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REPORT

Report no. (NGU): 2005.043 Report no. (SINTEF): 54.5272.00/01/05	ISSN 0800-3416	Grading: Open

Title:
Potential risks associated with CO_2 storage, Case Study Mid-Norway, CO2STORE project

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County:	Commune:
Map-sheet name (M=1:250.000)	Map-sheet no. and -name (M=1:50.000)
Deposit name and grid-reference:	Number of pages: 27 Price (NOK): 90,- Map enclosures: 0

Fieldwork carried out:	Date of report: 30th June 2005	Project no.: 299900 (NGU) 54.5272.00 (SINTEF)	Person responsible: Morten Smelror

Summary:

The sedimentary successions in the Beitstadfjord Basin, the Frohavet Basin and in the subsurface of the Froan Basin area of the Trøndelag Platform (Mid-Norway) have been assessed with regard to their suitability for long-term storage of CO_2. All three cases constitute open, dipping traps with only a very thin or absent cover of Quaternary sediments at their subcrop. CO_2 is in all three cases predicted to rise from the injection well's perforation roughly vertically within the storage formation and then to migrate updip below the top seal towards the formation's subcrop or outcrop at the seafloor. Local traps reached on the migration pathway, such as domes, anticlines, or sealed fault compartments, will cause some trapping. The suitability for CO_2 storage for the three cases depends largely on available pore volumes and distances between injection points and subcrop.

An assessment of the three sites, based on geological models and reservoir simulations, shows that:

- the Beitstadfjord Basin is not suitable for subsurface CO_2 storage;
- the Frohavet Basin may be suitable for subsurface CO_2 storage given a favourable combination of reservoir parameters;
- Jurassic rocks of the Froan Basin area of the Trøndelag Platform are most likely suitable for large, industrial scale, safe, long-term CO_2-storage.

Uncertainties, which are largely due to lack of data on subsurface geology (particularly well data), have been addressed by carrying out several reservoir simulations for each case, covering reasonable ranges of key reservoir parameters. Since all three storage sites are located beneath the ocean, and since the most well-suited case is far from human dwellings, the risk for adverse effects of potentially leaking CO_2 on humans is regarded to be very small. Adverse effects on the marine environment are difficult to assess. However, because the leakage rate from a selected site would be very small, these effects are likely to be minimal, especially when compared to the alternative of freely venting the CO_2, which would change ocean chemistry on a global scale.

This study is part of the EU project CO2STORE, and was stimulated by the geographical proximity of the Trøndelag Platform to planned CO_2 point sources in Mid Norway.

Keywords: Aquifer	CO_2	Carbon dioxide storage
Reservoir simulation	Numerical modelling	Trøndelag platform
Leakage rate	Storage capacity	Risk

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Figure 3.1 Interpreted seismic line across the Beitstadfjord. Note that the Jurassic sedimentary succession (blue) is downthrown in the northwest along a fault that is a branch of the Verran Fault System. Modified from Sommaruga & Bøe (2002).

Figure 3.2 Interpreted seismic line across Frohavet. Note that the Jurassic sedimentary succession (blue) is downthrown in the southeast along the Tarva Fault. Modified from Sommaruga & Bøe (2002).

Figure 1.3 Interpreted geoseismic section K partly based on seismic line ST8707-483 (modified from Blystad et al. 1995). The Froan Basin is filled with rocks of Late Palaeozoic and Triassic age, while the Lower-Middle Jurassic rocks suited for CO_2 storage are in blue.

1. EXECUTIVE SUMMARY

Plans for a combined heat and power plant (CHP) in Skogn in the inner part of Trondheimsfjorden (Mid-Norway) include options to capture approximately 2 000 000 tonnes CO_2 per year from the flue gas stream. At Tjeldbergodden in Mid-Norway, a methanol plant emits at present approximately 450 000 tonnes of CO_2 per year, and plans exist to build an additional methanol plant there with a similar CO_2 emission and a gas-fired power plant which would emit approximately 2 100 000 tonnes of CO_2 per year.

In order to reduce anthropogenic greenhouse gas emissions, potential sites for underground storage of CO_2 have been investigated as part of the EU- and industry-funded project CO2STORE. In Mid-Norway, potential sites for CO_2 storage were considered to be the Beitstadfjord Basin, the Frohavet Basin and the Trøndelag Platform. In an assessment of the the Beitstadfjord Basin, located close to the CHP in Skogn, it was concluded (Polak et al. 2004a) that that basin was not suitable for long-term CO_2 storage. Results from the study of the Frohavet Basin close to the coast were reported in Polak et al. (2004b), and a possible storage potential has been identified. An assessment of the Froan Basin area on the Trøndelag Platform concluded that that area has a large storage potential (Lundin et al. 2005).

The three cases share some basic similarities:

- the reservoir units consist probably of highly porous clastic rocks with good permeability;
- the reservoir units are overlain by thick argillaceous sequences which constitute capillary seals;
- the reservoirs have a slight dip;
- the reservoirs either outcrop at the sea floor or subcrop below thin, unlithified layers of Quaternary deposits;
- CO_2 is at the prevailing temperature and pressure present as a dense liquid (‘supercritical’), but with a density lower than that of brine.

The major scenario for injected CO_2 is thus that it is likely to rise within the storage formation roughly vertically from the injection well’s perforation depth to the contact between that formation and the overlying seal. It will then migrate updip below the top seal towards the formation’s subcrop or outcrop at the seafloor. Key parameters influencing the migration velocity are the presence of local traps and their volume, the density difference between CO_2 and brine (largely a function of pressure and temperature), reservoir rock permeability, vertical and horizontal reservoir heterogeneity and relative permeability of the reservoir to CO_2. Some CO_2 will be dissolved into formation water in the reservoir unit, but this process is slow, operating over a time scale of 1000s of years.

Uncertainties, which are largely due to the lack of data on the subsurface (particularly well data), have been addressed by carrying out several reservoir simulations for each case, covering reasonable ranges of key reservoir parameters.

The suitability of the three cases depends largely on the available pore volume and on the distance between the injection point and the subcrop. Available pore volume and distance are large for the Froan Basin area of the Trøndelag Platform, moderate for the Frohavet Basin and low for the Beitstadfjord Basin.

All three cases are located beneath ocean/fjord water. For the single really promising case, the Froan Basin area of the Trøndelag Platform, injection wells would be located more than 50 km from human settlements. Since furthermore the predicted leakage rates are very small (in the present simulations; none before 5000 years after the start of injection), the risk for adverse effects of any potentially leaking CO_2 on humans is regarded to be very small.

Adverse effects on the marine environment are more difficult to assess. However, because the leakage rate, particularly for the most suitable Froan Basin area site, would be small, effects on the marine ecosystem are likely to be minimal. It would be worth comparing local effects to those of the alternative of freely venting CO_2 on a global scale, which would cause a global change in ocean chemistry.

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 Trondheimsfjorden. The plant will utilize natural gas from Haltenbanken, off Mid-Norway. In the EU-funded GESTCO-project, the total storage capacity for CO_2 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).

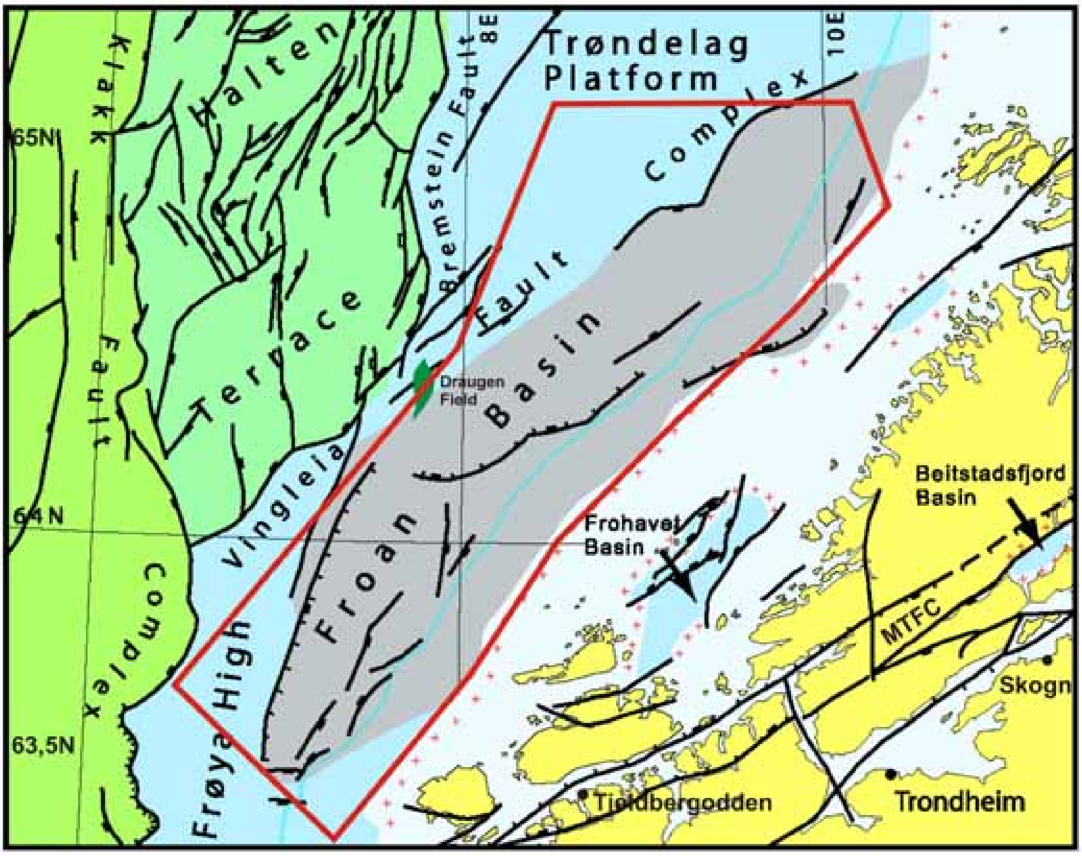

Figure 2.1 Geological map of Mid-Norway showing the location of the Beitstadfjord Basin, the Frohavet Basin, and the Froan Basin area (grey) of the Trøndelag Platform (blue plus grey), as well as the main structural provinces. The study area on the Trøndelag Platform is outlined in red. MTFC: Møre-Trøndelag Fault Complex. Modified from Blystad et al. (1995).

A significant portion of this storage capacity was assumed to be 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). CO_2 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 hydrocarbon exploitation. The alternative is thus to store CO_2 in aquifers east and south of the major hydrocarbon province, an area which has previously not been mapped in detail for the purpose of CO_2 storage. The area has the advantage of being closer to onshore CO_2 point sources, and this 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 CO_2. The project shall investigate how lessons learned from previous projects, e.g. SACS, GESTCO and NASCENT, can be implemented for CO_2 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 CO_2
- 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 CO_2 storage on the southeastern part of the Trøndelag Platform and in fjords along the coast of Mid-Norway.
- Determine storage capacity from regional mapping, reservoir parameter quantification, and simulation of migration and underground behavior of CO_2 in these aquifers.
- Suggest further investigations of prospective aquifers.
- Investigate and evaluate stability of CO_2 storage in the study area. The risk for, mechanism behind, and effect of potential leakages from the storage formations will be studied.

In this report, we present a qualitative risk assessment for CO_2 storage in the Beitstadfjord Basin, the Frohavet Basin, and in the Jurassic formations in the Froan Basin area of the Trøndelag Platform (bullet point four, Figure 2.1). The three first objectives are reported by Polak et al. (2004a, 2004b) and Lundin et al. (2005) earlier in the project, but the reports also include qualitative assessments of the risk for leakage. The present report consists in large parts of a summary of the previous reports. A quantitative risk assessment would require more data (from wells and seismic surveys) and detailed studies, particularly for the Frohavet Basin and the Trøndelag Platform. It would further require involvement of specialists on marine processes (transport and dissolution of CO_2), on marine ecology and on marine constructions (ships, platforms), which would be far beyond the scope of the present project.

3. GEOLOGY

3.1 Beitstadfjord Basin

The Beitstadfjord reaches a maximum water depth in excess of 200 m in its southwestern part. There is a gradual decrease in water depth towards the east and northeast. Above the geographical area of the Beitstadfjord Basin, water depths are everywhere more than 100 m, except for a small area in the east, where it is close to 50 m.

In the Beitstadfjord, the Jurassic succession is overlain by a succession of Quaternary deposits ranging from a few metres to approximately 200 m (Fig. 3.1, Bøe & Bjerkli 1989, Sommaruga & Bøe 2002). Generally, the thickness of the Quaternary succession does not exceed 30 m. The succession is dominated by till, but also marine and glaciomarine, fine-grained sediments occur. Erratic fragments of Middle Jurassic age are found in till and marginal marine deposits along the western shores of the Beitstadfjord. These samples were eroded from the Beitstadfjord Basin, beneath Beitstadfjorden, and deposited by ice streams moving in westerly directions during the final stages of the last glaciation.

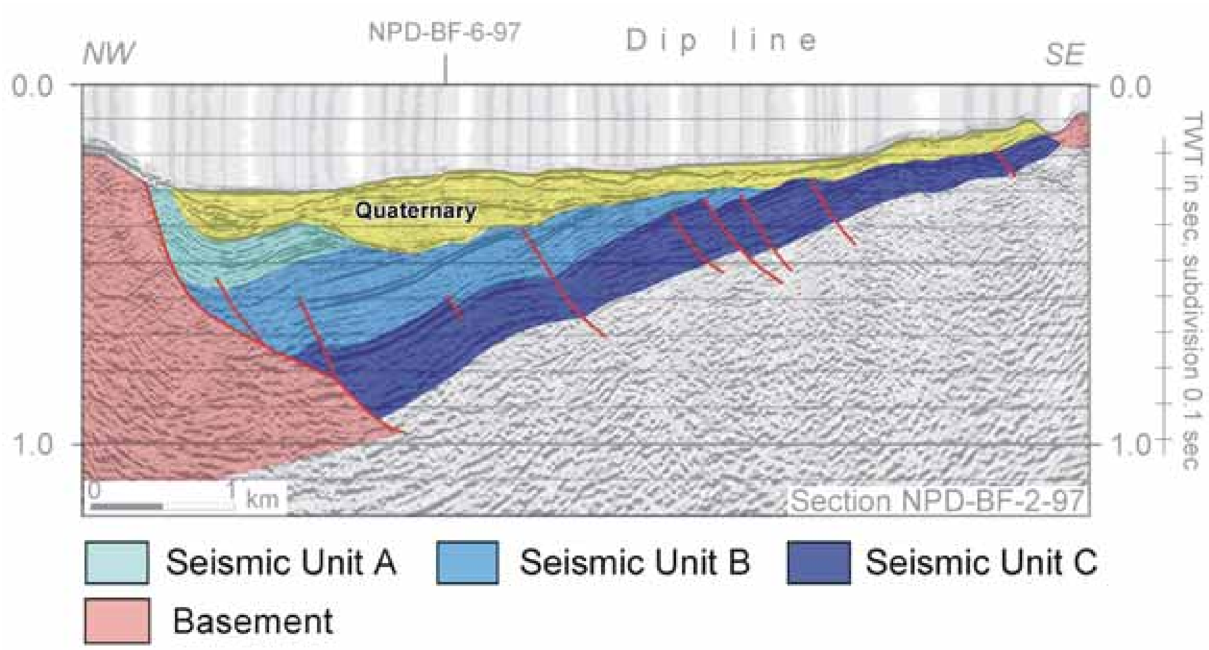

Figure 3.1 Interpreted seismic line across the Beitstadfjord. Note that the Jurassic sedimentary succession (blue) is downthrown in the northwest along a fault that is a branch of the Verran Fault System. Modified from Sommaruga & Bøe (2002).

The Beitstadfjord Basin, containing a sedimentary rock succession of Middle Jurassic age, is an approximately 14 km long by 6 km wide, NE-trending half graben located at the northeastern extremity of the Trondheimfjord (Bøe & Bjerkli 1989, Sommaruga & Bøe 2002). The basin is surrounded by Precambrian migmatitic rocks to the north and Lower Palaeozoic metasediments to the south (Sommaruga & Bøe 2002). The half graben dips to the NW, against its bounding normal fault, while to the southwest, southeast and northeast the Jurassic rocks lie unconformably on basement. The basin occurs along the Møre-Trøndlag Fault Complex (MTFC), which is a major Caledonian strike slip structure that has experienced several phases of movement between Devonian and Tertiary time (Gabrielsen et al. 1999).

Based on seismic character, the dipping succession has been divided into units A-C (Sommaruga & Bøe 2002). These workers postulated that the three units are correlative with the Middle Jurassic Ile, Garn, and Melke Formations known offshore mid-Norway. However, there is no well control in the Beitstadfjord Basin, and besides seismic character, the age and type of basin fill has only been estimated from loose fragments found on nearby shores. These are made up of Middle Jurassic sideritic ironstone and sandstone, and the petrology/chemical composition and the fossil content suggest deposition in shallow lakes in a warm climate (Oftedahl 1972).

The basin is relatively shallow, with a maximum depth of approximately 1.3 km (Polak et al. 2004a). It is clear that the basin has been uplifted and significantly eroded. An important consequence of uplift and erosion is that the basin is more compacted than it would have been otherwise, and that Cretaceous and younger successions have been removed. Organic matter maturation measured on Middle Jurassic sandstone fragments found along the shores of the Beitstadfjord (Oftedahl 1972) suggests a maximum burial depth of 1.8-2.3 km (Weisz 1992).

The Beitstadfjord Basin is characterized by a simple geometry, homoclinally dipping to the northwest. Although some minor faults do exist within the basin, these are not considered to be large enough to generate significant independent traps. With the present poor knowledge of the basin stratigraphy, it was considered inappropriate to include possible fault barriers in a model (Polak et al. 2004a). Thus, for the modelling purposes, the basin was treated as a simple NW-dipping homocline without top seal. The basin subcrops below a Quaternary cover, which is not considered to be an efficient top seal.

On the sideritic ironstones, Oftedahl (1972) measured porosities of 0.6-2.1%. These highly cemented samples are considered unrepresentative of the basin sequence as a whole since they likely are preferentially preserved because of their resistance to erosion; the preserved blocks are thought to represent highly cemented layers. Some samples do show better porosity. Similar samples from Froan have yielded porosities up to 8%, but also these are considered to be unrepresentative; porosities up to 20% should be expected in less cemented layers (Mørk et al. 2003).

3.2 Frohavet Basin

Frohavet reaches a water depth of more than 500 m in its southeastern part. The depth is greatest along a 20-km stretch north and northeast of the Tarva Island, along the trace of the Tarva Fault. There is a gradual decrease in water depth towards the west and northwest. Water depths are everywhere more than 200 m above the part of the Frohavet Basin that is considered for CO_2 storage.

The Quaternary succession below Frohavet is generally less than 10 m thick (in some areas close to zero) and is dominated by hemipelagic silty clays post-dating the last glaciation of the area (Fig. 3.2, Bøe 1991). Only in some topographic depressions are thicker Quaternary deposits (units of till and silty clay) preserved; these are up to 75 m thick. Middle Jurassic erratic blocks are also found in beach deposits on the Froan islands. These were eroded from the Jurassic Frohavet Basin and deposited by ice streams moving towards the northwest during the final stages of the last glaciation.

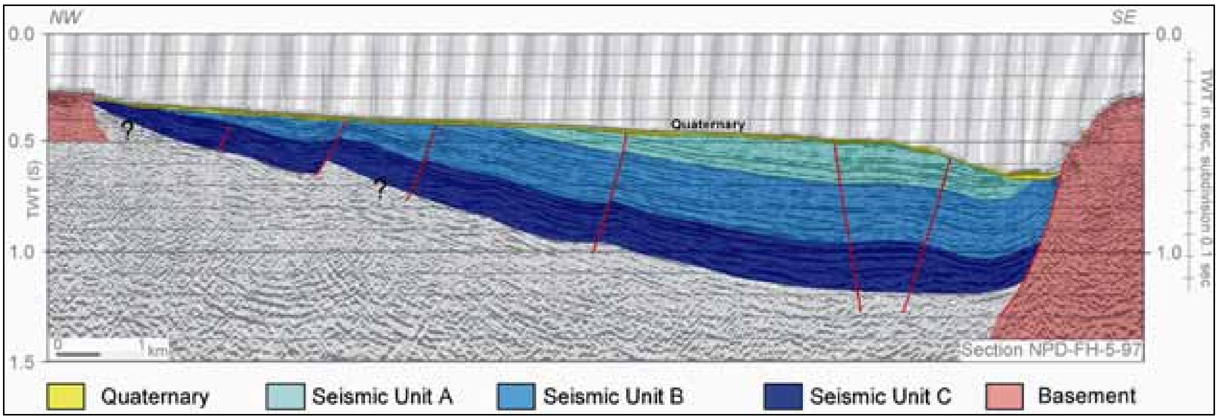

Figure 3.2 Interpreted seismic line across Frohavet. Note that the Jurassic sedimentary succession (blue) is downthrown in the southeast along the Tarva Fault. Modified from Sommaruga & Bøe (2002).

The Frohavet Basin, which contains a sedimentary rock succession of Middle Jurassic age, is an approximately 60 km long by 15 km wide half graben located northeast of Frøya, on the inner part of the Trøndelag Platform (Oftedahl 1975, Bøe 1991, Sommaruga & Bøe 2002). The basin is relatively shallow, with a maximum depth of ca. 1.6 km. Like the Beitstadfjord Basin, the Frohavet Basin also borders the MTFC. The basin is surrounded by Caledonian plutonic rocks to the northwest, west and southwest. Southeast of the basin, the bedrock is dominated by various gneisses overlain by Devonian sedimentary rocks. The Devonian rocks, which are very low grade metamorphosed and with practically zero porosity and permeability, may also be present below the Jurassic succession in Frohavet (Bøe 1991).

The NE-trending half graben dips to the SE, against the Tarva and Dolmsundet normal faults. To the southwest, northwest and northeast, the Jurassic rocks lie unconformably on basement.

The sedimentary succession in the Frohavet Basin displays a weak expansion towards the bounding faults, i.e. indicating syndepositional growth. Between the main Frohavet basin and the Froan islands, several smaller fault-bounded basins with Jurassic sedimentary rocks occur. The effect of the uniformly SE-dipping bedding is that closure depends on the seal of overlying sediments. The thin cover of Quaternary moraine and clays cannot be expected to provide a top seal for injected CO_2.

There is no well control in the Frohavet Basin. Besides seismic character, the age and type of basin fill have been assessed from loose blocks, plucked by the glaciers and deposited to the northwest on the Froan Islands (Nordhagen 1921, Oftedal 1975, Johansen et al. 1988, Rise et al. 1989). The erratic blocks are made up of various marine and nearshore, fine- to coarse-grained sandstones, conglomerates and mudstones. The blocks are usually cemented by carbonate, and siderite cement is common, especially in the mudstones. The blocks frequently contain coal fragments and shells. In contrast to the Beitstadfjord Basin samples, the Frohavet Basin samples do not contain freshwater fossils. In an unpublished biostratigraphic analysis of erratic blocks from the Frohavet Basin, Kelly (1988) concluded that the sediments were deposited in Late Bathonian to Early Callovian time. The marine fauna has a Boreal affinity, i.e. indicating that the marine seaway was connected with the Arctic. Kelly (1988) proposed that the sideritic mudstones formed during an earlier Middle Jurassic regression, while the marine sandstones were laid down during a later Middle Jurassic transgression.

The same stratigraphic subdivision has been suggested for the Frohavet Basin as for the Beitstadfjorden Basin (Bøe & Bjerkli 1989, Bøe 1991, Sommaruga & Bøe 2003), which in both cases is based on seismic character, age, and lithology of erratic blocks. The sedimentary succession has been divided into Units A-C, that are proposed to be correlative with the Middle Jurassic Melke, Garn and Ile Formations known offshore mid-Norway.

The Frohavet Basin is characterized by a simple geometry, homoclinally dipping to the southeast. Although some minor faults do exist within the basin, these are not considered to be large enough to generate significant independent traps (Polak et al. 2004b). With the present poor knowledge of the basin stratigraphy, it appears inappropriate to include possible fault barriers in a model. Thus, for the modelling purposes, the basin was treated as a simple SE-dipping homocline (Polak et al. 2004b). The basin subcrops below a very thin Quaternary cover, which is not considered to be an efficient top seal.

Polak et al. (2004b) estimated the maximum burial depth of the sedimentary rocks in the Frohavet Basin to have been 1.7 and 2.8 km for the shallowest and deepest parts of the basin, respectively. The porosity of the erratic sandstone blocks is poor (generally less than 8%) due to significant cementation (Johansen et al. 1988, Mørk et al. 2003). However, it is likely that these blocks are unrepresentative of the succession as a whole since they likely are preferentially preserved due to their resistance to erosion. The preserved blocks are thought to represent highly cemented layers, carbonate concretions in sandstone, and sideritic concretions in mudstone. Mørk et al. (2003) have estimated that the porosity in non-cemented sandstone beds may be 10-20%, even at the present burial depths.

3.3 Froan Basin area of the Trøndelag Platform

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 are 400-500 m. 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.

The Trøndelag Platform (Fig. 3.3) covers an area of more than 50 000 km^2. It is roughly rhomboid in shape and is situated between 63ºN - 65º50'N and 6º20'E - 12ºE (Blystad et al. 1995). This has been a large stable area since the Jurassic and the platform is covered by mostly parallel-bedded and relatively flat-lying strata, which along the coast dip up to 5° northwestwards.

The Trøndelag Platform (Fig. 2.1) 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 MTFC 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. To the southwest the study area is bound by the Klakk Fault Complex, and on a larger scale the region is separated from the Møre Basin by the Jan Mayen Lineament.

Most of the scattered NE- to NNE-trending normal faults on the platform have minor displacements. Cretaceous strata are thin and are 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).

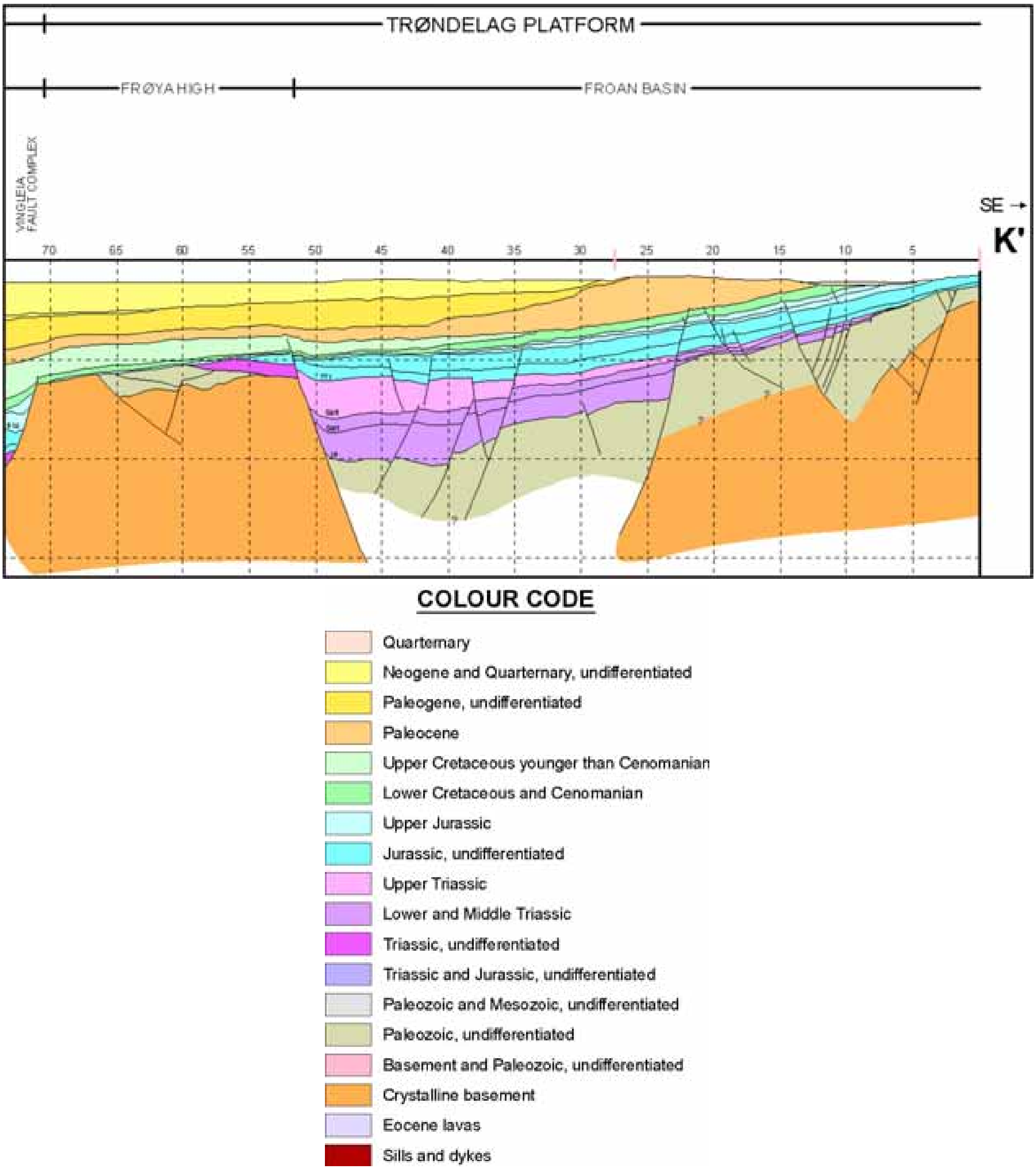

Figure 3.3 Interpreted geoseismic section K partly based on seismic line ST8707-483 (modified from Blystad et al. 1995). The Froan Basin is filled with rocks of Late Palaeozoic and Triassic age, while the Lower-Middle Jurassic rocks, suited for CO_2 storage, are in blue.

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.

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.

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, whereas most of the area rises eastward towards the coast. Overall, the study area is characterized by NE-trending, coast-parallel, normal faults. The faults dip both landward and basinward and displacements are generally less than ca. 250 m. 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.

On the Trøndelag Platform, Triassic and older rocks have very low porosities and permeabilities (Bugge et al. 1984). They are thus probably unsuitable for CO_2-storage and were not further considered in this study (Lundin et al. 2005). 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 (Dalland et al. 1988), and are considered as cap rocks to the Jurassic sandy formations. The formations with an assumed storage potential are the Åre, Tilje, Ile, and Garn Formations. These are internally separated by the shale-dominated Ror and Not Formations.

The reservoir interval considered for CO_2 storage is located between two regional seismic reflectors interpreted as Intra Lower Jurassic (ILJ) and Base Upper Jurassic (BUJ) (Lundin et al. 2005). 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 CO_2 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). 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.

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 (Lundin et al. 2005). According to the Norwegian Petroleum Directorate, the thickness of the Tilje Formation alone reaches 450 m (Bøe et al. 2002). Towards the northeast, the succession thins to ca. 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 Garn and Tilje Formations constitute ca. 27% each, while the Ile Formation constitutes ca. 14%.

The Jurassic reservoir rocks on the southeastern Trøndelag Platform are overlain by a thick succession of cap rocks (Fig. 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), 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 (Fig. 3.3). 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.

4. SIMULATION RESULTS AND RISK OF CO_2 LEAKAGE

4.1 Common features of the studied cases

The three cases share some basic similarities:

- the reservoir units consist probably of highly porous clastic rocks with probably good permeability;
- the reservoir units are overlain by thick argillaceous sequences which constitute capillary seals;
- the reservoirs have a sligth dip;
- the reservoirs either outcrop at the sea floor or subcrop below thin, unlithified layers of Quaternary deposits;
- CO_2 is, at the prevailing temperature and pressure, present as a dense liquid (‘supercritical’), but with a density lower than that of brine.

The most likely scenario for injected CO_2 is thus that it will rise vertically within the storage formation from the injection well’s perforation depth to the contact between that formation and the overlying seal. It will then migrate updip below the top seal towards the formation’s subcrop or outcrop at the seafloor. Key parameters influencing the migration velocity are:

- the presence of local traps and their volume;
- the density difference between CO_2 and brine (largely a function of pressure and temperature);
- reservoir rock permeability;
- vertical and horizontal reservoir heterogeneity;
- relative permeability of the reservoir to CO_2.

Buoyancy-driven updip migration is counteracted by processes which limit the speed of migration and the distance to which the CO_2-front can advance at all. The major counteracting process is dissolution of CO_2 into formation water in the reservoir unit. However this process is slow, operating over a time scale of 1000s of years. Brine with dissolved CO_2 will in many cases have a higher density than ordinary brine. It will thus tend to sink down within the formation, giving way for fresh brine to come in contact with CO_2 and leading to improved dissolution. Another counteracting process is trapping of gas in pores as residual gas. Both dissolution and residual gas trapping are more efficient if CO_2 is spread over a large volume of the pore space in the reservoir.

If formation water (and/or CO_2) can leave the storage reservoir only at a very low rate, e.g. due to efficient sealing, pore pressure in the reservoir will increase. This pore pressure increase may induce hydraulic fracturing of the seal, generating highly efficient pathways for pressure release and potentially migration of CO_2 from the reservoir into sea water.

Simulations of the subsurface behaviour of injected CO_2 were carried out with the commercial black-oil simulator Eclipse 100. The base case for the injection scenarios was an annual injection rate of 2 million tonnes CO_2 over a period of 25 years. This scenario corresponds to the output of a standard size power station over its typical lifetime.

Petrophysical properties of the potential reservoir formations were not known due to lack of wellbore data in the studied basins. These properties had therefore to be estimated based on offshore geological analogs. The implicit uncertainty was addressed by simulation of a range of cases with varying reservoir properties (porosity, horizontal reservoir permeability, k_v/k_h ratio, relative permeability, residual gas saturation, fluid saturation dependence on capillary pressure, permeability of the Quaternary seal).

4.2 Beitstadfjord Basin

Injection was assumed to take place at the maximum possible depth, around 1000 m b.s.l. (Polak et al. 2004a). At the most likely pressure and temperature conditions, CO_2 will have a relatively high density of approximately 800 kg/m^3 below a depth of about 500 m b.s.l. The critical pore pressure in the reservoir at which hydraulic fracturing of the seal is predicted to occur is estimated to be approximately 3.6 bars (0.36 MPa).

Reservoir simulations were carried out to test if CO_2 injected at a rate of 2 million tonnes per year would leak from the reservoir or if it would induce pore pressures causing hydraulic fracturing of the seal. The key simulations assume co-injection into the 'Ile' and 'Garn' formations with injection rates per formation being proportional to their calculated pore volume.

The simulation results show that if the Quaternary seal has a low permeability of approximately 0.1 milliDarcy (mD) or less, it can retain CO_2 initially. However, the pore pressure in the reservoir will increase very fast to a level at which the seal will undergo hydraulic fracturing, that is, it will acquire a high permeability at which CO_2 will leak rapidly. Pressure build-up will also occur at higher permeabilities up to approximately 1000 mD.

Alternatively, if the Quaternary has high permeability (more than 1000 mD), the pressure will not build-up to critical levels, but the leakage rates for the CO_2 will be very high and most of the injected CO_2 will have leaked already 50 years after the start of injection. Leakage may be somewhat slower if the reservoir permeability is lower than in the base case (which is 2000 mD horizontal permeability), but also here most of the injected CO_2 will have leaked after 500 years. Simulated cases of injection into only one of the two compartments yield even less favourable results.

Simulation results indicate that pressure build-up in case of a low-permeable seal and leakage rates in case of a high-permeable seal will be unacceptable also at an injection rate of 100 000 tonnes/year. This corresponds to approximately 5% of the emissions of the planned power plant.

The conclusion of the assessment (Polak et al. 2004a) is that the Beitstadfjord Basin is unsuitable for long-term CO_2 storage, even at a modest injection rate. The major problem with the Beitstadfjord Basin as a CO_2 storage site is a too small storage volume.

4.3 Frohavet Basin

Injection was assumed to take place at the maximum possible depth at approximately 1400 m b.s.l. (Polak et al. 2004b). At the probable pressure and temperature conditions in the Frohavet Basin, CO_2 will have a relatively high density of approximately 800 kg/m^3 below a depth of about 450 m b.s.l. The critical pore pressure in the reservoir at which hydraulic fracturing of the seal is predicted to occur, has been estimated to be approximately 13.6 bars (1.36 MPa). However, such an overpressure is unlikely to occur, because the site is an open system (the Quaternary is not sealing) and because the accessible pore volume in the basin is sufficiently large.

The simulations assume injection close to the base of the deepest of the two connected reservoir formations. The simulations predict early leakage and unacceptably high leakage rates in the case of high absolute permeability (2000 mD), high k_v/k_h ratio (1/10), and high relative permeability to gas. In the worst case (the 'base case'), leakage is predicted to start 10 years after injection start and cumulative leakage is predicted to be 86% of the injected quantity 50 years after injection start. However, if these parameters are moderate to low, there may be no leakage for several centuries, and leakage rates afterwards may be acceptable (annual leakage rate at approximately or below 0.01% of the total injected mass).

Sensitivity of the simulation results to some of the governing parameters could not be fully studied within the frame of the project. Further work is required especially to investigate which parameter combinations would be reasonable. In addition, simulated 'safe' storage as residual gas in pores should be analysed in more detail, because this process may have been overestimated due to up-scaling procedures.

The conclusion of the assessment (Polak et al. 2004b) is thus that the Frohavet Basin potentially is suitable for long-term CO_2 storage given favourable reservoir properties. Further studies should investigate the likelihood for and effect of favourable parameter combinations in more detail before taking the costly step to acquire reservoir data from a well.

4.4 Trøndelag Platform

At the probable pressure and temperature conditions in the Trøndelag Platform, CO_2 will have a relatively high density of 600-800 kg/m^3 below a depth of about 500 m b.s.l. (Lundin et al. 2005).

For simplicity, only two segments of the Trøndelag Platform of approximately 2250 km^2 (trap case) and 1450 km^2 (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) from its subcrop below the Quaternary/at the seafloor. In addition to the base case with simulated injection of 2 million tonnes per year over a period of 25 years, cases were for comparison also simulated with the same injection rate but with injection time extended to 50 years.

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. The faults were neglected in the simulations. Some anticlinal or domal traps exist but their volumes are small.

Simulations were carried out for two scenarios: injection below a local domal trap and injection at a position more likely to result in fast migration towards the subcrop. Neither of the simulations resulted in any leakage. The general feature of all simulations is that CO_2 migrates upwards along the base of the seal towards the subcrop. In most cases, all CO_2 is trapped in structural traps, which it reaches on its way. CO_2 not trapped in structural traps is dissolved into formation water before reaching the subcrop. Dissolution into the formation water entails an immobilization of the CO_2. In fact, formation water with dissolved CO_2 has a higher density than pristine formation water and it is likely to migrate downwards within the reservoir.

The overall conclusion (Lundin et al. 2005) is that the Froan Basin area of the Trøndelag Platform seems to be suitable for underground long-term CO_2 storage.

The simulations carried out so far utilized only one of three potential formations and only a small area of the Trøndelag Platform. The overall storage potential of the Jurassic formations of the Trøndelag Platform is estimated to be several 1000 Mtonnes. This estimate requires validation of at least one of two assumptions: (a) that sufficient structural traps are present everywhere in the basin, or (b) that CO_2 dissolution occurs fast enough to inhibit far migration of free CO_2. 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 CO_2 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.

5. MAJOR UNCERTAINTIES IN THE GEOLOGICAL INTERPRETATIONS AND SIMULATIONS

Simulation results for the Froan Basin area on the Trøndelag Platform indicate that none of the tested combinations of parameters is likely to cause leakage of CO_2 (Lundin et. al. 2005). Accordingly, storage at this site would probably fulfil relevant criteria to qualify this site for long-term CO_2 storage. For the Beitstadfjord Basin, all parameter combinations show that leakage will occur rapidly, and the area can therefore be excluded as a potential storage site (Polak et al. 2004a). The Frohavet Basin might have a storage potential given the right parameter combinations (Polak et al. 2004b).

The simulations contain several uncertainties which largely relate to the lack of relevant data and 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 Frohavet Basin and the Trøndelag

Platform themselves, by dedicated exploration-type wells, including a broad suite of wireline logs and cores from the seal and reservoir formations.

- Reservoir heterogeneity is not known from any of the areas. The distribution of sandstones, the interconnectivity and the lithological variations within individual sandstones are functions of depositional environment. Well data and seismic data (ideally 3D seismic) would be necessary to evaluate reservoir heterogeneity since this strongly influences CO_2 sweep efficiency.

- Two-phase flow properties of the rocks were not known and were taken from previous analyses of the Utsira Sand or not considered. These properties would have to be determined from samples from the potential storage formations. The choices made for the present simulations suggest that migration rates are overestimated meaning that the real migration rates and migration distances would be less than those simulated.

- Seal efficacy has been assumed to be complete, such that no CO_2 should to be able to leak from the storage formation into the overburden. However, this assumption must be confirmed by data from wireline logs and cores prior to injection.

- The downhole temperature and the temperature gradient influence CO_2 migration in several ways: at higher temperature CO_2 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 lines, 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 CO_2 and extending its migration pathways. Non-sealing faults in contrast could enable leakage from the storage formation into overburden formations from which CO_2 may potentially escape if suitable migration pathways exist. In the Frohavet Basin, faults typically extend throughout the sedimentary succession all the way to the base of the very thin Quaternary cover. In the case of non-sealing faults, which might be likely, this implies that CO_2 might leak along fault planes directly into the ocean. On the Trøndelag Platform, the situation is quite different. There, the faults that cut through the Jurassic storage formations typically terminate upwards at the base of the Cretaceous or in the Lower Createaceous fine-grained formations. In the case of non-sealing faults, CO_2 could leak upwards to a Lower Createaceous level, but there it would stop in the thick succession of fine-grained Createaceous and Tertiary rocks. The effects of faults should be thoroughly evaluated through detailed mapping (ideally 3D seismic) and fault seal evaluation (clay smear or faults gouge ratio determinations).

- CO_2 dissolution processes and the variation of CO_2 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 realistically in other simulators – which typically have other shortcomings.

- In addition to physical trapping in structural traps, and to trapping by dissolution, some CO_2 is likely to be trapped as residual gas due to hysteretic flow processes. This trapping mechanism has only been included in a few simulations. In general, residual gas trapping would reduce CO_2 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 CO_2 over large parts of the basins is likely, which will keep the overall increase small in the case of large pore volume available. However, injection at high rates at several places in the basins could lead to considerable pressure increases and should be studied in a comprehensive model for the whole basins.

6. POSSIBLE EFFECTS OF CO_2 LEAKAGE

Acceptable leakage rates for reservoirs are presently discussed in the scientific community. The effect of CO_2 as a greenhouse gas leading to increasing temperature on the earth is widely accepted. With respect to climatic effects, it is considered more favourable with a CO_2 reservoir leaking some of its CO_2 than to went all CO_2 directly into the atmosphere. A minimum requirement for the performance of underground CO_2 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 in 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 CO_2 (Tore Torp, pers. comm. 2004 on discussions in the IPCC work group on underground CO_2 storage, Hepple & Benson 2002).

In the present project, it has been documented that storage of CO_2 in the Beitstadfjord Basin is not an option because CO_2 will start to leak after a few years of injection (Polak et al. 2004a). The Frohavet Basin might have a storage potential given the right parameter combinations (Polak et al. 2004b), while it is shown that the Trøndelag Platform has a large storage potential (Lundin et al. 2005).

The simulations show that, for the Trøndelag Platform, it is very unlikely that a CO_2 leakage would occur within 5000 years, after which leakage might occur at a low rate. In the Frohavet Basin, the situation is more unclear. In the case of favourable parameter combinations, it might be possible to store CO_2 for thousands of years without leakage. However, more simulations, well data, and 3D seismic data are needed to evaluate this. The most critical parameter for the Frohavet Basin is probably wether faults are sealing or not. Sealing faults might increase the storage capacity and success of an injection project, while non-sealing faults might cause leakage of CO_2 into the ocean water.

The possibility of a sudden release of CO_2 (a blow-out) from a subsurface storage site is practically zero. Preventing a blow-out may be achieved by thorough investigations of the storage reservoirs and cap rocks prior to storage. Such investigations must include 3D seismic surveys, drilling/coring and reservoir and geomechanical simulations.

For both the Frohavet Basin and the Trøndelag Platform, CO_2 leaking at a slow rate would enter into the ocean. For the Frohavet Basin, leakage from non-sealing faults or subcropping storage formations could theoretically occur ca. 10 km from the nearest islands. On the Trøndelag Platform, leakage from subcropping storage formations could theoretically occur ca. 15 km from the nearest islands, but only after 5000 years. This implies that there is no danger of suffocation for people living on land due to leaking CO_2. Slow leakages of CO_2 from a storage reservoir beneath the ocean is not a threat to humans. In the open ocean, released CO_2 will be partly dissolved in the more than 200 m thick water column, and the remaining CO_2 escaping to the atmosphere will be mixed with air and rapidly diluted. For people on ships and offshore installations, the situation might possibly be different if they are located directly above the leakage site. However, from studies of natural analogues in the NASCENT project (http://www.bgs.ac.uk/nascent/), it is evident that leaking CO_2 from the subsurface constitutes only a small threat to human beings. A prerequisite for it to cause suffocation is that it accumulates in topographic depressions or in subsurface rooms, which is not the case offshore. Exposure to wind would cause fast mixing and dilution in the athmosphere.

Very few studies have been carried out to study the effect of CO_2 on living organisms and the seabed ecology. The following paragraphs are to a large degree based on information from Professor Egil Sakshaug at NTNU in Trondheim.

The partial pressure of CO_2 (pCO_2) is at present 380 μatm, and is expected to increase to 750 μatm in the next hundred years. The ocean can take up some of this increase but not all as it is an open system where much of the CO_2 uptake will be recycled to the atmosphere within a few hundred years. The concentration of free CO_2 in the upper layers of the oceans is already increasing because the supply from the atmosphere is more rapid than the export to greater depths. Therefore, a large part of the oceans upper layers buffer capacity will be used as pH decreases from 8.1 to 7.8 or less. Around year 2200, pH may be around 7.6. A CO_2 point source doubling the CO_2 concentration can in fact lower the local pH to 6.2.

A CO_2 leakage in water depths shallower than ca. 450 m will cause rising gas bubbles, while at greater depths, parts of the CO_2, in supercritical phase, will gradually be dissolved in sea water. The dense, CO_2 enriched sea water will tend to remain at the base of the water column. In cold water and under high pressure CO_2 hydrate may form and be deposited at the sea bed. These hydrates may be stable and biologically inactive. Potential CO_2 leakage from the Frohavet Basin or the Trøndelag Platform will occur in water depths shallower than 200 m.

Based on limited knowledge, it appears that marine animals react to changes in the O_2 concentration, but not the CO_2 concentration (as opposed to mammals and birds), probably because most marine organisms cannot adapt to such changes. This may be because the ocean, over the past 900 000 years, has been strongly buffered by inorganic carbon. Most marine organisms can therefore not detect an increase in CO_2 concentration, which means that even mobile organisms cannot escape from areas with increased CO_2 concentration. Marine organisms can be even more influenced by a decrease in pH, which can influence their respiration enzyms. The physiological responses to increased CO_2 and lower pH are therefore not similar. Slow benthic organisms with low metabolism are probably less influenced by such changes than animals that can move more rapidly.

As a whole, bacteria, arckaea and extracellular enzyms can tolerate pH values from 5.5 to 11.0. However, there are large variations, and changes in species populations will occur, which will again influence the predator populations. Especially calcifying organisms can be strongly influenced by low pH as carbonate dissolves around pH 7.0-7.5. One result may be that coccoliths produce thinner carbonate plates. Such effects will be very local around a CO_2 leakage, but may become a serious problem if the ocean as a whole becomes more acid. However, this will not be a result of CO_2 leaking from a storage site but rather be a consequence of a higher concentration of CO_2 in the atmosphere due to high releases of CO_2 and nothing being done to this.

7. FURTHER STUDIES

It has been shown that the Beitstadfjord Basin is unsuited for CO_2 storage (Polak et al. 2004a), and it is thus not necessary to study that area in greater detail. The suitability of the Frohavet Basin and the Trøndelag Platform for safe long-term CO_2 storage depends on slow migration of CO_2 towards the sea floor and no leakage along faults, and on the efficacy of counteracting processes such as residual gas trapping, trapping in small traps, dissolution of CO_2 into formation water, and possibly chemical reactions fixing CO_2 as a compound of minerals.

The simulations presented (Polak et al. 2004a,b, Lundin et al. 2005) are based on simplified subsurface models and employ reservoir parameters from the nearby Haltenbanken hydrocarbon province. They show that the Frohavet Basin may be suitable for safe long-term storage of CO_2, given favourable reservoir properties of the potential storage formations. These reservoir properties are presently unknown due to the complete lack of well data or subsurface samples. The Trøndelag Platform is likely to be suitable for safe, long-term subsurface CO_2 storage. Given injection deep enough and far from the subcrop of the storage formations, CO_2 is likely to be immobilized long before reaching the subcrop. 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 areas for long-term CO_2 storage needs to be assessed in more detail. Local geological and reservoir property data from dedicated wells are an indispensable part of such an assessment. However, more sophisticated simulations of potential subsurface CO_2 flow behaviour 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, and including hysteretic flow effects.

The quality of the seal formations should also be assessed. Prior to drilling a well, knowledge about the seal could be obtained from the Haltenbanken province and from shallow wells along the coast. Extrapolating these data with the help of depositional models and simulations can be done. 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 on lateral rock heterogeneity (seismic facies). Analysis of the seismic data, improved digital subsurface geology model and revised reservoir simulations.
4. Conclusion on suitability and decision about injection project based on all available data.

8. ACKNOWLEDGEMENT

NGU, SINTEF and Statoil would like to thank the Commission of the European Communities (EC-Contract No. ENK-CT-2002-00621), Industrikraft Midt-Norge and the Klimatek programme of the Norwegian Research Council (NFR) for financial support to this project.

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