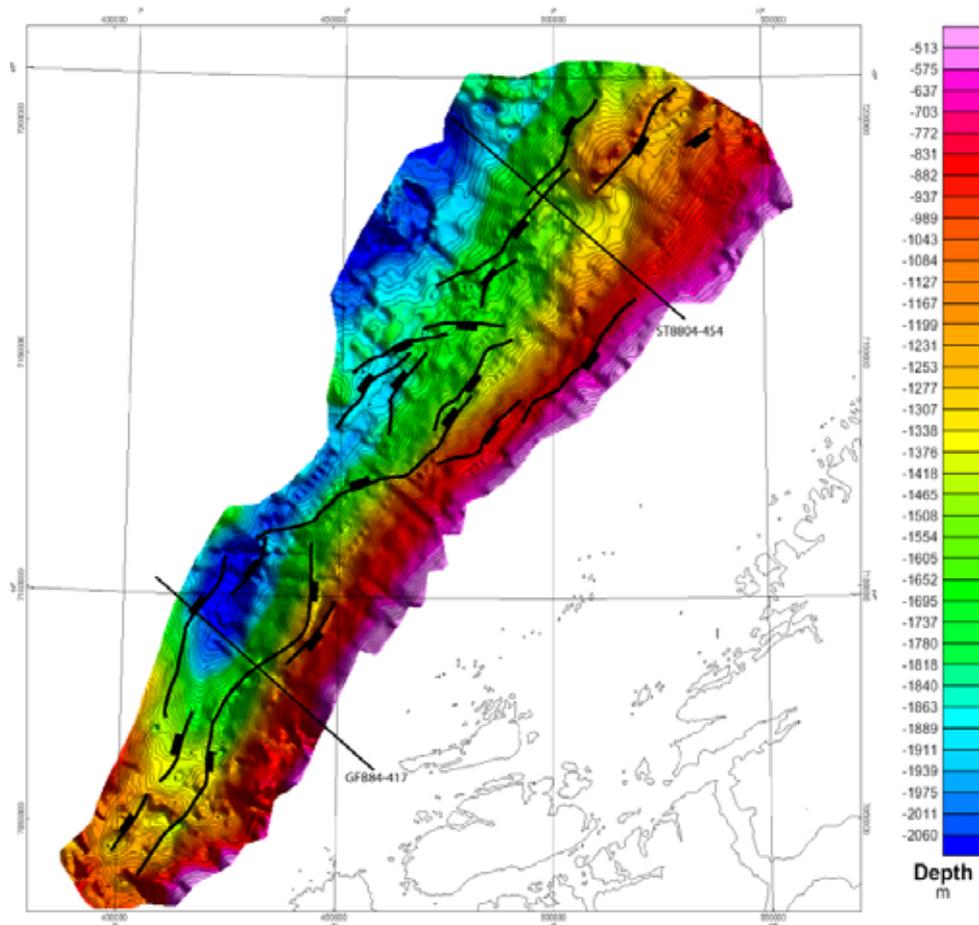


Figure 3.9 Structural map in depth (m) of the Intra Lower Jurassic horizon. The location of seismic profiles GFB84-417 (Figure 3.6) and ST8804-454 (Figure 3.7) are shown.

3.4.3 Depth conversion

The depth conversion was performed by Statoil, who used seismic stacking velocities from regional 2D seismic profiles in the study area to generate a velocity cube. The stacking velocities were filtered with a "Dix constrained" function in order to avoid incorporating unrealistic stacking velocities. Two-way-time (TWT) horizon grids were then loaded into the velocity cube and the velocity cube was structurally interpolated before the horizons were depth converted. The water velocity was set to 1480 m/sec. Finally, the results were calibrated against check shot data from wells in the region.

4. RESERVOIR SIMULATION

4.1 Rationale

The goal of the reservoir simulation study is to find out if the Jurassic formations of the Froan Basin area of the Trøndelag Platform may be suitable for safe and economically viable CO₂ storage. Given the lack of data on reservoir and seal properties, the approach chosen here is to carry out simulations applying a range of reservoir property parameters and to evaluate if a reasonable combination of these parameters yields a storage potential. If there is a favourable parameter combination, it may be worth making more detailed investigations, such as to drill exploration wells, determine the lithology in the basin, and to measure reservoir properties of rocks in the subsurface of the Trøndelag Platform. If there is no suitable parameter combination, the conclusion could be that this site is not suitable for underground CO₂ storage.

The conditions to be fulfilled for suitability of this site were:

- Only minor leakage of CO₂ during and after injection. Following Hepple & Benson (2002) a yearly leakage rate lower than 0.01 % of the total injected CO₂ may be acceptable. This would e.g. correspond to a cumulative leakage of 20% of the total injected CO₂ after 2000 years. However, leakage should ideally be especially low during the first few centuries when leakage would add to ongoing industrial emissions and leakage rates may increase somewhat later (Lindeberg 2003)
- Storage capacity for all or a large part of the emissions from a planned power station that is, up to a total of 50 million tonnes during 25 years of injection.

4.2 Major expected processes in the reservoir

CO₂ injected into the subsurface will at normal pressure-temperature conditions have a density lower than water. Depending on the temperature and pressure gradients there will be a transition from gaseous (low density) to 'super-critical' (high density, but still lower than water) CO₂ at a certain depth. Due to the density difference between water and CO₂, there will be buoyancy-driven upward migration of CO₂ from the perforated or open part of the injection well until it reaches a barrier for migration. Such barriers are typically low permeable rocks for which high capillary entrance pressures have to be overcome to allow CO₂ migration into them. CO₂ will then accumulate below the barrier and spread laterally below it. If there are permeable pathways through the barrier, they will be exploited when reached and parts of the CO₂ will migrate upwards through them. If the barrier is inclined, the CO₂ will migrate below the barrier up-dip.

Some CO₂ will dissolve in formation water. This is however a slow process as compared to migration. The establishment of convection in the reservoir will improve dissolution (Lindeberg & Bergmo 2003)

The process of gas entering a water-saturated, water-wet rock ('drainage') followed by subsequent re-entrance of water ('imbibition') is not symmetric but is strongly hysteretic. One consequence of this hysteresis is that a certain 'residual gas saturation' remains in the pore space. The residual gas is trapped and can leave the rock volume only by dissolution into the water phase and transport therein. This process reduces thus the amount of 'free' gas which might leak from the reservoir. In general, the higher the residual gas saturation (which is a

function of the pore space geometry and of the previously reached maximum gas saturation) the larger the positive contribution to reservoir safety will be.

It was assumed that the Jurassic formations in the Froan Basin area of the Trøndelag Platform constitute an open reservoir and that there will be only negligible pressure increase due to gas injection. The formations have a large pore volume that additionally will prevent pressure increase even in the case of a sealed reservoir. Therefore, fracturing of the seal is not expected to occur.

4.3 Reservoir model and input data

Reservoir model

Based on the geological concept for the Trøndelag Platform and the analysis of the available data on its sedimentary infill as presented in Chapter 3, a reservoir model has been generated using the Irap RMS software package.

The Trøndelag Platform is a large structure (50 000 km² – see Chapter 3) and a rough estimate showed that injection of approximately 50 Mtonnes of CO₂ would utilize only a small part of it in map view. Therefore the simulation model could be kept smaller in size, covering only a part of this structure. Two model segments were used (Figure 4.1) covering adjacent areas, one segment including a domal trap, the other one at first sight without any structural trap.

Faults were not included in the model. According to the seismic interpretation (Chapter 3) most of them had minor displacement and do not compartmentalize the area significantly. Thus even if they were perfectly sealing they cannot be expected to form large structural traps.

The model assumes three formations with suitable reservoir properties for CO₂ storage: the Garn Formation, the Ile Formation and the Tilje Formation. For simplicity only the Garn Formation was included in the simulations because it is the shallowest formation and has thus the shortest distance to potential leakage area at its subcrop. In addition it is likely to possess the highest permeability of the three formations which would also favour leakage. It is thus a ‘worst case’ – its suitability would also imply that the other two formations are suitable for safe CO₂ storage. The Not Formation which underlies the Garn Formation, and the formations overlying the Garn Formation were assumed to be completely tight.

The tilted formations are overlain by a Quaternary cover, which is considered not to be a seal – again a ‘worst case’ scenario.

Seawater was not represented in the model and therefore water could not escape from the reservoir through the Quaternary into the sea. This would have implied an unrealistic closed system with potential pressure build-up. For compensation in the simulations, cells with large virtual pore volume were placed at the flanks of the reservoir, which prevents unrealistic pressure increase. To obtain this effect the pore volume of normal cells at the margin of the model was multiplied in Eclipse 100 000 times.

The basement below the sedimentary succession is not included in the reservoir model. It is thus treated as impermeable.

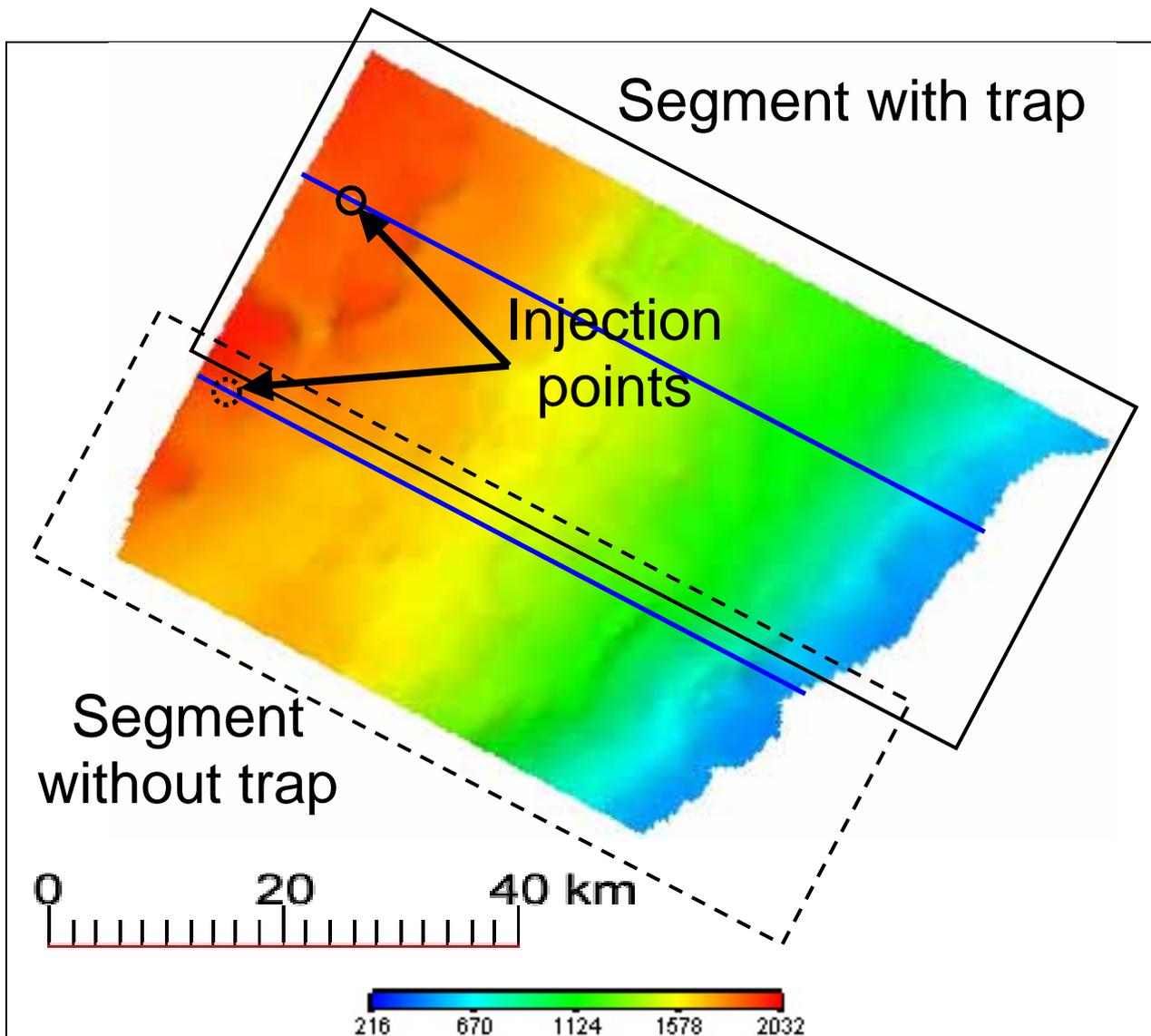


Figure 4.1 Depth map of the Top Garn horizon with indicated injection points and segments that were used for simulations. Cross-sections (Figure 4.2) marked as blue lines. The location of the area shown in this map is indicated by green lines in Figure 3.8.

The primary input for reservoir geometry were eight horizons from seismic interpretation:

1. Intra Triassic
2. Intra Lower Jurassic
3. Base Upper Jurassic
4. Base Cretaceous
5. Base Tertiary
6. Base Naust
7. Base Quaternary
8. Seabed

The interval between the two seismic horizons Base Upper Jurassic and Intra Lower Jurassic (Figure 3.6) was divided into five formations (Table 4.1) according to thickness ratios from regional trends (Table 3.2).

The horizons define ten sedimentary formations or subgrids (Table 4.1). All subgrids except for the Garn Formation and the Quaternary were treated as inactive and the resulting active model is thus relatively simple (Figure 4.2). Lateral cell boundaries were always vertical. Cell dimensions were approximately 400 m in both NE-SW and NW-SE directions. The number of active cells in each segment of the model used in simulation is shown in Table 4.2. The reservoir properties (see below) are constant within each subgrid.

Table 4.1 Formations and their status in simulations.

Formation/Subgrid		Status in simulations
Quaternary		Active
Naust		Inactive
Tertiary		Inactive
Cretaceous		Inactive
Upper Jurassic		Inactive
Lower & Middle Jurassic	Garn	Active
	Not	Inactive
	Ile	Inactive
	Ror	Inactive
	Tilje	Inactive

Table 4.2 Construction parameters for cells in the modelled formations in the subsurface geology model (Irap RMS).

Formation/Subgrid	Internal geometry	Number of active cells	
		Segment with trap	Segment without trap
Quaternary	1 layer, parallel to top	14013	8715
Intra Lower Jurassic (Garn only)	2 layers 5 m thick parallel to top + 8 layers 10 m thick parallel to top	68218	45740

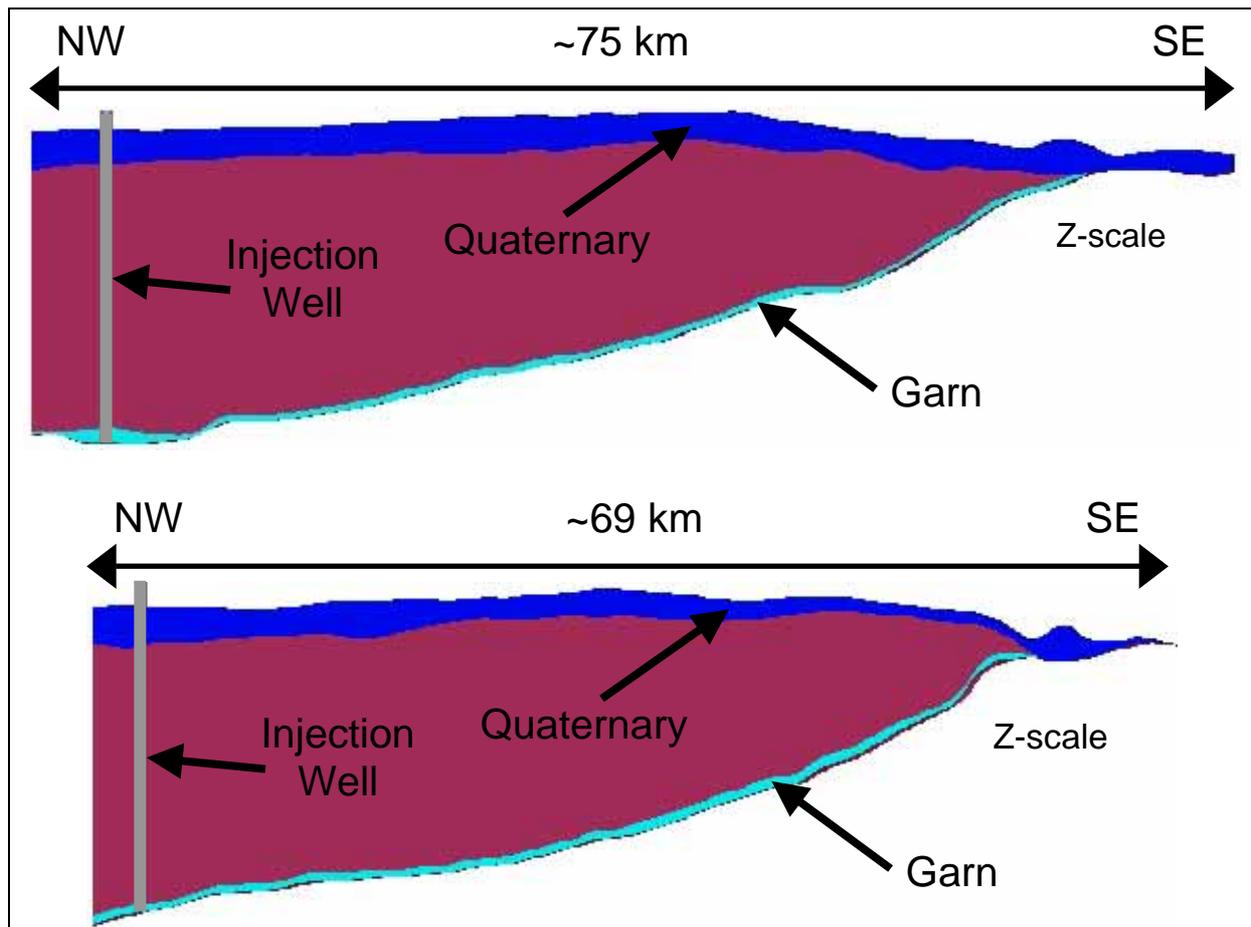


Figure 4.2 Cross-sections through the reservoir model of the Trøndelag Platform. The formation colour code is identical in the two cross-sections. The first figure shows a cross-section for the case of injection below a structural trap and the second in the case of injection without a structural trap (shortest time to leakage). Note that the z-scale is exaggerated ten times.

Reservoir properties

Porosity and permeability values for the relevant formations applied in the simulations are based on the arguments given in Chapter 3 (Table 3.1). By analogy to the formations in Haltenbanken, a range of parameters has been selected for the formations (Table 4.3). Base case values are similar to those reported in Ehrenberg (1990) and Koch & Heum (1995).

Table 4.3 Reservoir parameter range applied to the formations in the Froan Basin area of the Trøndelag Platform. Base case is marked in bold.

Formation	Net-to-Gross ratio	Net porosity	Net horizontal permeability
Quaternary	1	20%	2000 mD
Garn Formation	1, 0.85	30% , 20%, 12.5%	5000 mD , 1000 mD, 20 mD

Vertical heterogeneity within the formations was represented by a ratio of 0.1 (1/10) between vertical and horizontal permeability (k_v and k_h respectively). In addition, the effect of applying an alternative k_v/k_h ratio of 0.01 was tested.

No dependency of saturation to capillary pressure was assumed for the simulated cases. Accordingly the entry pressure of CO₂ into reservoir and seal rocks is 0 and saturation is not affected by the capillary pressure.

Reservoir conditions

An average seawater temperature of 5°C at the sea bottom was assumed. The calculated temperature gradient for the Trøndelag Platform is 41.3° C/km (Figure 4.3). This gradient was calculated based on data from exploration wells along the margins of the Trøndelag Platform (from NPF online data base).

Pore pressure at injection start was assumed to be hydrostatic (Figure 4.3).

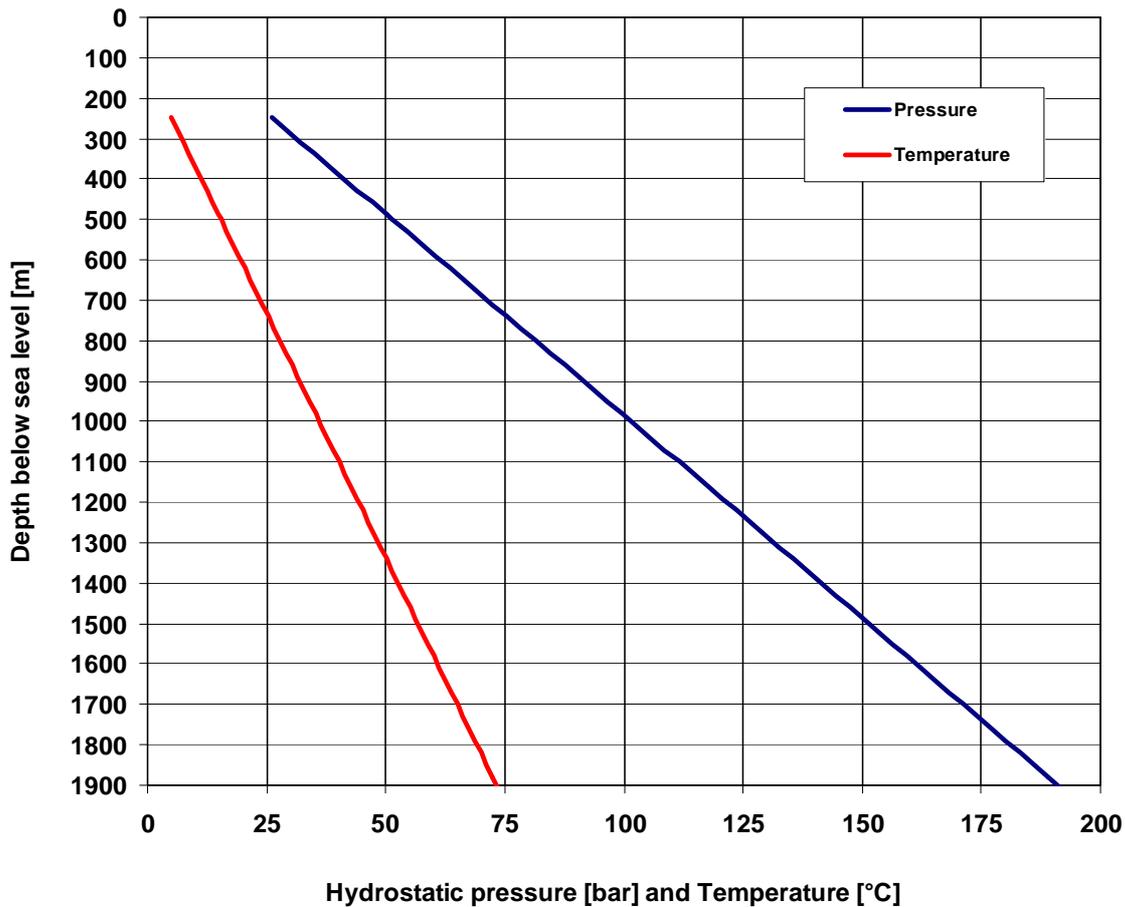


Figure 4.3 Calculated temperature and pore pressure versus depth for the Froan Basin area of the Trøndelag Platform.

Fluid properties

Density and viscosity of water and CO₂ were calculated using SINTEF's thermodynamic model for the CO₂-CH₄-H₂O system (Lindeberg et al. 2000). The physical properties of especially CO₂ vary with both pressure and temperature and a real density profile as function of depth is shown in Figure 4.4 (curve 1). Variation in pressure is assumed to occur only vertically due to the high permeability in the reservoir. The pressure dependence of the density can be taken care of in the simulator Eclipse 100, but the temperature dependence can not be included explicitly. There are two methods to overcome this problem. The standard method is to use a density profile at an average temperature in the reservoir. Another option is to mimic the temperature dependency by actually adjusting the pressure dependency to give a correct density versus depth profile. In this case the CO₂ density actually decreases with depth because the expansion due to increased temperature is larger than the compression due to increased pressure. If this change is contributed to pressure only it corresponds to a negative compressibility of CO₂ which can not be used as input in the flow simulator. The best representation of the density variation is therefore to use a constant density as function of depth (Figure 4.4, curve 2). This will give a smaller deviation from the real physical density profile than using an average temperature. For simplicity and to be able to handle isothermal pressure variations in the reservoir (due to injected CO₂), an isothermal model was used within the reservoir simulator Eclipse 100 and only the pressure dependence at a fixed temperature of 68.7° C was taken into account (Figure 4.4, curve 3). This corresponds to the depth of 1790 m b.s.l. for the temperature gradient. The (non-isothermal) density variation

with depth for the calculated temperature and pressure profiles is shown for comparison in Figure 4.4 (curve 1). The major feature of interest is the strong downward density decrease at approximately 500 m b.s.l., below which the CO₂ density is initially higher than 800 kg/m³, decreasing somewhat downwards. In the simulated cases, CO₂ was always below the depth of 500 m b.s.l. at which CO₂ transfers from liquid to gas (Figure 4.4, curve 1).

Figures illustrating the variation of water density with pressure and the dependency of water and CO₂ viscosity on pressure and temperature (with modifications for Eclipse 100 simulations) are shown in Figure 4.5, Figure 4.6, and Figure 4.7.

Dissolution of CO₂ into water is according to the model of Enick & Klara (1990).

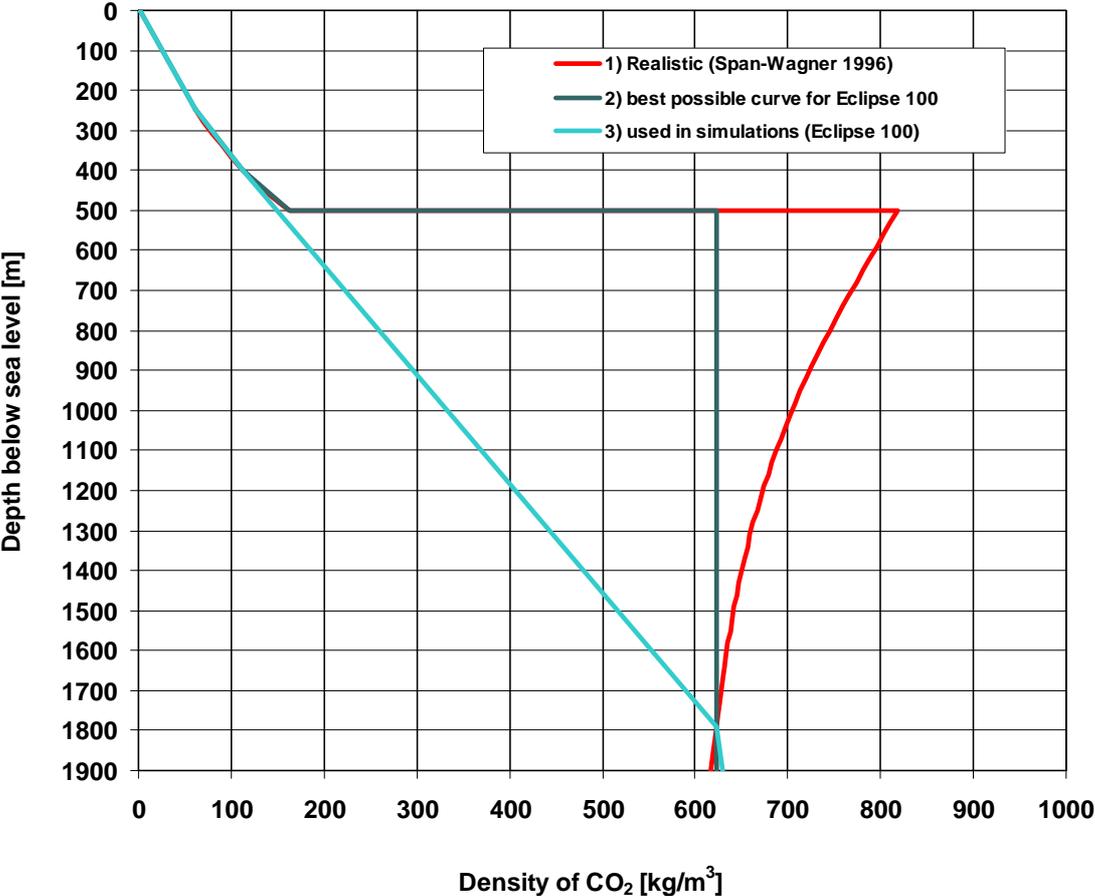


Figure 4.4 Calculated pT-dependent CO₂ density versus depth for the Froan Basin area of the Trøndelag Platform.

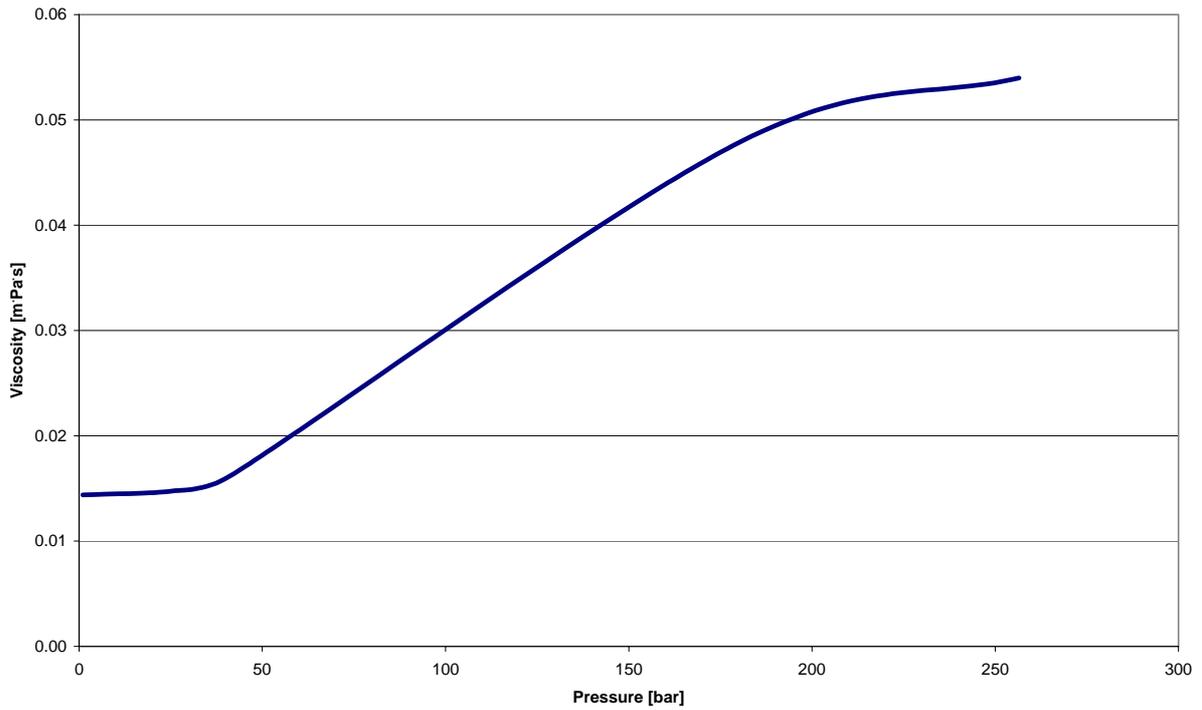


Figure 4.5 *CO₂ viscosity vs. pressure at a reservoir temperature of 68.7°C.*

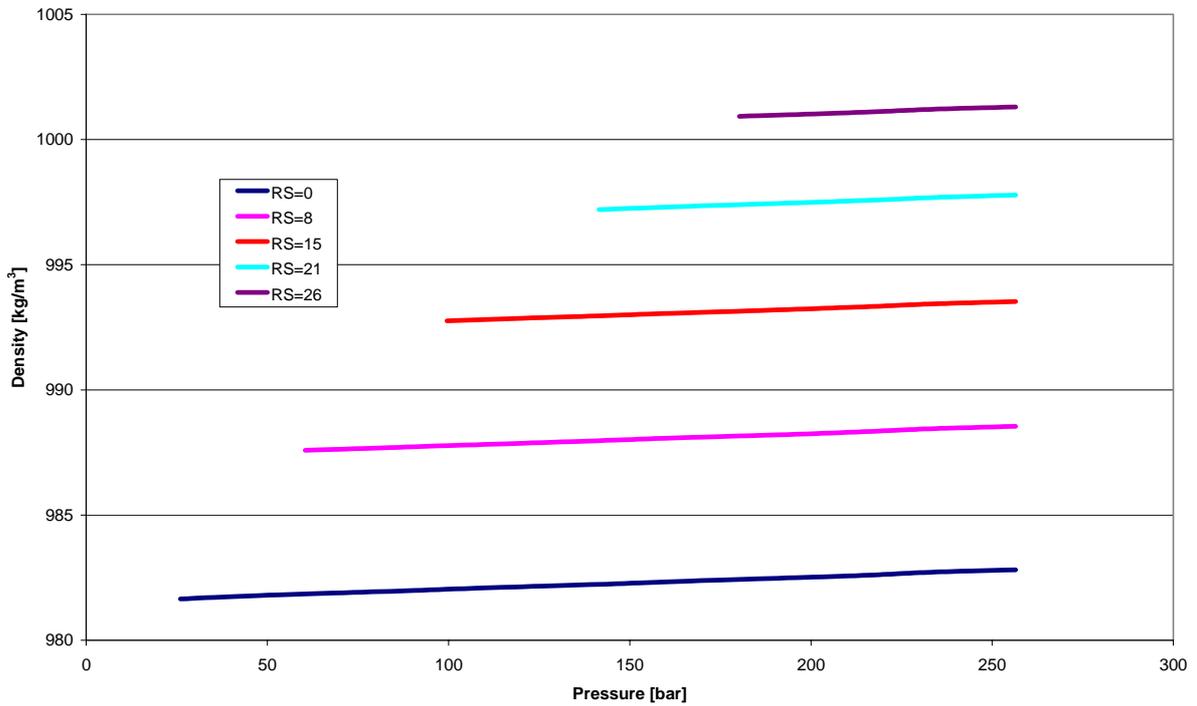


Figure 4.6 *Density of reservoir water at different CO₂ saturations vs. pressure at a reservoir temperature of 68.7°C.*

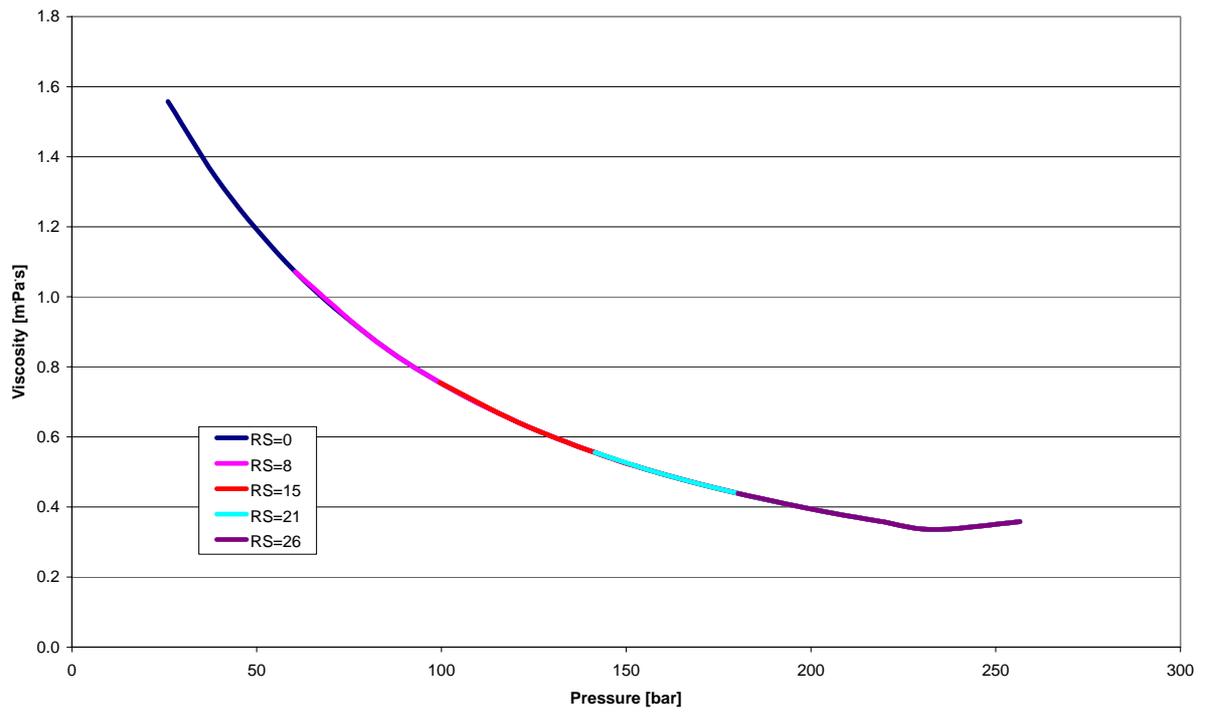


Figure 4.7 Viscosity of reservoir water at different CO_2 saturations vs. pressure at a reservoir temperature of $68.7^\circ C$.

Relative permeability and capillary pressure

Relative permeability curves used for water and CO₂ in the water-CO₂ system are shown in Figure 4.8. They are taken from core experiments with samples from the Utsira Formation in the Sleipner field (partly documented in Lindeberg et al. 2000). The CO₂ relative permeability curve corresponds to an irreducible water saturation of 0.1 and a residual CO₂ saturation in imbibition of 0. All relative permeability curves assume no hysteresis effects (identical curves for drainage and imbibition).

No dependency of fluid saturation on capillary pressure was assumed. The capillary entrance pressure for CO₂ is thus zero.

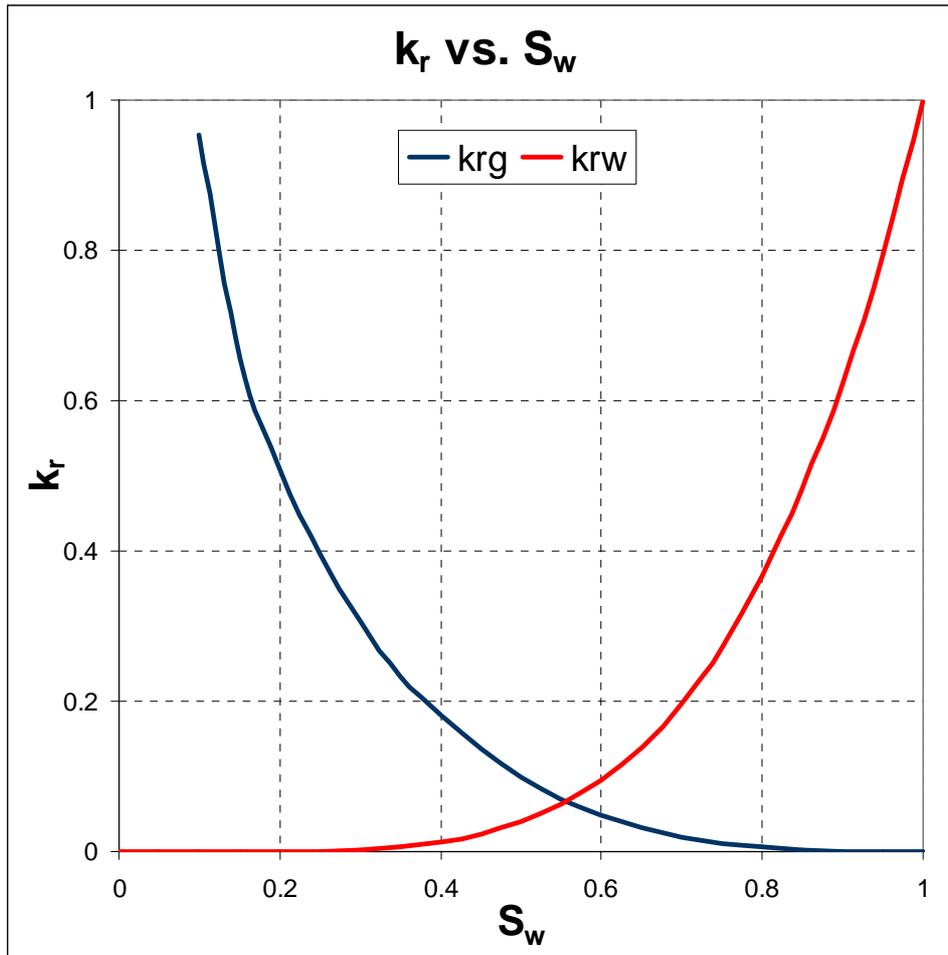


Figure 4.8 Relative permeability curves used for water and CO₂ in the water-CO₂ system

Other simulation specifications

Reservoir simulation was carried out with the commercial ‘Eclipse 100’ black-oil simulator.

The wells were treated as vertical. Perforations are placed immediately above the top of the basement. Two well positions were chosen, one below a domal trap and one in an area without any obvious structural trap (the latter being a ‘worst case’ scenario). The wells are approximately 61.6 km (trap case) and 55.6 km (no-trap case) from the subcrop of the Garn Formation. Injection takes place at a depth of approximately 1900 m. The coordinates of the injection wells are listed in Table 4.4.

The injection rate was defined as 2 million tonnes/year which corresponds to $2.93 \cdot 10^6$ Sm³/day and a total of $26.7 \cdot 10^9$ Sm³ over a period of 25 years. An alternative case with a doubled injection period (50 years) and thus doubled injection mass was also simulated.

The diffusion option of the Eclipse software was not applied.

All simulations were run for 5000 years in order to investigate the long-term CO₂ behaviour.

Table 4.4 Well coordinates.

	Case with trap		Case without trap	
	Easting	Northing	Easting	Northing
Well coordinates (cell centre)	467530.84	7184008.5	456720.94	7167081

4.4 Simulation results

The simulations are grouped into four sets:

- Base cases in which reservoir properties correspond to those listed in Table 3.1 (Chapter 3) for two different injection locations.
- Alternative cases 1 – in which reservoir properties were changed in order to test their effect on CO₂ behaviour.
- Alternative cases 2 – in which all properties and parameters are as in the base cases but injection time is doubled
- Alternative cases 3 – in which all properties and parameters are as in the base cases but dissolution of CO₂ into formation water has been ‘switched off’.

4.4.1 Base case

Parameters used in base case simulations are collected in Table 4.3 and Table 4.5.

Table 4.5 Key parameters used for simulations (base case).

Parameter	Value
Injection rate [Sm ³ /day]	2 930 188.26
[Mtonnes/year]	2 million
Injection time [years]	25
Net porosity in reservoir	0.30
k _h in reservoir [mD]	5 000
k _v in reservoir [mD]	500
NTG in reservoir	1
S _w (P _c)	no dependency

k_h = horizontal permeability, k_v = vertical permeability,
 NTG = net-to-gross ratio,
 S_w(P_c) = water saturation as function of capillary pressure

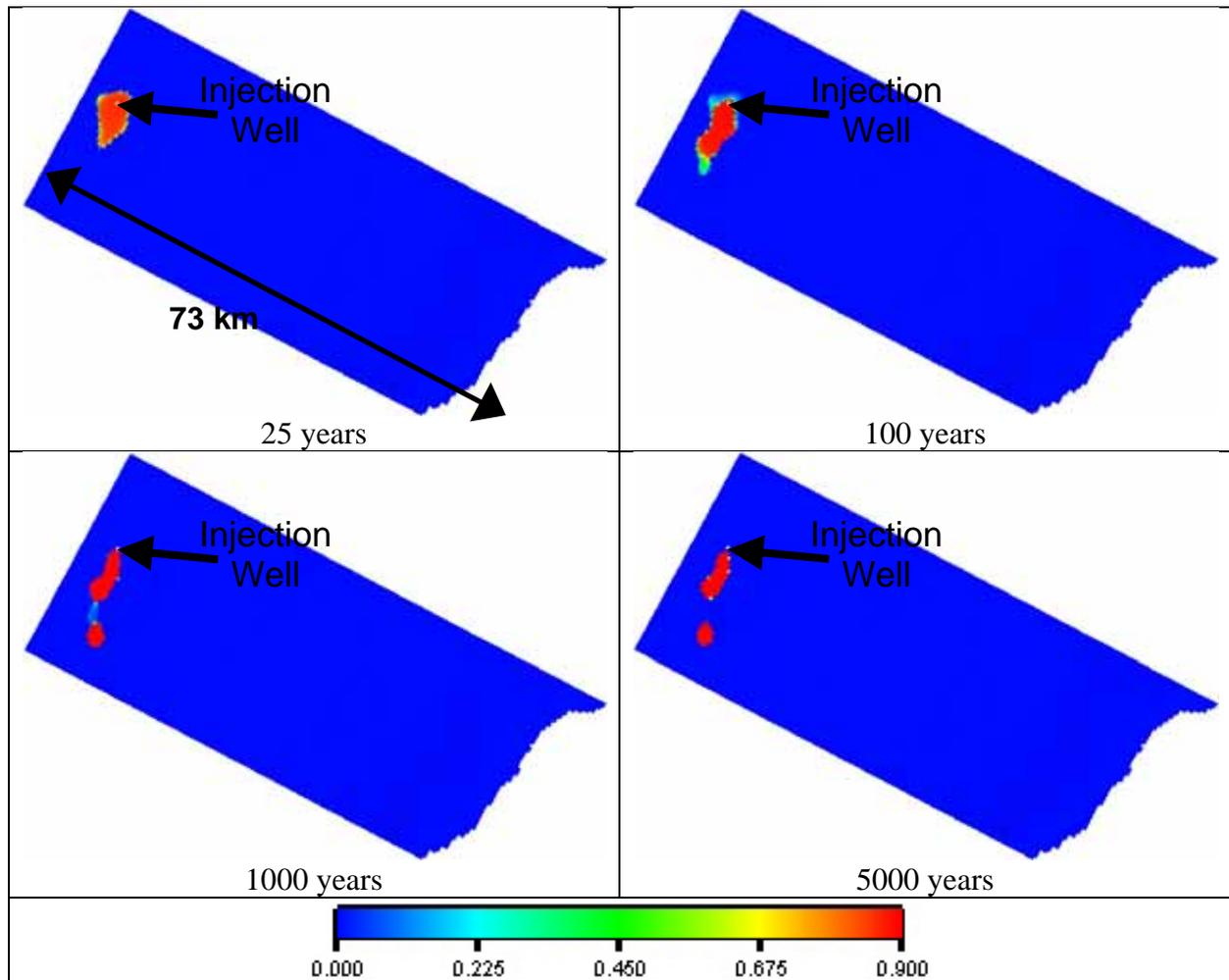


Figure 4.9 Gas saturation at the top of the Garn Formation after 25, 100, 1000 and 5000 years. Injection below the trap.

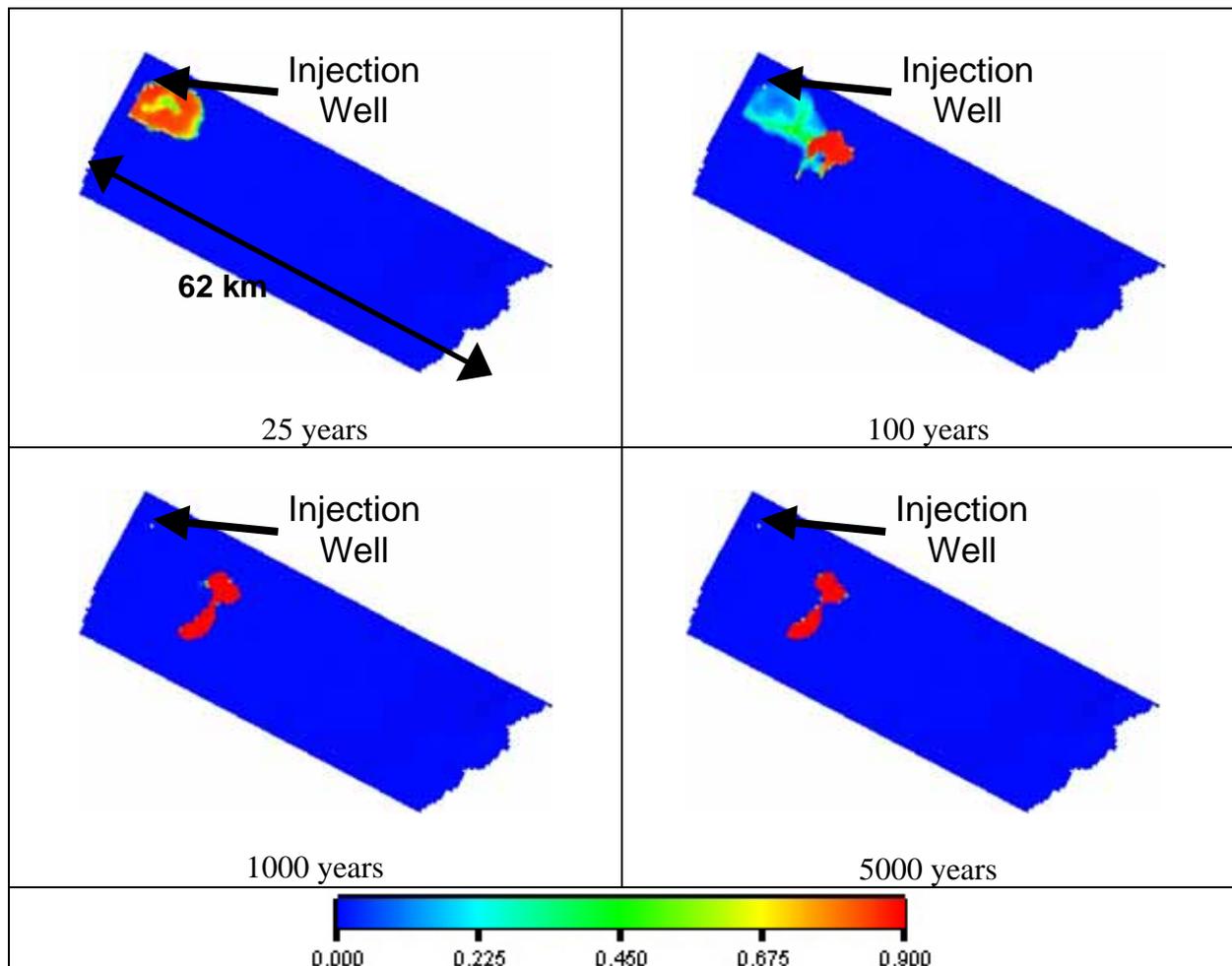


Figure 4.10 Gas saturation at the top of the Garn Formation after 25, 100, 1000 and 5000 years. Case with no primary trap.

The injection point for the first base case was carefully chosen according to the geological structure of the reservoir and is placed at the base of the Garn Formation vertically beneath a mapped domal trap (Figure 4.1 and Figure 4.2). However, the pore volume in the trap is too small to store all the CO₂ injected. The simulation predicts that part of the injected CO₂ will migrate from this primary trap and will reach a neighbouring domal trap (Figure 4.9). These two traps are capable to store all injected CO₂ and will prevent migration of CO₂ towards the sea floor. The simulation shows that leakage should not occur in 5000 years. The shortest distance of the CO₂ bubble to the formation subcrop is listed in Table 4.6. On the cross section (Figure 4.11) it can be seen that a large part of the injected CO₂ will be dissolved in water due to convection processes (Lindeberg & Bergmo 2003). At the end of the simulation (after 5000 years) nearly 40% of the injected CO₂ was dissolved (Figure 4.12).

In addition, a simulation with a different well location was performed (Figure 4.10). The results predict that the CO₂ will follow pathways to small traps and would accumulate in them while migrating towards the subcrop of the Garn Formation. The distance from the final front of the CO₂ 'bubble' to the formation subcrop (Table 4.6) would be shorter than in the case of injection below the domal trap, but no leakage is predicted.

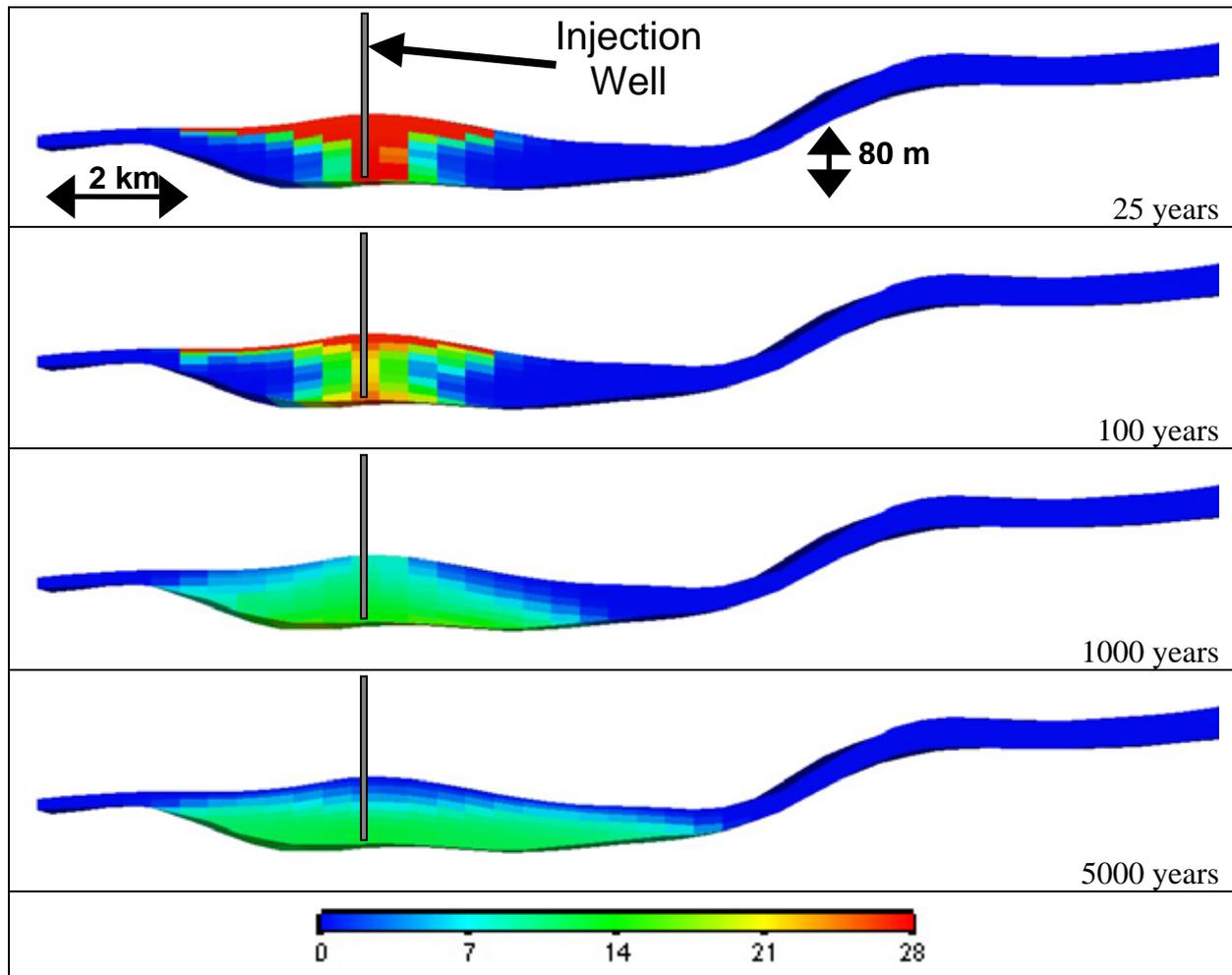


Figure 4.11 Dissolved CO₂ ($RS = Sm^3 \text{ gas}/m^3 \text{ liquid}$) in lower part of the reservoir after 25, 100, 1000 and 5000 years (convection process). Note Z-scale exaggerated ten times. Distance from left margin to the subcrop is approximately 66 km.

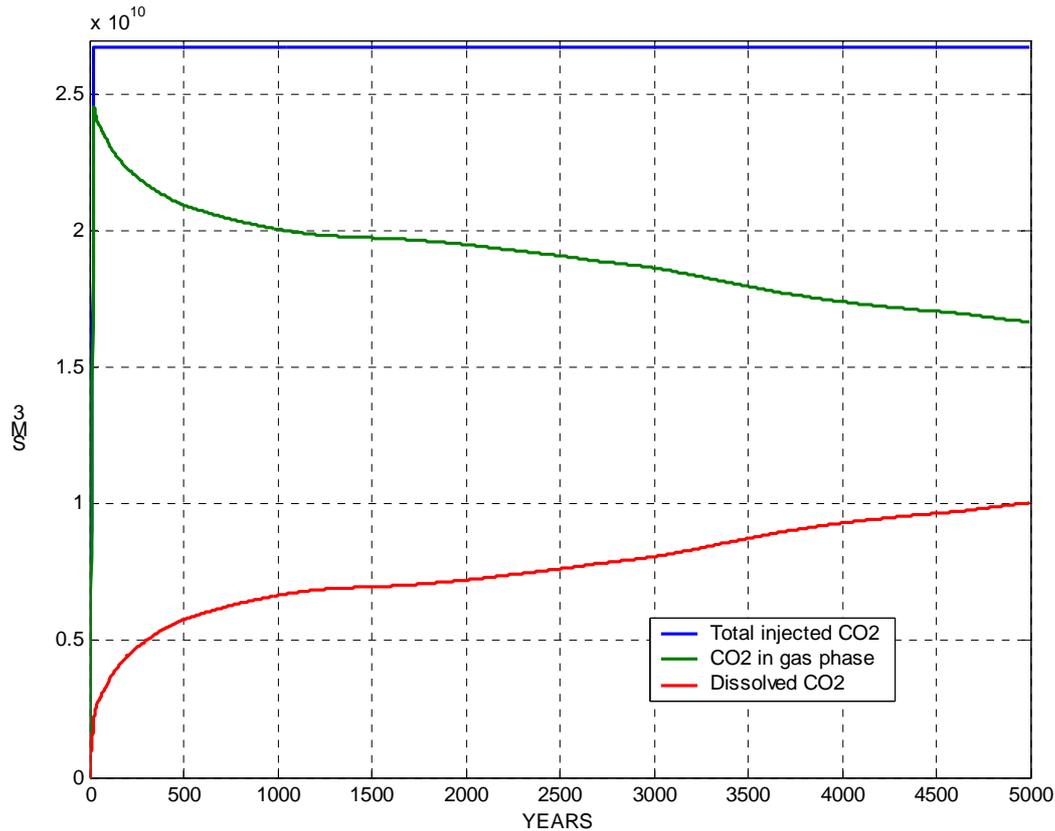


Figure 4.12 Simulated dissolution of CO₂ in the reservoir.

4.4.2 Alternative cases 1

The base cases constitute a scenario based on most likely data from regional geological data. Alternative cases were simulated with the aim to investigate the CO₂ behaviour at different conditions in the reservoir. The following modifications to the base case have thus been applied:

- reduced reservoir permeability and associated porosity
- reduced k_v/k_h ratio in the reservoir

Reduced permeability and porosity

A reduction in absolute permeability will reduce migration velocity. However, porosity and permeability are linked to each other, with a general trend in reservoir rocks of lower permeability corresponding to lower porosity. Lower porosity implies less pore space available for CO₂ and thus potentially an increased migration rate. Reduced porosity should also increase migration distance because lower pore volume means less space for CO₂ in the trap so more gas has to leave the trap. Porosity and permeability were here changed in a way to maintain a reasonable relationship between these two parameters.

Table 4.6 Parameters used for simulations and distance of CO₂ bubble to the subcrop of the Garn Formation.

#	Properties in reservoir				Distance from CO ₂ bubble to the subcrop after 5000 years [km]	
	Porosity	Permeability [mD]	NTG	k _v /k _h	Trap	No-trap
Base case						
1	0.30	5000	1	0.1	55.2	39.6
Alternative cases 1						
2	0.25	1000	0.85	0.1	55.2	39.2
3	0.25	1000	0.85	0.01	54.8	39.2
4	0.125	20	0.85	0.1	53.6	40.0

The applied changes in reservoir properties did not yield any significant change to the results. There was no leakage of CO₂ in any of the alternative cases.

Lower porosity increased generally the migration distance. This tendency is weakly indicated in the cases of injection below the trap (Table 4.6). The ‘no-trap’ case shows an opposite (but even weaker) trend, with decreasing migration distance with decreasing porosity. This can be explained by the permeability reduction accompanying the porosity decrease having caused slightly slower CO₂ migration.

A lower ratio between vertical and horizontal permeability (k_v/k_h) is expected to result in slower upward migration of CO₂ across the sedimentary layers within the reservoir formation. The simulation shows however that the effect is almost insignificant.

The results from this group of simulations show that absolute permeability, porosity and the k_v/k_h ratio do not significantly influence the migration. In none of the simulated cases leakage of CO₂ is predicted to occur. The main important parameter with an effect on the migration distance seems to be the location of the injection well. However, even a relatively unfavourable well location does not result in leakage in the simulations.

4.4.3 Alternative cases 2

In order to further check if leakage of CO₂ could occur from the hypothetical sites on the Trøndelag Platform the injection time was doubled. Injection lasted for 50 years with a constant rate of 2930188.26 Sm³/day. Properties of the reservoir and all other parameters were the same as in the base case simulation runs (Chapter 4.4.1, Table 4.3, Table 4.5).

Table 4.7 Parameters used for simulations and distance of CO₂ bubble to the subcrop of the Garn Formation. 50 years of gas injection.

#	Properties in reservoir				Distance from CO ₂ bubble to the subcrop after 5000 years [km]	
	Porosity	Permeability [mD]	NTG	k _v /k _h	Trap	No-trap
Alternative cases 2						
5	0.30	5000	1	0.1	52.4	16.8

The simulation results show that even if the quantity of injected gas was doubled there is no leakage predicted to occur in 5000 years. As expected, the migration distance was much longer than in the base cases (especially for the no-trap case, Table 4.7), but CO₂ still was not able to reach the subcrop of the Garn Formation.

4.4.4 Alternative cases 3

In order to check the influence of CO₂ dissolution into formation water on migration distance, cases were run in which CO₂ dissolution was switched off in the simulator. All other parameters and properties of the reservoir were the same as in the base case simulation runs (Chapter 4.4.1, Table 4.3, Table 4.5).

Table 4.8 Parameters used for simulations and distance of CO₂ bubble to the subcrop of the Garn Formation. No dissolution of CO₂ in water.

#	Properties in reservoir				Distance from CO ₂ bubble to the subcrop after 5000 years [km]	
	Porosity	Permeability [mD]	NTG	k _v /k _h	Trap	No-trap
Alternative cases 3						
5	0.30	5000	1	0.1	55.2	39.6

The simulation results show that even if the dissolution of injected CO₂ was neglected there was no leakage predicted to occur in 5000 years. Simulated maximum migration distances (minimum distance from the bubble to the Garn subcrop) are exactly the same as for the base cases (Table 4.8; compare with Table 4.6). This indicates that physical trapping in structural traps is the main trapping mechanism in the simulated cases. The dome-shaped traps at the top of the reservoir, which are reached during the progressive migration of the CO₂, provide enough accessible volume to store the entire injected CO₂. (Figure 4.9; compare with Figure 4.10).

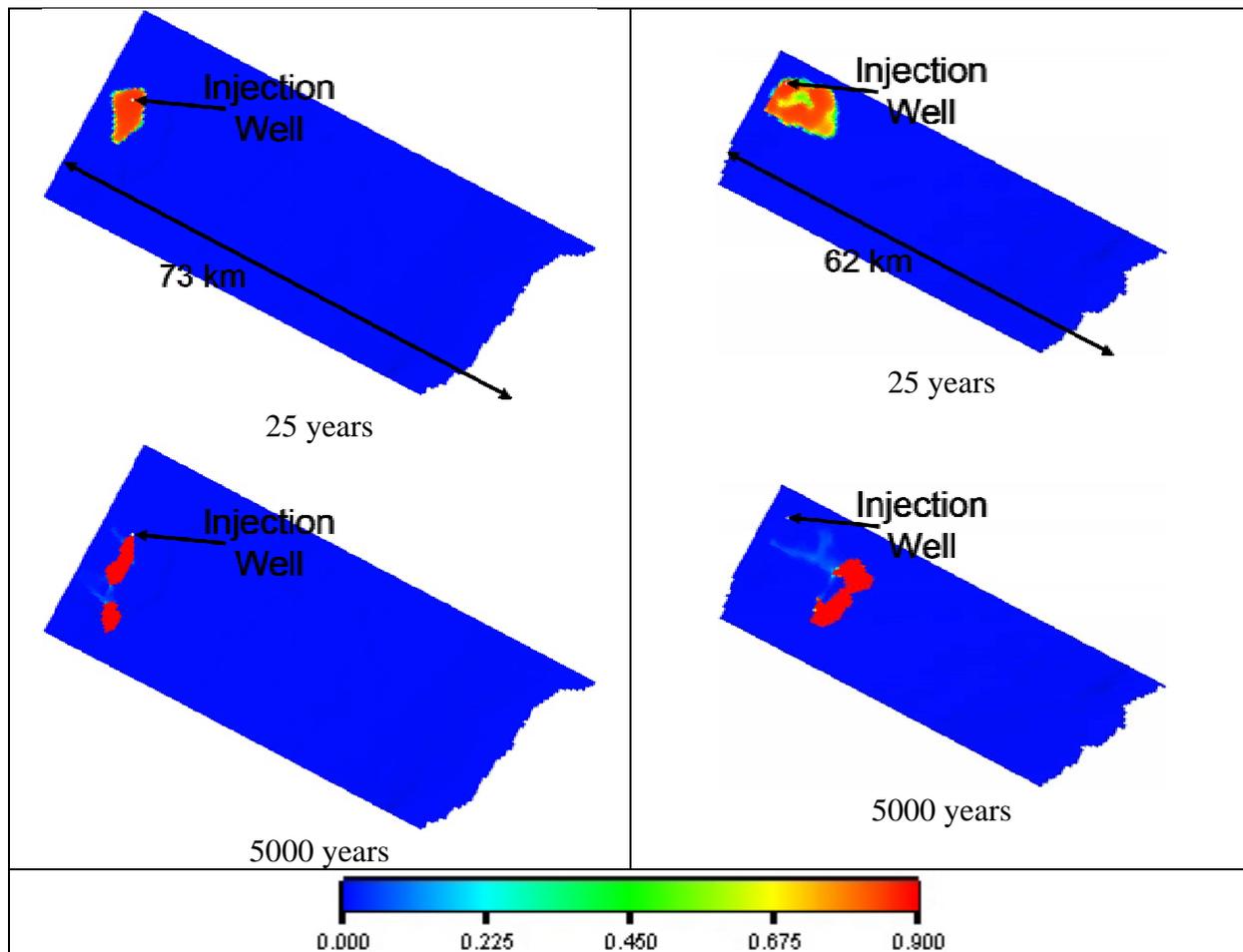


Figure 4.13 Gas saturation at the top of the Garn Formation after 25 and 5000 years. No dissolution of CO_2 in water. Injection below the trap on the left; case with no primary trap on the right.

5. DISCUSSION AND CONCLUSIONS

Summary of observations

Mapping of the Froan Basin area of the Trøndelag Platform and the simulation results presented in the previous chapters show some general features:

- Sedimentary sequences with reservoir properties potentially suitable for underground CO₂ storage are likely to exist in the subsurface of the southeastern Trøndelag Platform. Particularly the clastic Tilje, Ile and Garn formations of Jurassic age appear promising, based on their reservoir properties in the nearby Haltenbanken hydrocarbon province. Porosity may be approximately 30% with net-to-gross ratios close to 1 and a total gross thickness of the three formations of approximately 90 m. The three formations are probably separated from each other by very low permeable clay-rich formations.
- The potential reservoir constitutes an open, north-westward dipping monocline with a typical migration distance of ca. 60 km from a potential injection sites to the subcrop of the reservoir formation below the Quaternary or at the sea floor.
- CO₂ is expected to move upward in the reservoir unit into which it is injected until it reaches the base of the next sealing formation and then to migrate laterally below the seal towards the sea floor.
- Leakage is not predicted in any of the studied cases for total injected masses of up to 100 Mtonnes into segments of the Garn Formation.
- Physical trapping in structural traps reached on the migration pathway is the main trapping mechanism. This is aided by dissolution of CO₂ into formation water (this has been simulated) and by residual gas trapping (not simulated here).
- There is probably no danger of pressure build-up that would cause fracturing, because the reservoir is not tightly sealed and it has large enough pore volume to accommodate the injected CO₂ volume by water compressibility (an increase in water density).
- The present simulations used only approximately 25 km wide dip segments and focussed on one out of three potentially suitable storage formations. Given a total length of the Froan Basin area of the Trøndelag Platform of approximately 200 km (8 times the simulated segment width) and a total thickness of the three potentially storage formations of approximately 2.5 times the thickness of the Garn Formation (Garn Formation having the shortest distance to the subcrop), the total storage potential may be approximately 20 times that of the Garn Formation in the studied offshore dipping segments. It would thus be of the order of 2000 Mtonnes. This estimate assumes that structural traps of similar size exist in all other 'segments' of the Froan Basin. The seismic data available to the project indicate undulations of the relevant horizons in large parts of the basin, which makes the presence of domal traps likely. In addition, traps due to normal faults have not been included in our models, and they may provide additional volume in structural traps.
- In addition, we assume that there is a relatively large storage potential in the Jurassic formations in structural traps along the Frøya High and the Vingleia Fault Complex, along the western and northwesternmost parts of the Trøndelag Platform, and on the Trøndelag Platform north of the Froan Basin. Those areas were not mapped and investigated in this project.
- Storage in the basin may also be possible without leakage in the case of only minor structural traps available, if CO₂-dissolution is fast enough to disable far migration of CO₂. This scenario has not been simulated.

Difference to the Beitstadjorden and Frohavet cases

The results for the Trøndelag Platform are much more promising than those presented earlier for the Beitstadjorden (Polak et al. 2004a) and for the Frohavet (Polak et al. 2004b). The main differences which make the Trøndelag Platform suitable for long-term storage are:

- Large pore volume in the reservoir units. This reduces the overpressure generated. Even for the hypothetical case of complete sealing, overpressure in the Trøndelag Platform would be much lower than in the Beitstadjorden or Frohavet Basins.
- Much longer migration distance from the optimal injection location to the reservoir subcrop below the Quaternary or the sea floor. This directly delays arrival of CO₂ at the sea floor and indirectly improves dissolution of CO₂ due to a larger surface area in contact with formation water over longer time, which in turn reduces leakage rates and cumulative leaked mass fraction. The migration distance from suitably chosen injection sites in the Trøndelag Platform is of the order of 60 km while it is 4-10 km for the Frohavet Basin and only up to 4 km for the Beitstadjord Basin.
- Presence of natural domal traps that could store injected CO₂. There is no single structural trap large enough to store all injected CO₂ but there are several small ones that accumulate CO₂ while it migrates upward within the storage formation.

Fulfilment of leakage rate criteria

Acceptable leakage rates for reservoirs are presently discussed in the scientific community. A minimum requirement for the performance of underground CO₂ storage sites would be that leakage from them into the atmosphere should not cause worse climatic conditions in the future than we can expect in the case of direct emission. Recent work indicates that the average storage time should be of the order of a few thousand years or more (Lindeberg 2003) or that annual leakage rates from each single storage site should be less than 0.01 % of the total injected CO₂ (Tore Torp, pers. comm. 2004 on discussions in the IPCC work group on underground CO₂ storage, Hepple & Benson 2002).

Simulation results for the Froan Basin area of the Trøndelag Platform indicate that none of the tested combinations of parameters is likely to cause leakage of CO₂. Accordingly, storage at this site would probably fulfil relevant criteria to qualify this site for long-term CO₂ storage.

Principle uncertainties

The simulations contain several uncertainties which are largely due to lack of relevant data and due to limitations of the simulator software:

- Reservoir properties employed in the simulations (porosity, permeability, net-to-gross ratio) are extrapolated from the Haltenbanken area. Their validity would have to be certified prior to any injection by data from the Trøndelag Platform itself, that is from a dedicated exploration-type well, including a broad suite of wireline logs and cores from the seal and reservoir formations. Well data and seismic data (ideally 3D seismic) would be necessary to evaluate reservoir heterogeneity which may strongly influence CO₂ sweep efficiency.
- Two-phase flow properties of the rocks were not known and were taken from previous analyses of the Utsira Sand (relative permeability) or neglected (capillary pressure curves). These properties would have to be determined from samples from the potential storage formations on the Trøndelag Platform. The choices made for the present simulations imply that migration rates are rather simulated too large, that is the real migration rates and migration distances would be less than those from the simulations.

- Seal efficacy has been assumed to be complete, that is no CO₂ was assumed to be able to leak from the storage formation into the overburden. Seal efficacy would require to be confirmed by data from wireline logs and cores prior to injection.
- The downhole temperature and the temperature gradient influence CO₂ migration in several ways: at higher temperature CO₂ has a lower density, which implies less efficient use of available storage pore volume and a stronger buoyancy force driving migration; also viscosity would be reduced, which would result in increased migration rates. Temperature and its gradient can be measured in a borehole in the area.
- Faults have been identified on seismic (Figure 3.6 to Figure 3.9) but they have not been incorporated into the reservoir simulations. They may have several, partly opposing effects on migration. Sealing faults can constitute traps, thereby both trapping CO₂ and extending its migration pathways. Non-sealing faults in contrast could enable leakage from the storage formation into overburden formations from which CO₂ may potentially escape if suitable migration pathways exist. Faults would require further assessment prior to injection, based on more detailed mapping (ideally 3D seismic) and on fault seal evaluation (clay smear or faults gouge ratio determinations).
- CO₂ dissolution processes and the variation of CO₂ density as a function of pressure and temperature have been treated in a simplified way due to the limitations of the reservoir simulator Eclipse 100. These aspects could be simulated more realistic in a compositional simulator such as Eclipse 300.
- In addition to physical trapping in structural traps and to trapping by dissolution, some CO₂ is likely to be trapped as residual gas due to hysteretic flow processes. This trapping mechanism has not been included in the simulations due to limitations of the reservoir simulator to handle flow hysteresis in an adequate way. In general, residual gas trapping would reduce CO₂ migration and would thus contribute to the safety of the storage site.
- Effects of pressure increase have not been assessed in detail. A distribution of pressure increase due to injected CO₂ over large parts of the basin is likely, which will keep the overall increase small. Injection at high rates at several places in the basin may however lead to pressure increases, which should be studied in a comprehensive model for the whole basin.
- Extrapolation of simulation results to the whole basin rests on the assumption of the presence of sufficient structural traps everywhere. This assumption has only been qualitatively verified.

Summary and proposed way forward

The potential storage formations of the southeasternmost part of the Trøndelag Platform constitute an open, dipping monocline, that is, this site as a whole does not constitute a closed structural trap and CO₂ could in principle escape. The two segments studied in detail do however contain minor structural traps which emerged to be able to store up to at least 50 Mtonnes CO₂ in each segment.

The suitability of this site for safe long-term CO₂ storage depends on slow migration of CO₂ towards the sea floor and on the efficacy of counteracting processes such as residual gas trapping, trapping in small-scale traps, dissolution of CO₂ into the formation water, and possibly chemical reactions fixing the CO₂ as a compound of minerals.

The simulations presented in this report are based on simplified subsurface models and employ reservoir parameters from outside the Trøndelag Platform, from the nearby Haltenbanken hydrocarbon province. The simulations indicate that the Trøndelag Platform is likely to be suitable for safe, long-term subsurface CO₂ storage. Given injection deep enough and far from the subcrop of the storage formations, CO₂ is likely to be immobilized long before reaching the subcrop. Extrapolating the storage potential identified in the simulations to the whole offshore dipping Jurassic succession in the Froan Basin area yields a total storage potential of the order of 2 000 Mtonnes CO₂. In addition, there is probably a significant storage potential in structural traps along the westernmost part of the Trøndelag Platform, and on the Trøndelag Platform north of the Froan Basin. The assumption of the presence of structural traps in the Froan Basin area needs to be verified and their volume must be quantified prior to any decisions on major investments.

Prior to any injection, the suitability of the area for long-term CO₂ storage needs to be assessed in more detail. Local geological and reservoir property data from a dedicated well are an indispensable part of such an assessment. However, more sophisticated simulations of potential subsurface CO₂ flow behaviour than the ones presented here can be carried out already prior to drilling a well. Such simulations should include more detailed reservoir models with internal heterogeneity (representing the depositional environment) and an adequate upscaling procedure. They should be carried out with a simulator handling compositional and pVT effects in a realistic way (e.g. Eclipse 300), and including hysteretic flow effects.

The suitability of the area for subsurface CO₂ storage *without* structural traps will be investigated (in another CO₂STORE work package) in simple simulations involving a straight, dipping reservoir top. These simulations will inspect the influence of dissolution of CO₂ into formation water on migration distances as a function of various parameters.

The potential quality of the seal formations should also be assessed. Prior to drilling a well, knowledge about the seal could already be improved by gathering data on the relevant formations from the Haltenbanken province and from shallow wells in the area and extrapolating these data with the help of depositional models and simulations. This work can then be refined with data from a dedicated exploration-type well.

Appraisal of the area could be carried out in the following sequence of work:

1. Improved assessment of the area as outlined above (reservoir and seal) prior to drilling.
If results are positive:
2. Acquisition of subsurface data and samples from an exploration-type well (ideally from more wells). These samples should cover the seal and the reservoir interval. Analysis of the data and samples. Revised reservoir simulations and seal efficacy assessment using the new data.
If the well log, samples, and simulations indicate suitable parameters:
3. Acquisition of a 3D seismic survey to determine the subsurface geometry in detail and to derive seismic information about lateral rock heterogeneity (seismic facies). Analysis of the seismic data, improved digital subsurface geology model and revised reservoir simulations.
4. Conclusion about suitability and decision about injection project based on all available data.

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