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CO_2 point sources and subsurface storage capacities for CO_2 in aquifers in Norway

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REPORT

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CO_2 point sources and subsurface storage capacities for CO_2 in aquifers in Norway

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Summary: The GESTCO (GEological STorage of CO_2 from fossil fuel combustion) project comprises a study of the distribution and coincidence of thermal CO_2 emission sources and location/quality of geological storage capacity in Europe. The GESTCO project is a joint research project conducted by 8 national geological surveys and several industry partners/end users, partly funded by the European Union 5th Framework Programme for Research and Development. Four of the most promising types of geological storage are being studied: 1) onshore/offshore saline aquifers with or without lateral seal, 2) low entalpy geothermal reservoirs, 3) deep methane-bearing coal beds and abandoned coal and salt mines, and 4) exhausted or near exhausted hydrocarbon structures.

In this report, we present an inventory of CO_2 point sources in Norway (1999) and the results of the work within Study Area C: deep saline aquifers offshore/near shore Northern and Central Norway. Also offshore/nearshore Southern Norway has been included, while the Barents Sea is not described in any detail. The most detailed studies are on the Tilje and Åre Formations, on the Trøndelag Platform off Mid-Norway, and on the Sognefjord, Fensfjord and Krossfjord Formations, southeast of the Troll Field off Western Norway. The Tilje Formation has been chosen as one of the cases to be studied in greater detail (numerical modeling) in the project. This report shows that offshore Norway, there are concentrations of large CO_2 point sources in Haltenbanken, the Northern Viking Graben/Tampen Spur area, the Southern Viking Graben and the Central Trough, while onshore Norway there are concentrations of point sources in the Oslofjord/Porsgrunn area, along the coast of western Norway, and in Trøndelag. A number of aquifers with large theoretical CO_2 storage potential are pointed out in the North Sea, the Norwegian Sea and in the Southern Barents Sea. The storage capacity in the depth interval 0.8-4 km below sea level is estimated to be ca. 13 Gt (13 000 000 000 tonnes) CO_2 in geological traps (outside hydrocarbon fields), while the storage capacity in aquifers not confined to traps is estimated to be at least 280 Gt CO_2.

Keywords: Norway	Aquifer	Carbondioxide
Carbondioxide sequestration	Carbondioxide storage	Climate
Greenhouse gas	Stratigraphy	Carbondioxide point source

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1. INTRODUCTION

The objective of the GESTCO (GEological STorage of CO_2 from fossil fuel combustion) project is to contribute to CO_2 abatement from power genereation and heavy industry. The project comprises a study of the distribution and coincidence of thermal CO_2 emission sources and location/quality of geological storage capacity. Studies are made of four promising types of geological storage throughout Europe. Project participants (contractors) are GEUS (Denmark), BGR (Germany), BGS (Great Britain), BRGM (France), GSB (Belgium), IGME (Greece), NGU (Norway), NITG-TNO (Netherlands) and ECOFYS (Netherlands). The Norwegian Petroleum Directorate (NPD) is one of several end users, and has participated in the preparation of this report together with NGU.

Using case studies from different regions, the project will aim at determining the true potential of subsurface storage for CO_2 in Europe. The case studies will:

- Define the location of potential storage areas relative to large point sources of CO_2
- Produce detailed geological data for each area
- Conduct reservoir simulations for each potential storage area
- Make an economic evaluation of the storage potential in each area
- Evaluate the significance of all possibilities for alternative uses of the subsurface
- Evaluate the impact of any leak that may occur
- Make economic comparisons of carbon dioxide-free electricity production cost from conventional and renewable energy sources

The results of the project will encompass evaluation of the underground storage potential in the representative areas combined with inventories of power plant (and major industrial) point sources of CO_2 emission. Through a number of realistic scenarios, cost of CO_2 storage will be calculated, per tonne of CO_2 avoided and as increase in the cost of electricity production. Abatment cost will be compared to other energy sources.

A dedicated decision support system will be developed in the project, and this facility will be made publicly available on the internet, enabling other users (e.g. power companies and policy makers) to evaluate their own "emission source - storage site " scenarios.

In this report we present the inventory of CO_2 point sources in Norway (1999), and the results obtained during activities within Study Area C (deep saline aquifers offshore/nearshore Northern and Central Norway) (Fig. 1). Also offshore/nearshore Southern Norway has been included, while the Barents Sea is not described in any detail. The most detailed studies are on the Tilje and Åre Formation, on the Trøndelag Platform off Mid-Norway, and on the Sognefjord, Fensfjord and Krossfjord Formations (regarded as one aquifer), southeast of the Troll Field off Western Norway. The Tilje Formation has been selected as one of several cases to be studied in more detail, and will be subject to numerical modeling.

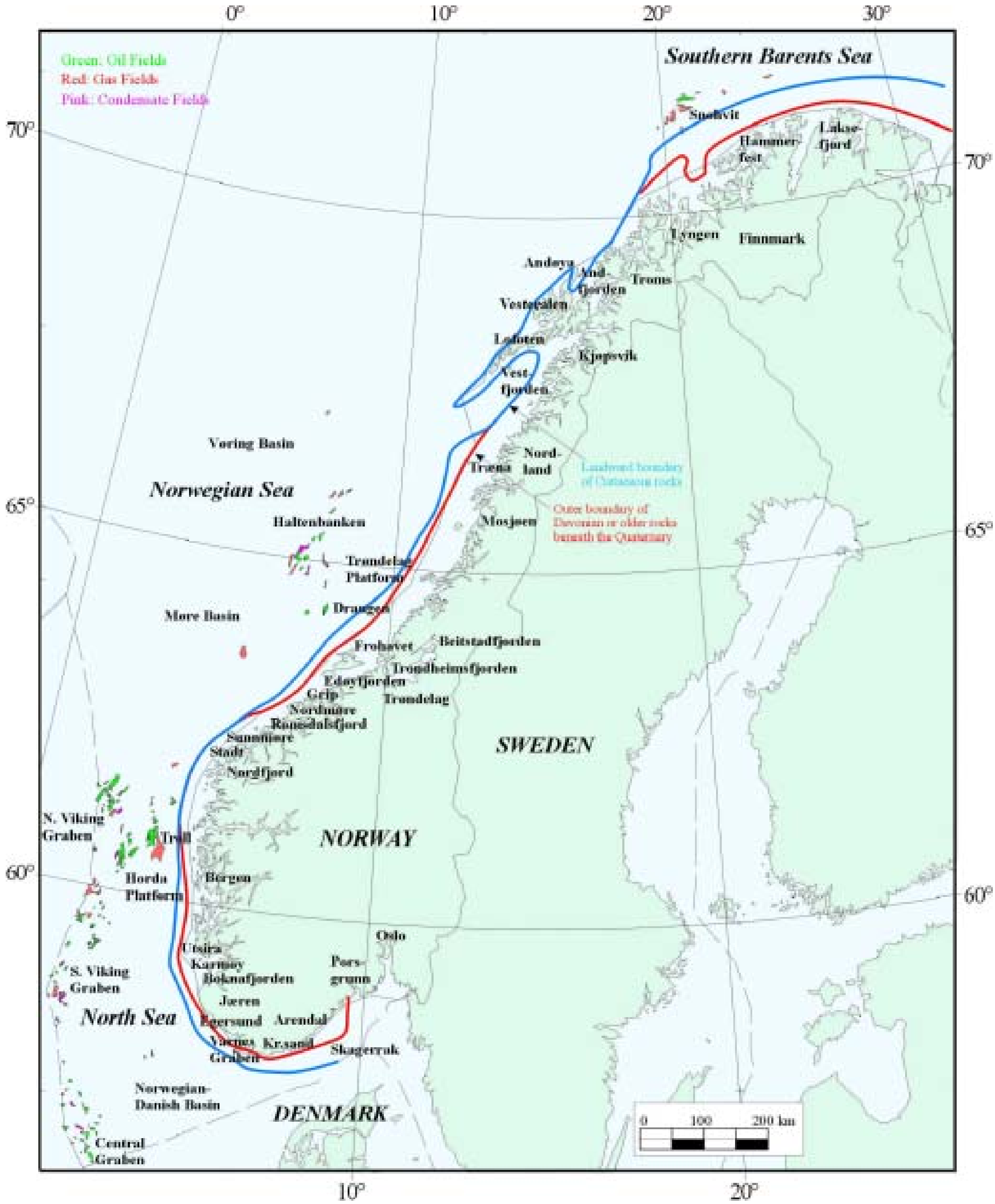

Figure 1. Map of the studied area (Study Area C) showing the inner boundary (towards land) of rocks that might be candidates for CO_2 storage. Place names and hydrocarbon fields mentioned in the text are shown. Modified from Bøe et al. (1998).

2. CO_2 POINT SOURCES IN NORWAY

Most of the information presented on CO_2 point sources in Norway has been obtained from the web-pages (http://www.sft.no/bmi/) of the Norwegian Pollution Control Authority (Statens Forurensningstilsyn, SFT) and from the Norwegian Petroleum Directorate (NPD). For the onland point sources, this includes company names, site names, type of operation and CO_2 emissions in 1999. Geographical coordinates have been obtained from digital maps. For the offshore point sources, all data have been obtained from NPD. The geographical coordinates for the oil and gas fields represent the discovery well.

2.1 Industrial point sources on land

Approximately 70 of the largest onland industrial point sources for greenhouse gas emissions have been considered in this study (Table 1). These point sources, of which the majority have greenhouse gas emissions of more than 20 000 tonnes CO_2-equivalents, contribute to more than 95 % of the greenhouse gas emissions from industrial point sources on land in Norway. In 1998, CO_2 contributed to 74% (41.7 million tonnes) of the total greenhouse gas emissions in Norway (http://www.sft.no, Statistisk sentralbyrå 2000). In 1999, the total CO_2 emissions were 42.3 million tonnes.

In 1998, the largest CO_2 process emissions (point sources) came from the manufacturing of iron, steel and ferro alloys (4 million tonnes) and aluminium (1.7 million tonnes), but also process emissions from the manufacturing of chemicals and mineral products contributed significantly (Table 2). The largest emissions from stationary combustion came from refining (2 million tonnes), and from the manufacturing of chemicals and mineral products.

The industrial point sources on land are spread over much of Norway (Figs. 2a, b), but approximately 6 regions with clusters of CO_2 point sources can be mapped. The 1999 CO_2 emissions from industrial point sources in these regions are summarized in Table 3. As can be seen, there are several concentrations of large point sources, especially in the Porsgrunn area (3 point sources larger than 0.5 million tonnes in 1999) and in Western Norway (2 point sources larger than 0.5 million tonnes in 1999). In addition, one isolated large point source occurs at Finnsnes in Troms (Figs. 2a, b).

According to SFT, by 2010 there will be significant increases in CO_2 emissions from Statoil Mongstad and Statoil Kårstø (Western Norway), Statoil Tjeldbergodden (Nordmøre), Hydro Porsgrunn Industripark (Porsgrunn area), while Norske Shell AS at Sola (a refinery which released 253 000 tonnes in 1999) is now closed down.

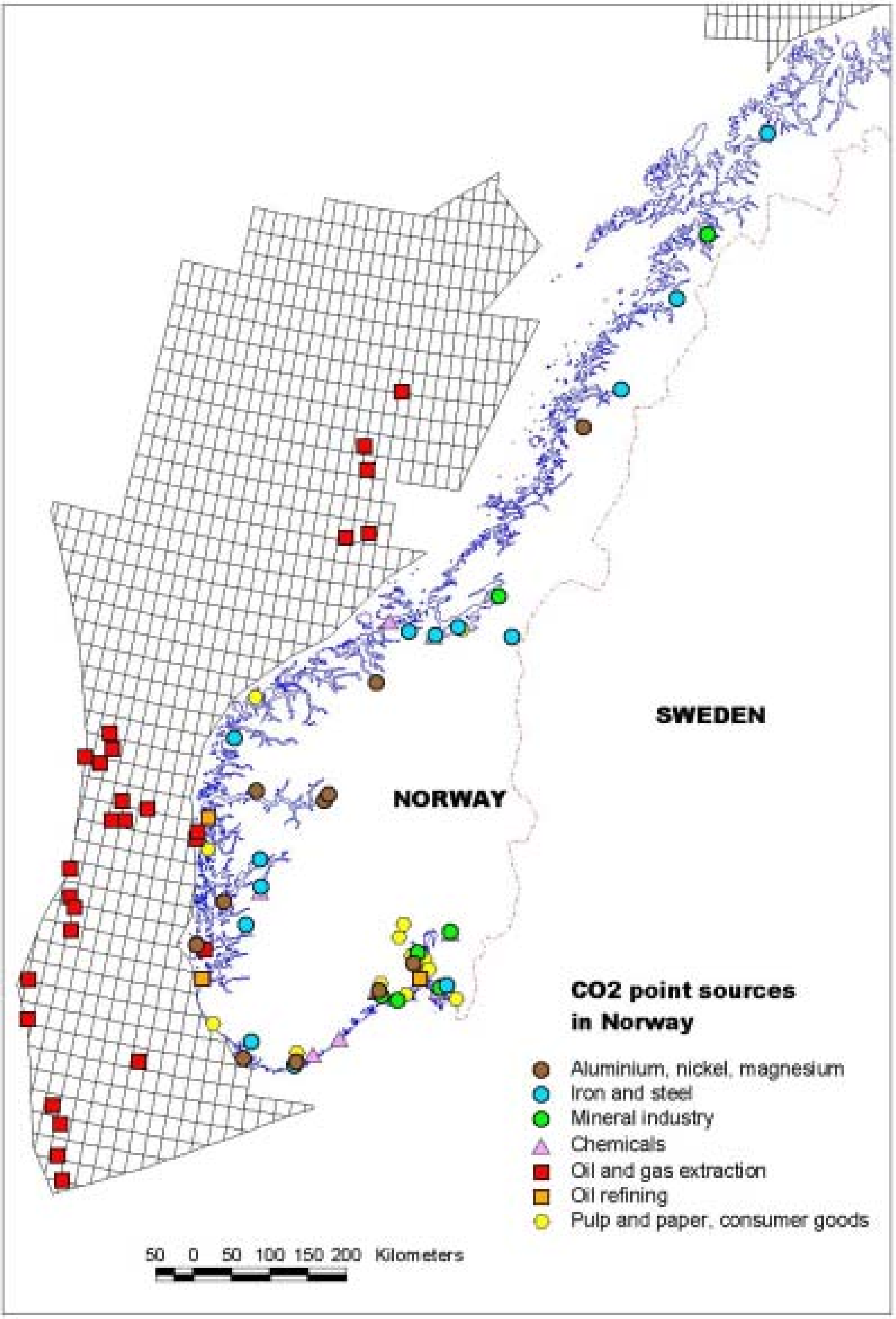

Figure 2a. Large (> ca. 20 000 tonnes/year) CO_2 point sources (process emissions and emissions from stationary combustion combined) onshore and offshore Norway in 1999. Data obtained from the Norwegian Pollution Control Authority, the Norwegian Petroleum Directorate and the Geological Survey of Norway.

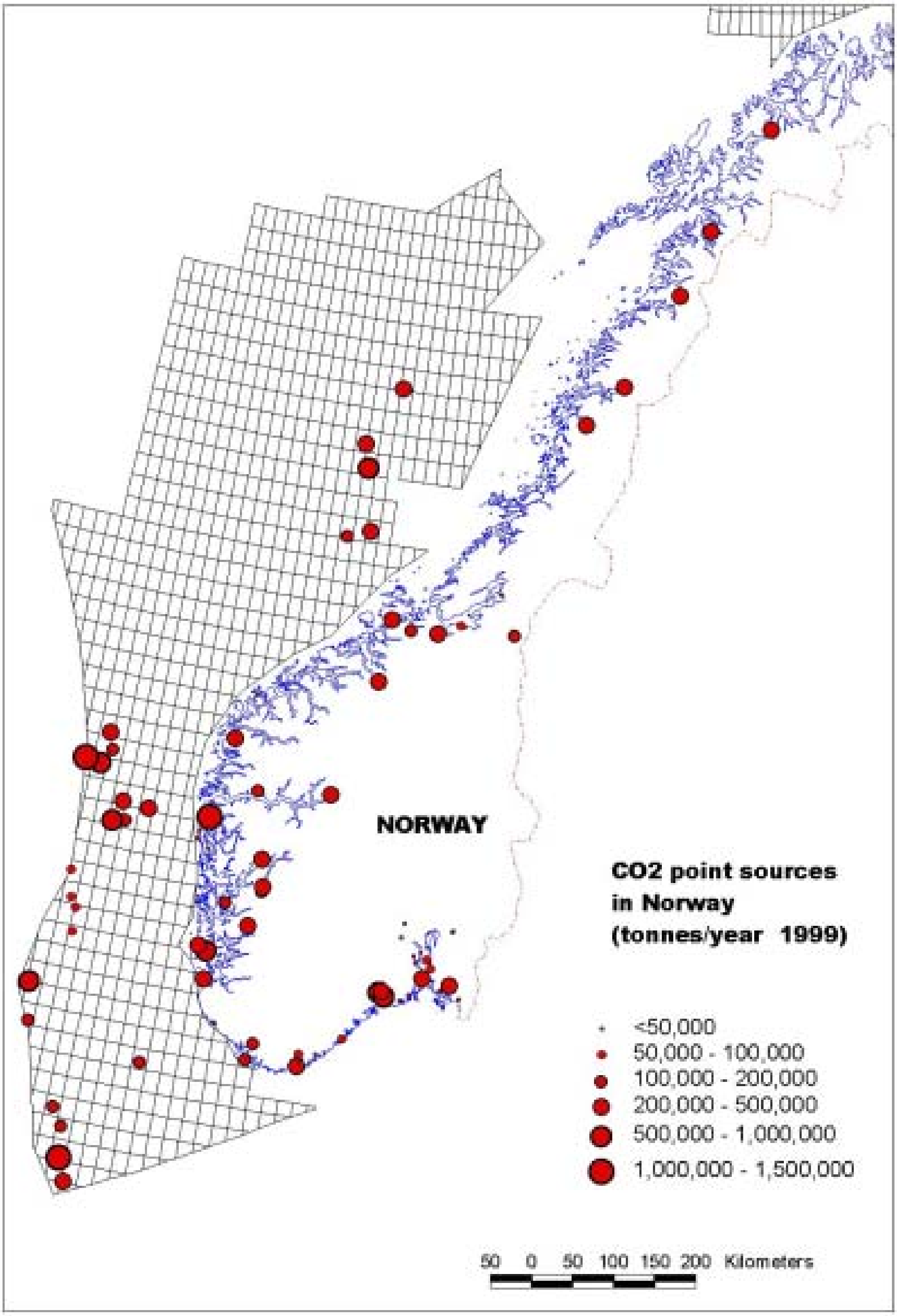

Figure 2b. Large (> ca. 20 000 tonnes/year) CO_2 point sources (process emissions and emissions from stationary combustion combined) onshore and offshore Norway in 1999. Data obtained from the Norwegian Pollution Control Authority, the Norwegian Petroleum Directorate and the Geological Survey of Norway.

Table 1. Norwegian onshore and offshore sites with reportable releases of CO_2 in 1999. Data on CO_2 emissions have been obtained from the Norwegian Pollution Control Authority and the Norwegian Petroleum Directorate. Geographical coordinates for land sites have been obtained from digital maps, while coordinates for oil and gas fields represent discovery wells.

Company name/oil and gas field	Site name	Lambert N	Lambert E	Type of operation	Emissions, tonnes CO_2	Comments
Silfas Egersund AS	Grønehaugen, Egersund	6846863	-808476	Vegetable and animal oils	25000	1998 emissions
Silfas Moldtustranda AS	Moltustranda	7274742	-752298	Vegetable and animal oils	16000	
Silfas Karmsund AS	Husøy, Avaldsnes	6953555	-829794	Vegetable and animal oils	21000	1998 emissions
Silfas Horsøy AS	Tveit, Hauglandsosen, Askøy	7075550	-815463	Vegetable and animal oils	12000	
Hydro Oleochemicals AS	Vera, Sandefjord	6884608	-555527	Vegetable and animal oils	27000	
Denofa AS	Gamle Fredrikstad	6890212	-513378	Vegetable and animal oils	32000	
Norsk Wallboard AS	Vigeland, Vennesla	6807934	-698621	Pulp and paper	15000	
Borregaard Industrier Ltd. Energiavdelingen	Sarpsborg	6897238	-502836	Pulp and paper	154000	Will increase
Borregaard Industrier Ltd. Cellulosesektor	Sarpsborg	6897238	-502836	Pulp and paper	21000	
Union AS	Geithus	6977149	-559589	Pulp and paper	14000	
Union AS, Union Bruk	Skien	6899037	-589182	Pulp and paper	15000	
Norske Skog Saugbruks	Halden	6878776	-489458	Pulp and paper	17000	
Sødra Cell Tofte AS	Tofte	6930830	-530833	Pulp and paper	67000	
Peterson Linerboard AS	Verket, Moss	6919008	-526149	Pulp and paper	74000	
Peterson Linerboard AS	Ranheim	7363812	-481801	Pulp and paper	19000	
Peterson Scanproof AS	Greåker	6896625	-508255	Pulp and paper	31000	1998 emissions
Hunsfoss Fabrikker AS	Vigeland, Vennesla	6808622	-698490	Pulp and paper	69000	
Sande Paper Mill AS	Selvik, Sande i Vestfold	6935404	-548177	Pulp and paper	31000	
Borregaard Hellefos AS	Hokksund	6959417	-564962	Pulp and paper	20000	1998 emissions
Esso Norge AS, Slagentangen	Slagentangen, Tønsberg	6905992	-536944	Oil Refinery	342000	
Norske Shell AS	Sola	6906280	-821969	Oil Refinery	253000	Now stopped
Statoil Mongstad	Mongstad	7117116	-813502	Oil Refinery	1310000	Will increase
Statoil Troll gassanlegg	Kollsnes	7089438	-829376	Oil and gas terminal	25000	
Statoil Kårstø	Kårstø	6943392	-818650	Oil and gas terminal	650000	1998 emissions
Norsk Hydro Produksjon AS	Stureterminalen, Rønningen	7098272	-827370	Oil and gas terminal	1000	Will increase
Borealis AS	Rafnes	6888053	-592709	Polyethylen, polypropylen	62000	
Borregaard Industrier Ltd. Svovelsyrefabrikken	Sarpsborg	6897243	-502936	Sulphuric acid	33000	Will decrease
Dyno Industrier AS	Lillestrøm Industisenter	6966282	-497312	Glue	25000	
Hydro Polymers AS, Rafnes	Herre	6889095	-593654	Vinyl chloride monomer	516000	

Statoil Tjeldbergodden	Tjeldbergodden	7374291	-576530	Methanol	413000	Will increase
Kronos Titan AS	Øya, Fredrikstad	6888543	-513864	Titan dioxide	50000	
Saint-Gobain Ceramic Materials A.S. Arendal Smelteverk	Eydehavn	6827791	-641855	Silicium carbide	72000	
Saint-Gobain Ceramic Materials A.S. Lillesand	Lillesand	6806697	-676181	Silicium carbide	47000	
Odda Smelteverk AS	Odda	7019953	-745812	Carbide	108000	
Orkla Exolon KS	Orkanger	7355470	-518459	Carbide	39000	
Hydro Porsgrunn Industripark	Porsgrunn	6890211	-590014	Fertilizer, ammonia, nitric acid	435000	Will increase
Norcem AS, Brevik	Brevik	6882783	-586794	Cement works	948000	
Norcem AS, Kjøpsvik	Kjøpsvik	7880338	-160387	Cement works	432000	
Verdalskalk AS	Hylla	7405777	-433751	Cement works	40000	
Norgips AS Tørkop	Svelvik	6939340	-539089	Mineral industry	35000	
Norsk Leca AS, Leca Borge	Borge	6892563	-510662	Leca	22000	
Norsk Leca AS, Leca Rælingen	Rælingen	6966871	-497081	Leca	25000	
Rockwool AS, Fabrikk Larvik	Revet, Larvik	6876977	-566171	Rockwool	19000	
Fundia Armeringsstål AS	Mo i Rana	7677474	-272882	Iron and steel	62000	
Rautaruukki Profiler AS	Mo i Rana	7677480	-272986	Iron and steel	41000	
Bjølvefossen AS	Ålvik	7061339	-745674	Iron and steel, ferro alloys	229000	
Elkem AS, Bremanger Smelteverk	Svelgen	7220254	-779759	Iron and steel, ferro alloys	273000	
Elkem AS, Fiskaa Silikon	Vågsbygd, Kristiansand	6792069	-700439	Iron and steel, ferro alloys	253000	
Elkem AS, Salten Verk	Valljord	7795987	-200010	Iron and steel, ferro alloys	403000	
Elkem Meraker AS	Kopperå	7353031	-415599	Iron and steel, ferro alloys	152000	
Elkem Rana AS	Mo i Rana	7677370	-272888	Iron and steel, ferro alloys	152000	
Elkem Thamshavn Verk AS	Thamshavn, Orkanger	7355788	-516504	Iron and steel, ferro alloys	229000	
Eramet Norway AS, Porsgrunn	Porsgrunn	6890206	-589914	Iron and steel, ferro alloys	135000	
Eramet Norway AS, Sauda	Sauda	6975690	-764093	Iron and steel, ferro alloys	288000	
FESIL AS, Holla Metall	Kyrksæterøra	7360498	-550487	Iron and steel, ferro alloys	155000	
FESIL AS, Lilleby Metall	Lilleby, Trondheim	7366193	-486019	Iron and steel, ferro alloys	65000	
FESIL Rana Metall	Mo i Rana	7677265	-272894	Iron and steel, ferro alloys	266000	
Finnfjord Smelteverk AS	Finnfjordbotn	8012551	-81403	Iron and steel, ferro alloys	311000	Will increase
Globe Norge AS, Hafslund Metall	Sarpsborg	6896661	-501371	Iron and steel, ferro alloys	206000	
Tinfos Jernverk AS, Øye Smelteverk	Øyestranda, Kvinesdal	6822245	-757520	Iron and steel, ferro alloys	158000	Will increase
Tinfos Titan & Iron KS	Tyssedal	7025491	-744392	Iron and steel, ferro alloys	253000	
Hydro Aluminium AS, Holmestrand Valseverk	Holmestrand	6925798	-545766	Aluminium rolling mill	31000	
Elkem Aluminium ANS, Lista	Farsund	6800709	-767656	Aluminium	163000	
Elkem Aluminium ANS, Mosjøen	Mosjøen	7627233	-323152	Aluminium	220000	
Hydro Aluminium AS, Årdal Karbon	Årdalstangen	7138939	-662153	Aluminium	36000	

Hydro Aluminium AS, Årdal Metallverk	Øvre Årdal	7146230	-656010	Aluminium	353000	
Hydro Aluminium AS, Høyanger Metallverk	Høyanger	7151735	-749944	Aluminium	119000	
Hydro Aluminium AS, Karmøy Fabrikker	Håvik	6949743	-828844	Aluminium	475000	
Hydro Aluminium AS, Sunndal Verk	Sunndalsøra	7293152	-593852	Aluminium	285000	
Sør-Norge Aluminium AS	Husnes	7006213	-792657	Aluminium	177000	
Falconbridge Nikkelverk AS	Kristiansand S.	6796457	-698950	Nickel	19000	
Hydro Porsgrunn Industripark, Magnesiumfabrikken	Porsgrunn	6890202	-589815	Magnesium	281000	Will increase
Draugen	Quadrant 6407	7489086	-603927	Oil field	225257	
Heidrun	Quadrant 6507	7603099	-609809	Oil and gas field	337939	
Njord	Quadrant 6407	7483389	-634175	Oil field	171805	
Norne	Quadrant 6608	7674985	-561725	Oil and gas field	347060	
Åsgard	Quadrants 6506, 6507, 6407	7572346	-605851	Oil and gas field	564717	
Balder	Quadrant 26	6968752	-993725	Oil field	53671	
Brage	Quadrant 31	7113270	-922743	Oil and gas field	197548	
Ekofisk	Quadrants 1 and 2	6673696	-1010489	Oil and gas field	1068745	
Frigg	Quadrant 25	7049329	-994557	Gas field	83635	
Gullfaks	Quadrant 34	7188454	-955464	Oil and gas field	861370	
Gyda	Quadrant 2	6715150	-1007190	Oil and gas field	100232	
Heimdal	Quadrant 25	7013475	-994367	Oil and gas field	72568	
Jotun	Quadrant 25	6999065	-989413	Oil and gas field	94503	
Oseberg	Quadrant 30	7113400	-940533	Oil and gas field	897168	
Sleipner	Quadrant 15	6904394	-1049370	Gas field	746954	
Snorre	Quadrant 34	7227966	-943178	Oil and gas field	475001	
Statfjord	Quadrants 33 and 34	7195759	-975088	Oil and gas field	1344884	
Troll	Quadrant 31	7128318	-893745	Oil and gas field	372692	
Ula	Quadrant 7	6739926	-1017845	Oil and gas field	173742	
Valhall	Quadrant 2	6641871	-1005041	Oil and gas field	289800	
Varg	Quadrant 15	6853245	-1049714	Oil field	152086	
Veslefrikk	Quadrant 30	7138251	-927022	Oil and gas field	221338	
Visund	Quadrant 34	7206122	-939287	Oil field	168395	
Yme	Quadrant 9	6797548	-904398	Oil field	152978	

Three gas-fired power plants are at the planning stages. Kårstø and Kollsnes, which are located in Western Norway, might increase annual CO_2 emissions by a total of 2.1 mill. tonnes CO_2, while a plant at Skogn (Trondheimsfjorden area) is planned to release 2.2 mill. tonnes CO_2 annually.

If Statoil decides to start production of LNG from the Snøhvit field in the Barents Sea, several million tonnes of CO_2 (separated from the natural gas at a landbased plant) will probably have to be disposed of in the underground somewhere to the north of Hammerfest, in the Barents Sea (Fig. 1).

Table 2. CO_2 emissions to air by source (major point sources) in 1998. The data have been obtained from Statistisk sentralbyrå (2000).

Stationary combustion	
Oil and gas extraction, natural gas	6.8
Oil and gas extraction, flaring	1.2
Oil and gas extraction, diesel combustion	0.5
Oil and gas extraction, gas terminal	0.6
Refining	2.0
Manufacture of pulp and paper	0.6
Manufacture of mineral products	0.9
Manufacture of chemicals	1.2
Manufacture of metals	0.3
Other manufacture and industry, minor and major sources	2.2
Process emissions	
Manufacture of chemicals	0.9
Manufacture of mineral products	0.9
Manufacture of iron, steel and ferro alloys	4.0
Manufacture of aluminium	1.7

2.2 Point sources offshore

In 1999, approximately 9.4 mill. tonnes CO_2 was emitted by the offshore petroleum industry. These emissions were mainly from point sources (platforms) located at the various oil and gas fields in production (Figs. 2a, b, Table 1), and are predominantly related to stationary combustion. In 1998, combustion of natural gas produced 6.8 mill. tonnes of CO_2, flaring 1.2 mill. tonnes and diesel combustion 0.5 mill. tonnes (Table 2).

The 1999 CO_2 emissions from offshore point sources in various regions are summarized in Table 4. As can be seen, the area with the largest emissions is the Northern Viking Graben/Tampen Spur with 3 point sources emitting more than 0.5 mill. tonnes in 1999. In this area the total emissions were 4.55 mill. tonnes in 1999.

Table 3. Large CO_2 point sources by region on land in 1999. Data from the Norwegian Pollution Control Authority.

Area/region	CO_2-emissions >20 000 tonnes/ year (number)	CO_2-emissions >50 000 tonnes/ year (number)	CO_2-emissions >100 000 tonnes/ year (number)	CO_2 emissions >500 000 tonnes/ year (number)	CO_2 emissions in 1999(Mt)
Oslofjord region (Mjøsa-Larvik-Halden triangle)	16	6	3	0	1.2
Porsgrunn area	7	6	5	3	2.4
Southern Norway from Egersund to Arendal	7	5	3	0	0.8
Western Norway from Boknafjord to Sunnmøre	15	12	12	2	4.6
Nordmøre and Trondheimsfjorden area	8	6	5	0	1.4
Nordland from Mosjøen to Kjøpsvik	7	7	5	0	1.6

Table 4. Large CO_2 point sources by region offshore in 1999. Data from the Norwegian Petroleum Directorate.

Area/region	Fields in production with CO_2 emissions in 1999	CO_2 emissions >50 000 tonnes in 1999 (number)	CO_2 emissions >100 000 tonnes in 1999 (number)	CO_2 emissions >500 000 tonnes in 1999 (number)	CO_2 emissions in 1999 (Mt)
Central Trough/Norwegian Danish Basin	5	5	5	1	1.80
Southern Viking Graben	5	5	2	1	1.10
Northern Viking Graben/Tampen Spur	8	8	8	3	4.55
Halten and Dønna Terraces	5	5	5	1	1.65

For the next 15 years, NPD expects an increase in CO_2 emissions from the offshore oil and gas industry to a maximum of 14 mill. tonnes/year in 2006-2007, and then a gradual reduction to the year 2000 level.

3. GEOLOGY OF NORWAY

3.1 Onshore geology

The onshore geology of the coastal regions of Norway is characterised by a wide variety of rocks of differing origin, compostion and structure (Sigmond et al. 1984, Sigmond 1992). Common for the vast majority of the rocks is that they are old, compact and have virtually zero porosity, with the exception of the porosity attendant on the jointing of the rocks. The oldest rocks in Norway are of Precambrian age (>545 Ma old).

The geology of onshore Norway can be divided into:

- a Precambrian basement complex of mainly crystalline metamorphic rocks and the great thrust-fold belt of the Norwegian Caledonides,
- Devonian low-grade metamorphic sediments,
- Carboniferous-Permian rocks of the Oslo Graben,
- a few fault-bounded relics of Mesozoic sediments,
- a variable cover of Quaternary.

The Precambrian basement complex comprises a great range of variably metamorphosed metasedimentary, metavolcanic and igneous rocks, and the age of these varies from Archaen to Neo-Proterozoic. There are large areas in Finnmark and southern Norway with Neo-Proterozoic sedimentarey rocks. The Precambrian rocks all have low porosities and permeabilities.

The Norwegian Caledonides (e.g. Gee & Sturt 1985) are made up of major thrust nappes, which were emplaced towards the east-southeast during the Scandian Orogeny in Middle-Late Silurian times. The lower nappes contain basement-cover assemblages of Precambrian crystallines and Late Precambrian/Lower Palaeozoic metasediments. The upper nappes of the Caledonian Belt contain a variety of sedimentary successions and also ophiolites and products of island arc volcanism. These nappes also contain elements of Precambrian crystallines. Along the coast (in Nordland, Hitra-Smøla (west-central Norway), and in the Bømlo-Stord district of western Norway) major areas of granitic rocks (batholiths) of Lower Palaeozoic age occur. The rocks of the Caledonides are all metamorphosed and thus have very low porosities and permeabilities.

Devonian sediments (e.g. Steel et al. 1985), dominantly sandstones and conglomerates, are found in a number of substantial developments along the coast of western and central Norway. These are metamorphosed to Lower Greenschist facies grade, and thus have low porosities and permeabilities.

The Oslo Graben (e.g. Dons & Larsen 1978), located between lake Mjøsa and Skagerrak, developed in Late Carboniferous-Permian times and has locally preserved a few tens of metres of undeformed and weakly metamorphosed sediments beneath the lavas. The lavas reach several thousand metres in thickness. Sandstones and conglomerates, a few metres up to a few tens of metres thick, also occur between the lava flows. A thick succession of syn-rift conglomerates occur along the eastern boundary fault of the Oslo Graben. In the southeastern part of the Oslo Graben, Cambrosilurian sediments (mainly shales and limestones) are practically unmetamorphosed and little deformed.

The only place where Mesozoic sedimentary rocks are preserved onshore is on Andøya (Fig. 1, Dalland 1979), but Mesozoic sedimentary rocks have also been found in several fjords along the coast (see below). The preserved sediments are mainly of Middle Jurassic-Lower Cretaceous age (ca. 170-120 mill. years old), and are thus of approximately the same age as the rocks that contain oil and gas offshore Norway. The succession comprises mainly shales, siltstones and sandstones with horizons of coal and limestone. A number of dykes of Mesozoic age are found at a number of localities along the coast of western Norway, and are considered to be related to extensional tectonics in the North Sea.

3.2 Geology of the fjords and the marine areas of the coastal zone

In fjords and marine areas of the coastal zone, the geology is not very different from the geology onshore. Basins and down-faulted blocks with sedimentary rocks of broadly similar age (Jurassic-Cretaceous) to those found on Andøya and in the marine areas offshore have been mapped e.g. in Andfjorden, Vestfjorden, Sortlandsundet, Frohavet, Edøyfjorden and Beistadfjorden (Fig. 1, Sigmond 1992). The sediments in these areas comprise shales, siltstones, sandstones and conglomerates, with horizons of coal and limestone. In most of the areas the Mesozoic rocks have been preserved in downfaulted elongate blocks, protected from erosion during the Quaternary glaciations. It is probable that the sandstones, in some instances, have a relatively high porosity, possibly similar to that of sandstone resevoirs containing oil and gas in the offshore.

The sedimentary rocks in these basins along the coast are remnants of a more continuous sedimentary succession that formerly covered a large part of the older basement rock complex of the coastal zone, though how far this cover extended inland is not known. Due to Neogene uplift and Plio-Pleistocene glacial erosion, the offshore sedimentary succession is truncated (i.e. sub-cropping). Away from the coast, sedimentary rocks are preserved as a more or less continuous blanket. The inner subcrop boundary describes a number of swings and arcs, at a distance varying from a few kilometres up to ca. 50 km, beyond the outermost shoals. Generally, the oldest sedimentary rocks occur closest to land because the rocks dip towards the offshore. If present, Carboniferous, Permian and Triassic rocks subcrop between the Pre-Carboniferous basement and the Jurassic, Cretaceous and Tertiary rocks further offshore, particularly along the Finnmark coast from Laksefjord in the northeast to Lyngenfjorden in the west, and off the Nordland and Rogaland coasts (Sigmond 1992).

3.3 Offshore geology

The geology of the Norwegian continental shelf is varied, both with respect to age and rock/sediment type (Sigmond 1992). The areas of the present continental shelf were strongly influenced by the Caledonian Orogeny 500-400 million years ago. The Devonian, ca. 400-350 million years ago, was a period of collapse, erosion and molasse sedimentation of the orogen.

Thick sedimentary units were deposited in Carboniferous and Permian times on Svalbard and in the Barents Sea (Fig. 1). The Permian was a period of extensive stretching of the continental crust, widespread faulting and deposition of thick sedimentary successions, especially in the Skagerrak, in the North Sea and off Mid-Norway. Skagerrak (Fig. 1) experienced significant volcanic activity associated with rifting. In the Triassic, thick sedimentary units were deposited in the Barents Sea, on the Trøndelag Platform (Fig. 3) and in the North Sea (Fig. 4). In the North Sea and the Norwegian Sea this was accompanied by exstensive normal falting.

Extensive rifting and normal faulting occurred in the North Sea and the Norwegian Sea in the Jurassic, and source rocks and reservoir rocks very important for the Norwegian hydrocarbon production were deposited. Other phases of rifting and normal faulting, in the Cretaceous and Tertiary, were associated with extension leading to opening of the North Atlantic Ocean. Especially during Cretaceous times sedimentary successions approaching 10 kilometers in thickness were deposited in the Møre and Vøring Basins. Cretaceous rocks are widespread on the Norwegian continental shelf.

In the Pliocene and Pleistocene, the continental shelf was strongly influenced by glacial processes. Major uplift and erosion took place on the Norwegian mainland, in the Barents Sea, and in the Skagerrak area. The erosional products occur as large slope aprons along the continental margin, especially off the Svalbard-Barents Sea margin (thickness of several kilometers), and in the Norwegian Sea off Mid-Norway and in the Møre Basin.

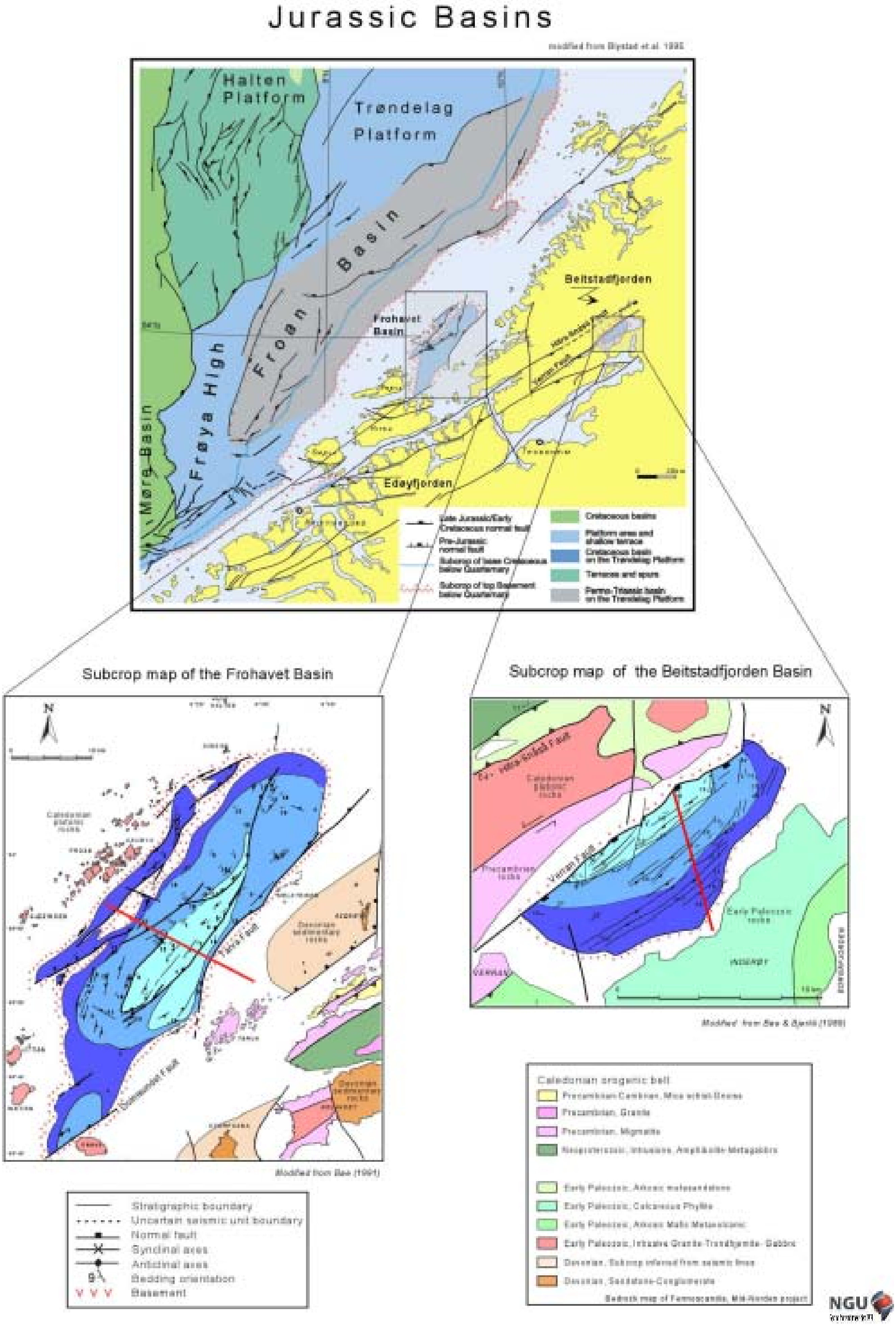

Figure 3. Structural elements and shallow basins, Mid-Norway. Modified from Sommaruga and Bøe (2002).

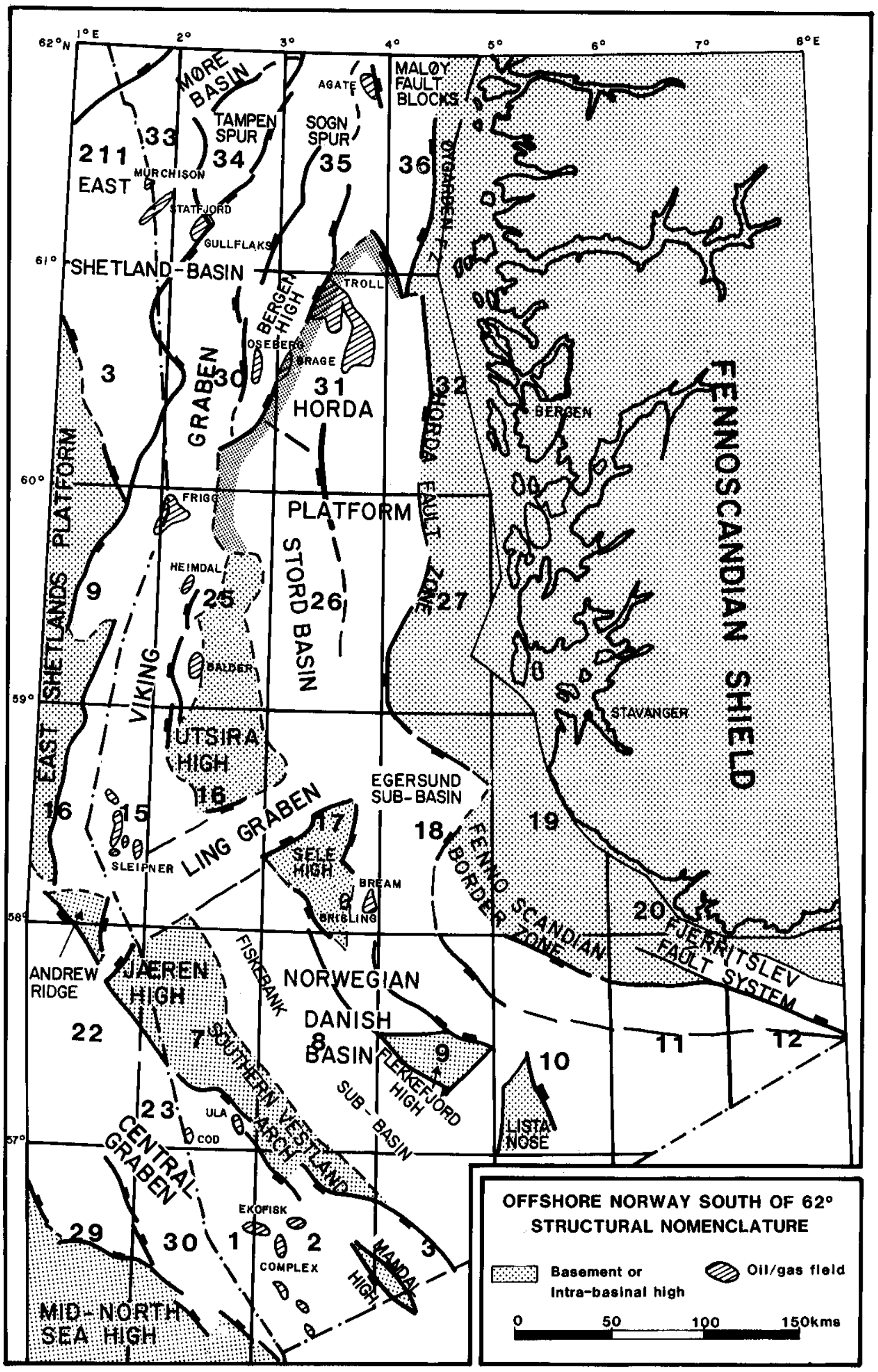

Figure 4. Structural nomenclature offshore Norway south of 62 °N. From Vollset and Doré (1984).

4. ROCKS AND FORMATIONS POTENTIALLY SUITABLE FOR CO_2 STORAGE IN NORWAY

A number of parameters are important to CO_2 injection and storage in rocks and sediments (see Holloway 1996). Many of these are discussed in greater detail in Chapter 6. Some of the most important parametres are:

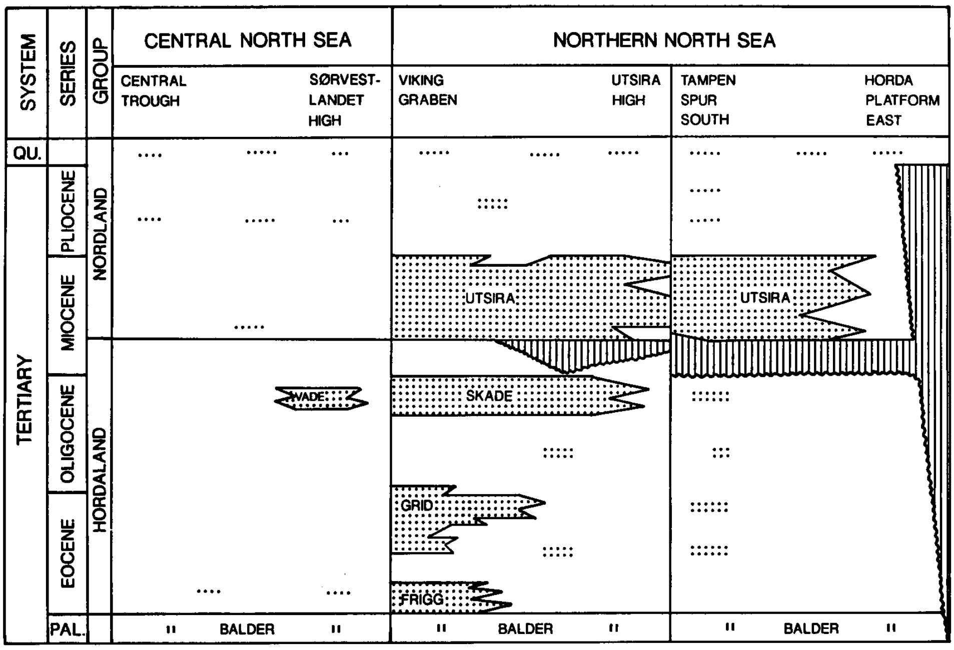

Figure 5a. Lithostratigraphic nomenclature in the Hordaland and Nordland Groups (Tertiary), Norwegian North Sea. From Isaksen and Tonstad (1989).

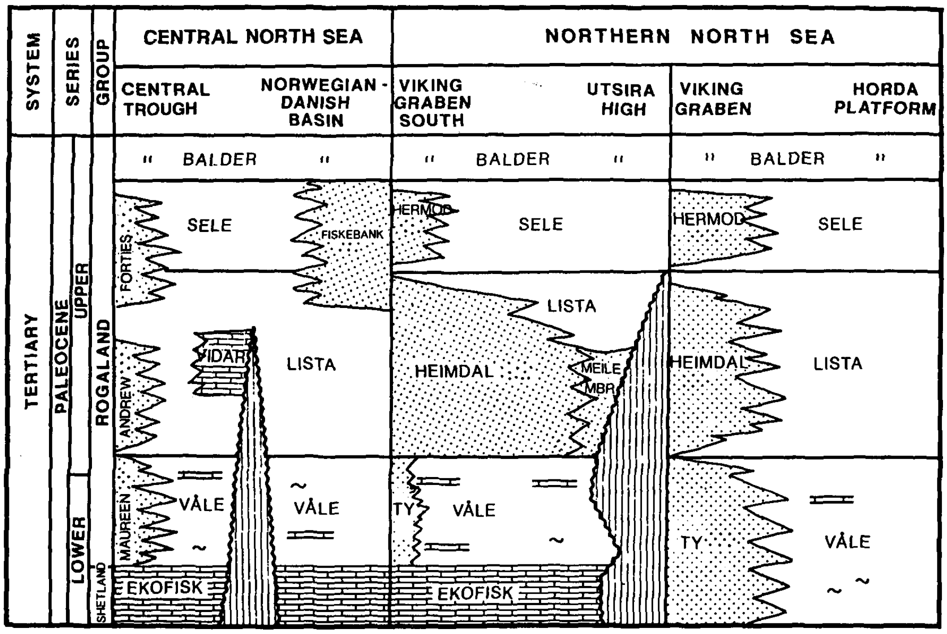

Figure 5b. Palaeocene lithostratigraphic nomenclature, Norwegian North Sea. From Isaksen and Tonstad (1989).

- Permeability. Reservoir rocks have to be permeable to allow CO_2 migration away from the injection point.

- Porosity. Reservoirs have to be porous to allow storage of large volumes of CO_2.

- Volume. Thickness and areal distribution of the reservoir has to be sufficiently large, and the communication between the various reservoir bodies good, to generate large enough volumes available for storage.

● Depth. Reservoirs have to be deeper than 800 m to allow storage of CO_2 as a supercritical fluid (a fluid that is neither liquid nor gas, but posesses some characteristics of both, being compressible and having liquid-like densities) (Czernichowski-Lauriol et al. 1996). Storage at great depths is not economically feasible. Aquifers within the depth range 800-4000 m are included in this report.

● Seal. Storage reservoirs have to be sealed by a tight cap rock to prevent gas leakages to the surface.

● Tectonic activity. Storage areas should be tectonically stable, without significant earthquake activiy.

● Mineralogy. Reservoirs should not contain minerals that will lead to deterioration of the reservoir quality during injection.

As a result of the thermodynamic limits for the injection of CO_2 in liquid form, nearshore storage in Plio-Pleistocene and Holocene sediments (gravel, sand and silt) is not possible. Plio-Pleistocene deposits of sufficient volume or depth are generally not present in the fjords or in the coastal zone. Plio-Pleistocne sediments of sufficient volume to represent theoretical candidates for CO_2 storage are however found in the central parts of the North Sea, at the mouth of the Norwegian Channel in the Norwegian Sea, offshore Mid-Norway and at the confluence of the Barents and Norwegian Seas, south of Bjørnøya (Vorren et al. 1998). Especially the Kai and Naust Formations off Mid-Norway have a potential for storage (see Chapter 6.2).

5. CO_2 STORAGE POTENTIAL ON LAND AND NEARSHORE NORWAY

5.1 CO_2 storage potential in rock formations on land

Virtually all rock formations on land are unsuitable for the storage of CO_2. The only potential could have been the Permo-Carboniferous lavas along the coast between Langesund and Oslo. Here the porosity is probably so high, that if this was the only criteria for storage, they might have represented a candidate. However, the lavas have low permeability, occur at shallow depths and probably have no good cap rocks. Furthermore the Oslofjord region is densely populated, such that considerable care would have to be taken to avoid groundwater reservoirs. Lindeberg (in Holloway 1996) also concluded that the rock formations of onshore Norway have little or no potential for CO_2 storage.

5.2 CO_2 storage potential in nearshore Tertiary deposits

Tertiary deposits of the North Sea (Figs. 5a-c) contain many sandstones which may be suitable aquifers for CO_2storage. The Skade and Vade Formations (deposited in the Miocene and Oligocene), and the Frigg and Grid Formations (deposited mainly in the Eocene) were developed more than 100 km from the Norwegian coast. The same is the case for the Paleocene sandstones of the Forties, Fiskebank, Andrew, Heimdal, Maureen and Ty Formations. The Paleocene (Egga Member of the Våle-Tang Formations) and Eocene sediments, north of the Troll Field are, on the other hand, are located closer to the Norwegian mainland. It is also possible that local developments of Tertiary sandstones can be found closer to the coast.

The Utsira Formation, deposited in late Middle Miocene to Early Pliocene times (Eidvin et al. 2002), appears to be one of the most important potential storage reservoirs for CO_2. At the Sleipner Field, Statoil is conducting a major project (SACS), to investigate the effects of injecting CO_2 into a deep saline aquifer (Chrisensen 1998, Torp and Christensen 1998). Approximately 1 million tonnes of CO_2 is yearly pumped into the aquifer at a depth of 900 m below seabed. The Utsira Formation is of such considerable thickness and extent that it alone could store CO_2 emissions from all north European power stations and other large industrial plants for several hundred years (Torp and Christensen 1998). The shortest distance to the formation from the Norwegian coast is ca. 60-70 km. This formation is described in detail in a later chapter.

In the upper part of the Tertiary succession off Mid-Norway (Fig. 6), the Kai Formation (Miocene-Pliocene) and Naust Formation (Pliocene-Pleistocene) contain sand and coarse gravel. These deposits lie ca. 50-60 km from the coast (Tveten et al. 1998a). In the eastern part of the Brygge Formation, Dalland et al. (1988) refer to sandstones which inter-finger with fine grained sediments. The deposits can probably be correlated with the Lower Oligocene Frøyrygg Formation (Askvik and Rokoengen 1985). The nearest these sediments come to land is ca. 40 km, outside the coast of Møre. The oldest Tertiary sediments off Mid-Norway are the Paleocene Tang and Tare Formations. These formations are dominated by shales, though it is conceivable that near the coast they contain sandstones (e.g. the Egga Member). The storage potential of such sandstones, as well as those in the Brygge Formation must be evaluated further, although many are probably not well suited for storage as they are markedly inclined upwards towards the coast. CO_2 stored in such reservoirs could rapidly migrate up towards the surface.

Tertiary sequences, which could provide potential CO_2 storage resevoirs, have not been described off the coast of Northern Norway. The one possible exception, is the area north of Vesterålen and west of Troms, where Tertiary and Pliocene/Quaternary sediments lie only 5-10 km from the coast (Zwaan et al. 1998). However, the type of sediment contained in these deposits are not known. In order to evaluate their suitability as storage reservoirs, they would have to be drilled to establish lithologies and physical parameters.

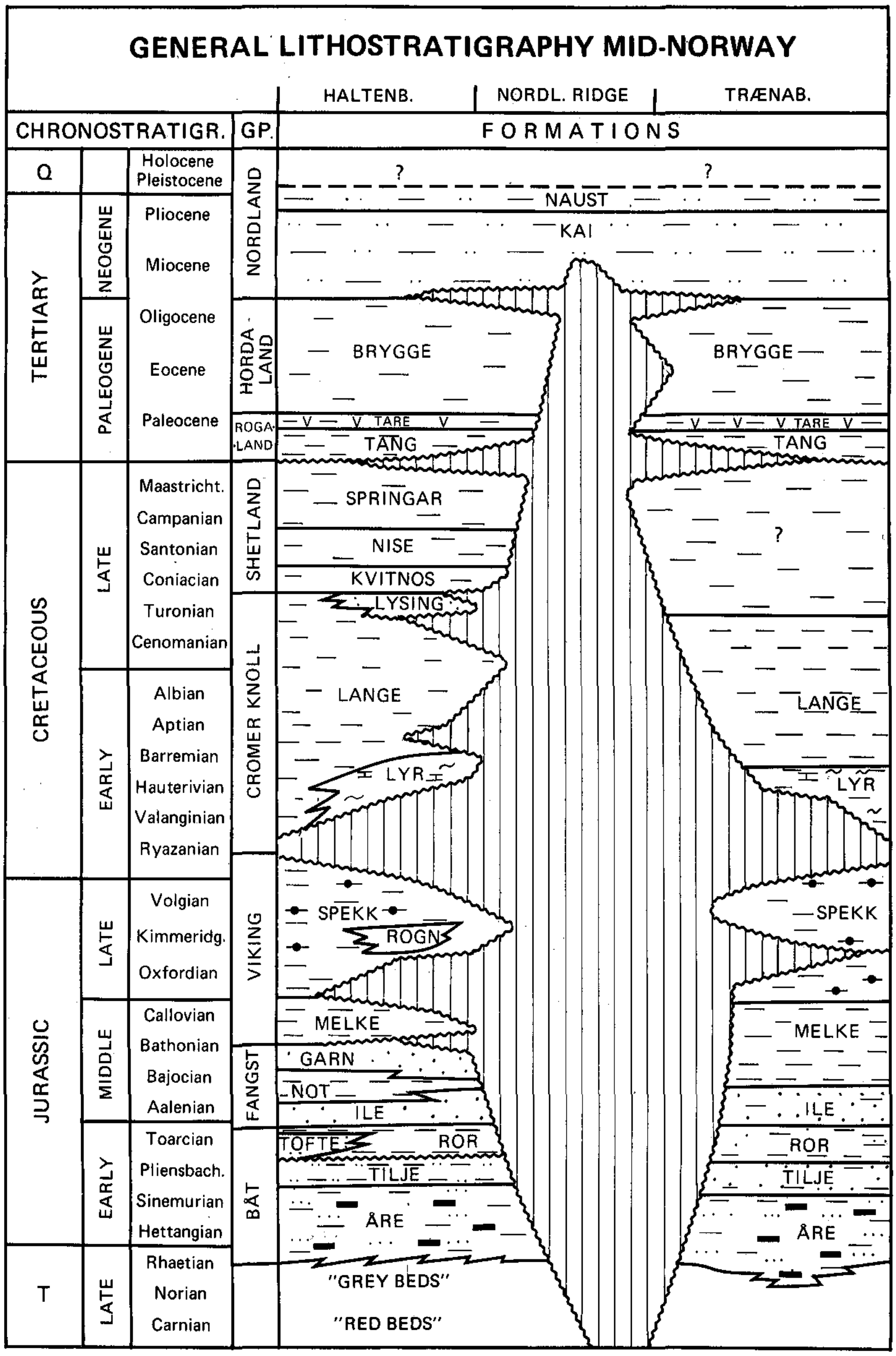

Figure 6. Generalized time- and lithostratigraphic section from the Halten Terrace to the Trænabanken area, Mid-Norway. From Dalland et al. (1988).

In summary, Tertiary sediments along the Norwegian coast are probably not candidates for CO_2 storage, with the possible exceptions of the sequences north of the Troll Field, in the greater Ormen Lange area (Egga Member) and those outside of Troms/Vesterålen (Table 5).

Table 5. Rock units with a possible storage potential for CO_2, nearshore Norway.

Area	Storage unit	Age
Western Finnmark	Tubåen, Nordmela and Stø Formations	Early-Middle Jurassic
	Havert, Klappmys, Kobbe, Snadd and Fruholm Formations	Triassic
	?	Permian-Carboniferous
Lofoten-Vesterålen-Troms	?	Tertiary
	Kviting Formation	Late Cretaceous
	Tubåen, Nordmela and Stø Formations	Early-Middle Jurassic
Andfjorden	Ramså Formation	Middle Jurassic
	?	Early Jurassic
Vestfjorden	?	Middle Jurassic-Cretaceous
Vikna-Vega-Træna	Ile and Garn Formations	Middle Jurassic
	Åre and Tilje Formations	Early Jurassic
	?	Triassic-Permian
Beitstadfjorden and Frohavet	Ile and Garn Formations	Middle Jurassic
Romsdal-Nordmøre-Smøla-Hitra-Frøya-Froan-Vikna	Ile and Garn Formations	Middle Jurassic
	Åre and Tilje Formations	Early Jurassic
	?	Triassic-Permian
Bergen-Møre	Egga member	Paleocene
	Agat Formation	Early Cretaceous
Western Norway (fault basins E of the Øygarden/Horda Fault Zone	Etive, Krossfjord, Fensfjord and Sognefjord Formations	Middle-Late Jurassic
Bergen-Nordfjord (west of the Øygarden Fault Zone)	Sognefjord Formation	Late Jurassic
	Etive, Krossfjord and Fensfjord Formations	Middle Jurassic
	Statfjord, Johansen and Cook Formations	Early Jurassic
Western Norway	Hegre Group ++	Triassic-Permian-Carboniferous
Southwest Norway/Varnes Graben	Ekofisk, Tor and Hod Formations	Late Cretaceous
	Bryne and Sandnes Formations	Middle Jurassic
	Gassum formation	Early Jurassic
Skagerrak	Bryne Formation	Middle Jurassic
	Gassum Formation	Early Jurassic
	?	Permian-Carboniferous

5.3 CO_2 Storage potential in nearshore Cretaceous deposits

The Cretaceous rocks of the North Sea (Figs. 7a-e) comprise mainly Upper Cretaceous limestones (generally as far north as the Utsira High) and shales (Lower and Upper Cretaceous), though a variety of other sediments occur locally. The Cretaceous deposits all appear to be marine.

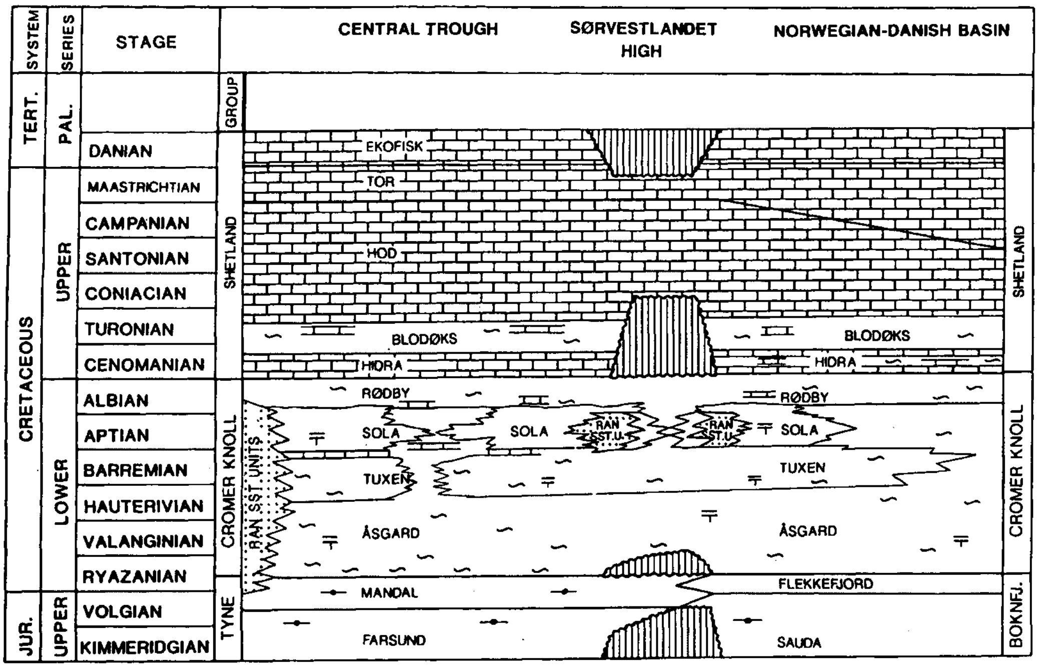

Figure 7a. Cretaceous lithostratigraphic nomenclature, Norwegian North Sea.Central Trough - Sørvestlandet High - Norwegian-Danish Basin. From Isaksen and Tonstad (1989).

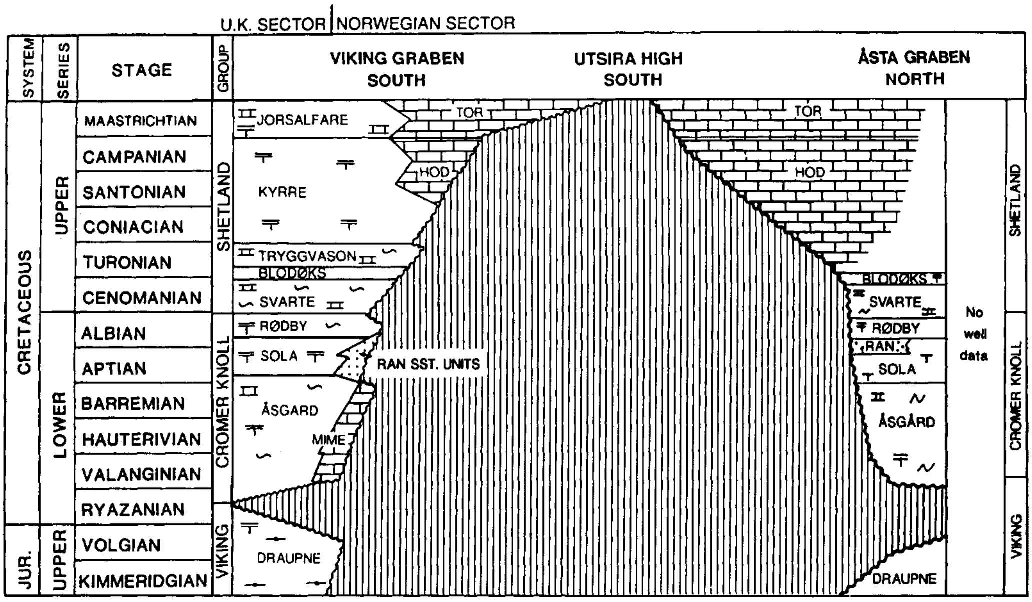

Figure 7b. Cretaceous lithostratigraphic nomenclature, Norwegian North Sea.Southern Viking Graben - Southern Utsira High - Northern Åsta Graben. From Isaksen and Tonstad (1989).

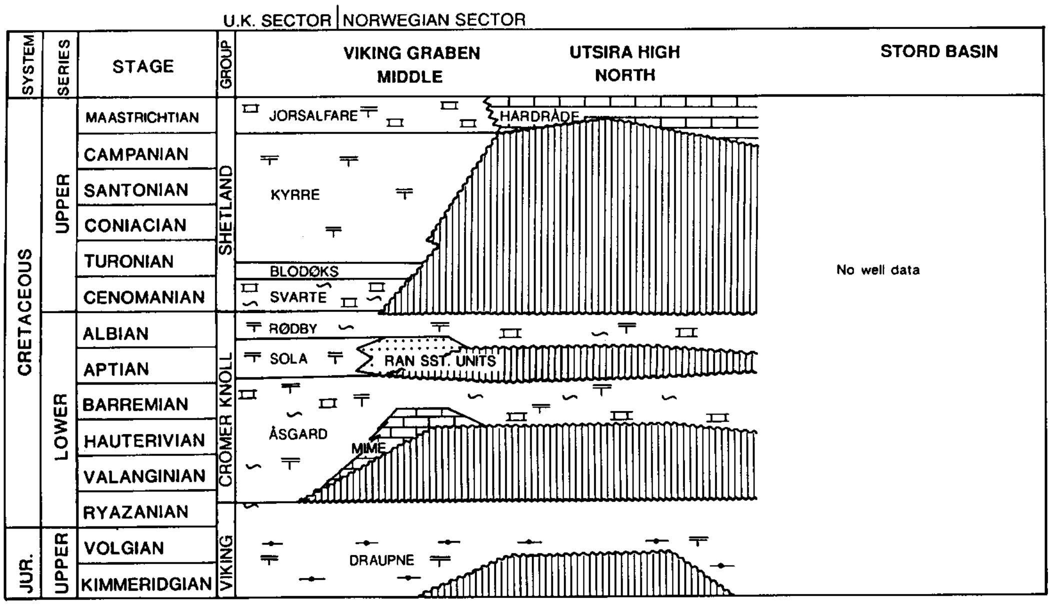

Figure 7c. Cretaceous lithostratigraphic nomenclature, Norwegian North Sea. Middle Viking Graben - Northern Utsira High - Stord Basin. From Isaksen and Tonstad (1989).

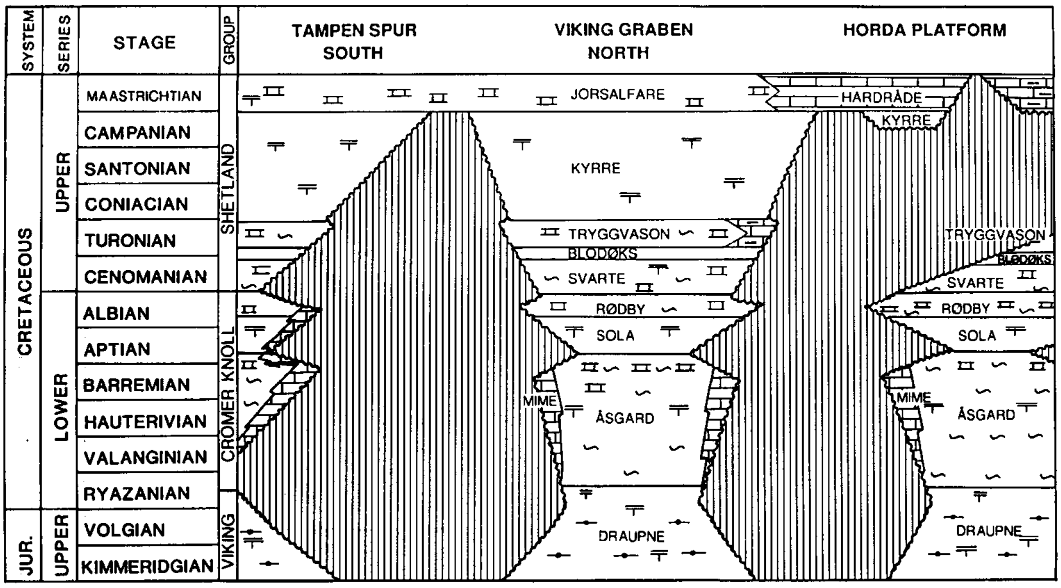

Figure 7d. Cretaceous lithostratigraphic nomenclature, Norwegian North Sea. Southern Tampen Spur - Northern Viking Graben - Horda Platform. From Isaksen and Tonstad (1989).

Sandstones play a subordinate role in the Cretaceous successions, but have been mapped in smaller areas over the larger part of the Norwegian North Sea. They have particularly been reported in the Ran sandstone units (7b,c) and the Agat Formation (Fig. 7e) (Isaksen and Tonstad 1989). Both of these were deposited in the Early Cretaceous. The Ran sandstone units have not been reported closer than 60-70 km from land, and is described as containing shales, limestone and glauconitic sandstones. They have also been considered to be poor reservoir rocks. These units therefore would appear to be unsuitable for CO_2 storage.

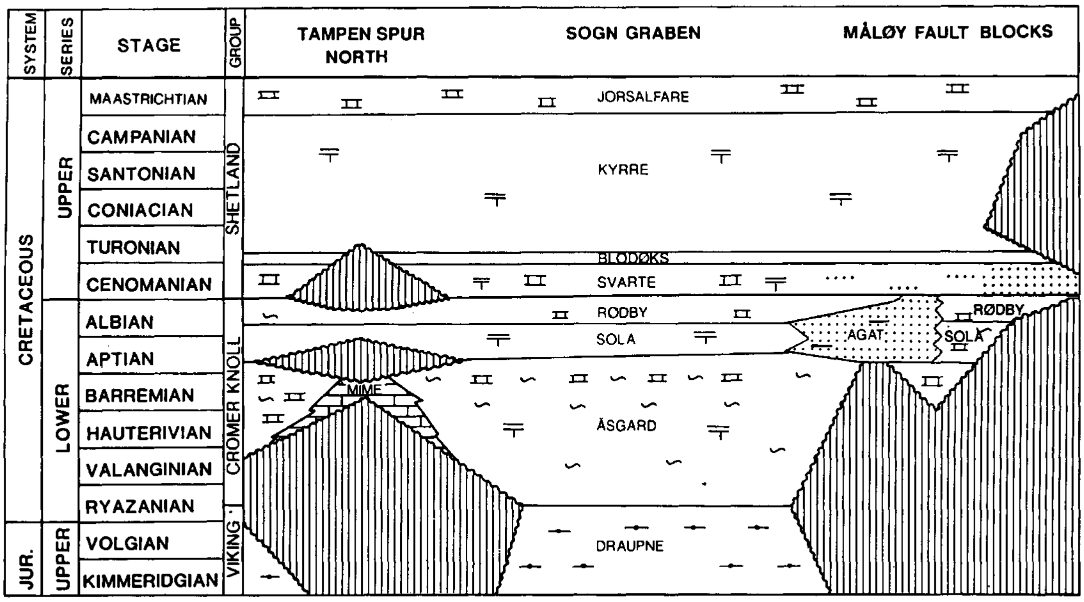

Figure 7e. Cretaceous lithostratigraphic nomenclature, Norwegian North Sea. Northern Tampen Spur - Sogn Graben - Måløy Fault Blocks. From Isaksen and Tonstad (1989).

The Agat Formation, mapped around the Agat Field some 45 km west of Stadt (Fig. 1), is considered to have been deposited in a belt along the coast of western Norway and to continue northwards of Stadt (Vergara et al. 2001). The sandstones pass into shales away from the coast. Towards the coast, they are bounded by large faults or by the Quaternary unconformity. The Agat Formation, and rocks of similar age, are located close to land in an area from Bergen extending northwards. These represent potential candidates for CO_2 storage.

The Danian-Upper Creaceous rocks of the Ekofisk, Tor and Hod Formations are nearest land (ca. 15 km) southwest of Jæren and in the Varnes Graben. These formations are dominated by limestones and chalks with low matrix porosities, though shales and calcareous shales also occur. The high incidence of fractures (joints) in the chalk reservoirs, provides a good potential for the injection of gas. Indeed this is something that has been successfully tested at the oil fields.

Off the coast of Mid-Norway, the Cretaceous rocks (Fig. 6) are dominated by shales and marls, although limestones and thin sandstones occur. Cretaceous sediments are found nearest land off the coast of Møre (ca. 15 km), in Vestfjorden, and outside Vesterålen/Lofoten. In the two latter areas, they can be mapped almost to the shore (Sigmond 1992, Gustavson and Blystad 1995, Henningsen and Tveten 1998, Zwaan et al. 1998). Sand-prone slope fans of the Agat, Lange and Lysing Formations occur along the Møre Basin Margin (Vergara et al. 2001), but the storage potential in these is unknown. Both in Vestfjorden and Andfjorden the major part of the Cretaceous succession is dominated by shales and siltstones, but it is not inconceivable that significant sandstone aprons may be present. On Andøya, sandstones have been mapped in the lower part of the Cretaceous unit. The presence of Cretaceous sandstones can only be documented by drilling. Along the northwestern boundary of Vestfjorden, towards the Lofoten Islands, the rocks are steeply inclined towards the surface, and the basin is partly bounded by a large fault system. Possible CO_2 storage in Cretaceous successions in Andfjorden and Vestfjorden depend on whether or not they are enclosed in impermeable shales or sealed by tight faults.

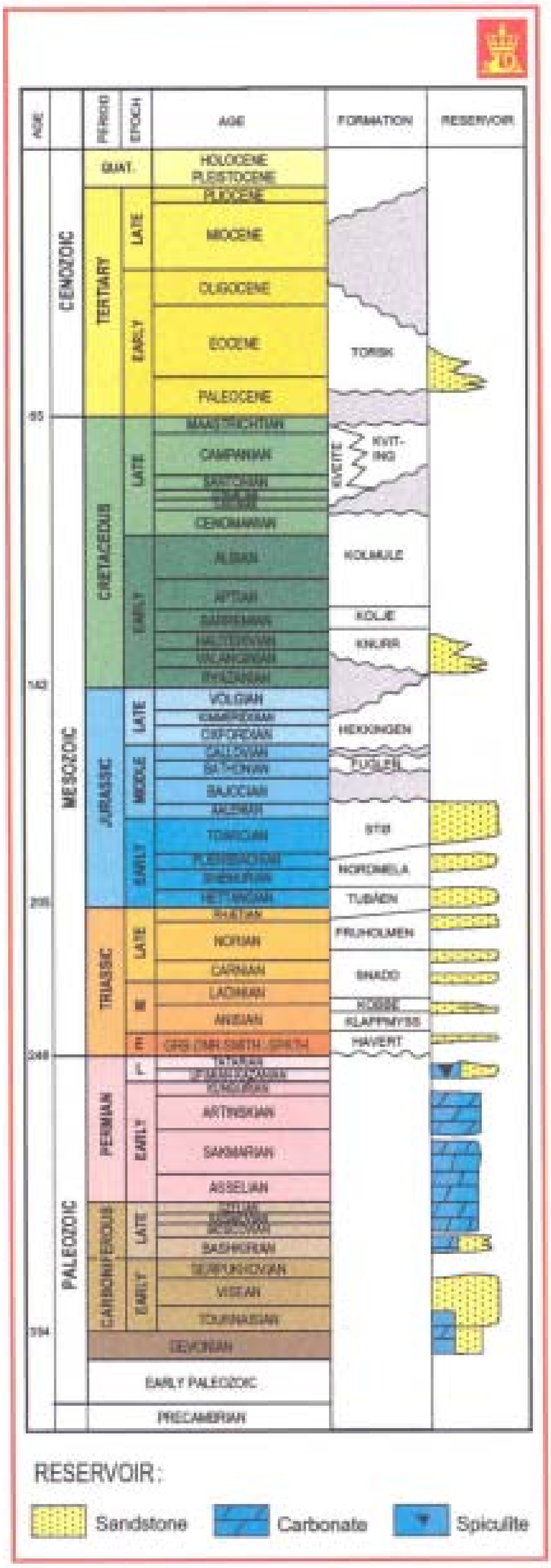

Figure 8. Stratigraphic column, Barents Sea. From NPD (1996).

Along the coast of West Finnmark, Cretaceous sediments occur more than 30 km offshore. Off East Finnmark, they occur 60-70 km from the coast (Grogan and Zwaan 1997). The lithologies are similar to those off Mid-Norway. Sandstones have been documented in the Kviting Formation (Campanian) and the Knorr Formation (Valanginian-Hauterivian) (Fig. 8), but it is not known how far the sandstones continue towards land.

The Cretaceous rocks along the coast locally contain sand intervals/sand-prone slope fans (Table 5). However, a great del of seismic mapping is required in conjunction with drilling, before the storage potential of these can be determined. The sediments generally dip away from land such that the sandstones would have to be sealed within shales or by faults to be considered as potential reservoirs for CO_2 storage.

5.4 CO_2 storage potential in nearshore Jurassic deposits

Sedimentary rocks of Jurassic age probably have the best potential for nearshore CO_2 storage (Table 5). Sandstones of this age are found in many areas relatively close to the coast. In addition to local occurrences in the fjords and coastal zone, the rocks can be followed almost continuously from Skagerrak and northwards.

In the Skagerrak area and off the coast of southern Norway (Fig. 1), Lower, Middle and Upper Jurassic sedimentary rocks are extensively developed (Figs. 9a-c). In Skagerrak, the Lower Jurassic unit occurs some 15-20 km from the coast (Fig. 1, Rise et al. 1999, Bøe et al. 2000), consists of conglomerates and sandstones (Smelror et al. 1989, confidential report), and probably belong to the Gassum Formation (Fig. 9a). Further offshore occurs the Middle Jurassic Bryne Formation, which is dominated by sandstones. Otherwise, the Jurassic units in the Skagerrak area are dominated by finer grained sediments. South of the coastal strip between Kristiansand and Lindesnes the geological relationships are complicated, and more seismic data must be collected and drilling carried out, before it is possible to assess the CO_2 storage potential. It is possible that this area has sandstone units with good storage potential.

In the Norwegian-Danish Basin (Figs. 1 and 4), considerable developments of sandstones occur in the Gassum Formation (Lower Jurassic) and in the Bryne and Sandnes Formations (Middle Jurassic). At present, it is not known how far these formations extend shorewards, but the Sandnes Formation has been mapped in the Egersund Sub-basin, some 50 km offshore.

In the Varnes Graben, west of Lista (Fig. 1), Jurassic sedimentary rocks are preserved almost to the shoreline (Bøe et al. 2000). The rocks closest to the coast were previously considered to be Late Triassic and Early Jurassic (Holtedahl 1988). New data suggest that they are Early Jurassic, and that some distance away from the coast they are covered by sediments of

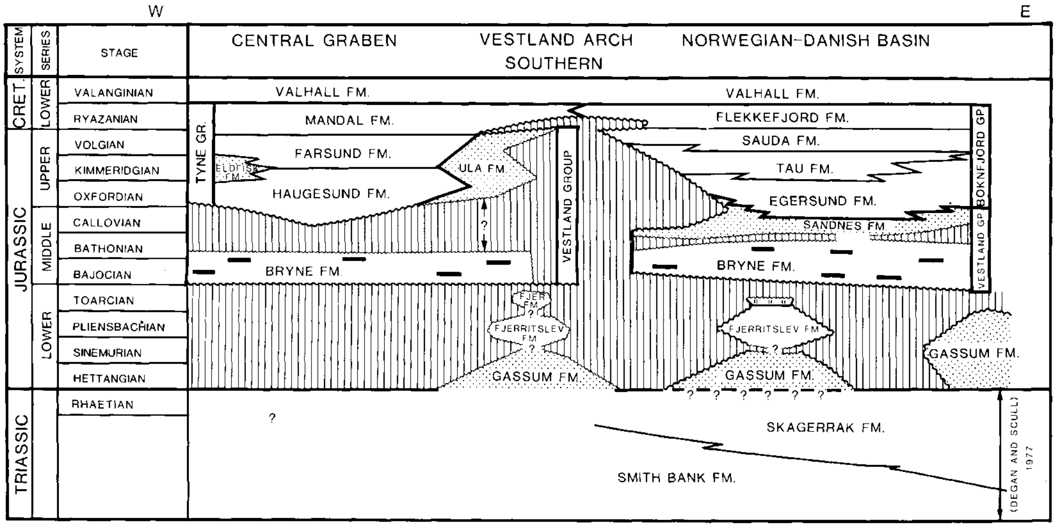

Figure 9a. Jurassic-Triassic lithostratigraphic nomenclature, Norwegian North Sea. Central North Sea - Norwegian Danish Basin. From Vollset and Doré (1984).

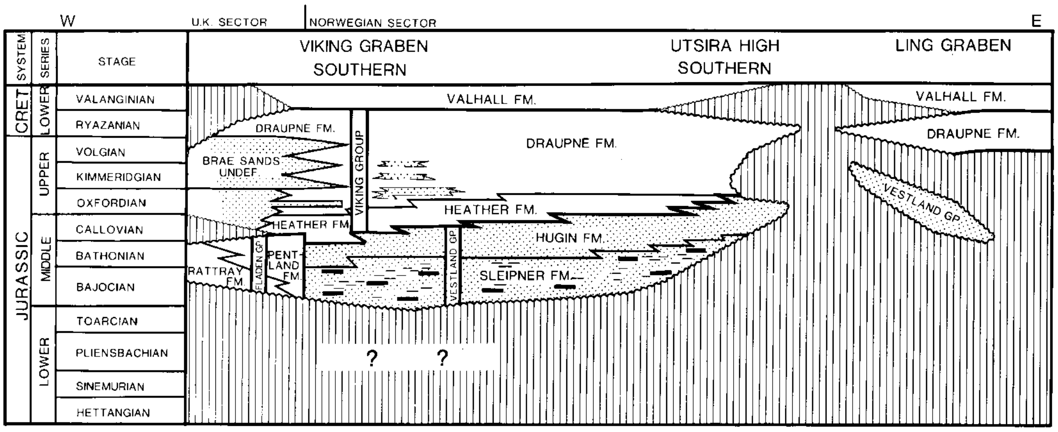

Figure 9b. Jurassic-Triassic lithostratigraphic nomenclature, Norwegian North Sea. Southern Viking Graben - Southern Utsira High - Ling Graben. From Vollset and Doré (1984).

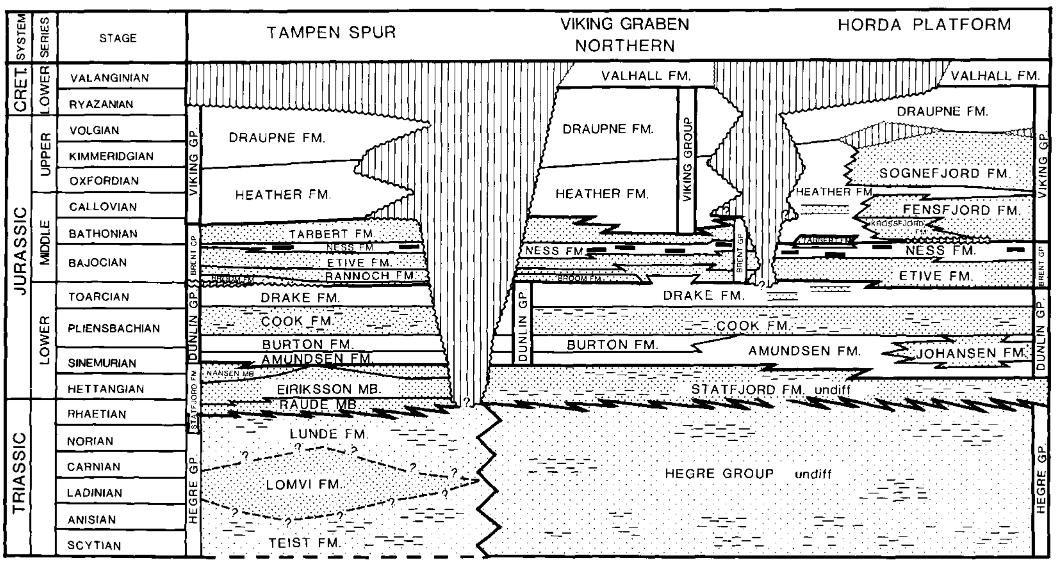

Figure 9c. Jurassic-Triassic lithostratigraphic nomenclature, Norwegian North Sea. Northern North Sea north of approximately 60°N. From Vollset and Doré (1984).

Middle-Late Jurassic age (Bøe et al. 2000). Rock fragments collected from the seabed comprise Lower Jurassic sandstones, siltstones and shales (Holtedahl 1988), and probably stem from the Gassum Formation. It is probable that the sandstones in the Jurassic succession of the Varnes graben represent good resvoir rocks for storage of CO_2. West of Lindesnes, the base of the sedimentary succession lies some 1200 m below sea level. It is essential that the sandstones have a tight cap rock so that gas cannot leak up to the surface. The sediments dip away from land, and stored CO_2 would potentially migrate up towards land. The best possibilities for CO_2 storage appear to be in the central parts of the Varnes Graben, i.e. some 15 km from the coast.

Further north along the west coast of Norway, Jurassic rocks occur at a distance of ca. 20 km from the outermost skerries (Sigmond 1992, Jorde et al. 1995, Fossen et al. 1997, Fossen 1998). At Utsira (Fig. 1) however, Upper Jurassic rocks occur only 2-3 km from the island (Rokoengen & Sørensen 1990, Ragnhildstveit al. 1998). The Horda and Øygarden Fault Zones (Fig. 4) are major structures that trend in north ca. 40-50 km from the coast south of Bergen, and ca. 20-30 km offshore between Bergen and Nordfjord (Vollset & Doré 1984, Brekke et al. 1992). West of these structures, thick units of Jurassic rocks are present (Fig. 9c). The deposits include sandstones, which are most likely suitable for the storage of CO_2. The Jurassic rocks are blanketed by Cretaceous shales, which may function as good cap rocks. Rocks of this area are described in detail in a later chapter.

East of the fault zones which bound the Fennoscandian Shield in SW Norway (Øygarden and Horda Fault Zones), and west of Jæren, the Jurassic successions are mainly of Middle and Late Jurassic age. The Lower Jurassic sandstones of the Statfjord, Johansen and Cook Formations are essentially bounded to the east by the fault zones (Vollset & Doré 1984). The detailed nature of the Middle and Late Jurassic sediments is not known, but it can be assumed that both sandstones and shales are common. In the Middle and Late Jurassic, extensive deposition of sand occurred on the Horda Platform (Brent and Viking Groups). The sandstones of the Middle-Upper Jurassic Viking Group are predominantly derived from the east. It is uncertain which sandstone formations one can expect to find east of the fault zones, but the Etive Formation and the lateral equivalents of the sandstone formations in the Troll Field (Krossfjord, Fensfjord and Sognefjord Formations) are all possible candidates.

On the shelf west of Sotra, a small fault-bounded basin containing Middle Jurassic sediments has been mapped, ca. 10 km from the coast (Fossen et al. 1997, Ragnhildstveit & Helliksen 1997, Fossen 1998). If this basin contains sandstones blanketed by shales, it could represent a potential storage site for CO_2. A detailed study would have to be made, including collection of more seismic data and core drilling to assess the potential. The sediments in the basin are deep enough for CO_2 to be stored in a liquid phase.

Along the coast between Nordfjord and the outlet of Romsdalsfjorden, Jurassic rocks are probably too deep for CO_2 storage (Tveten et al. 1998a, 1998b). Further north, between Romsdalsfjorden and Vestfjorden, the conditions are probably more suitable, with Jurassic sedimentary basins appearing to be the most obvious potential storage sites for CO_2. In the majority of these, however, the deposits are not particularly thick. In Edøyfjorden (Fig. 3), south of Smøla, for example, the depth from sea-level to the base of the sedimentary succession is <800 m (Bøe and Bjerkli 1989). This area is thus unsuitable for CO_2 storage.

In Beitstadfjorden, in the innermost part of Trondheimsfjorden (Fig. 3), an area ca. 5x15 km of layered sedimentary rocks is preserved below the Quaternary of the fjord bottom. Fragments of coal, sideritic ironstone and calcareous sandstone were scraped up by the ice and deposited on land during the last glaciation. These sediments are Lower-Middle Jurassic, and the Middle Jurassic can in all probability be correlated with sediments of the Fangst Group (Fig. 6) on Haltenbanken (Bøe and Bjerkli 1989). Recent seismic data, collected by NPD, shows that the succession is up to 1000 m thick at its thickest along the northwest side of the fjord, at a water depth of ca. 200 m (Fig. 10) (Sommaruga and Bøe, submitted). If this succession contains sandstones of sufficient thickness in its basal part, they could represent a potential storage resevoir for CO_2. It must be pointed out, however, that only a restricted volume of these rocks lie at depths >800 m below sea-level. They have relatively steep dips and a number of small faults, which would allow movement of the gas up-dip. There is no tight cap rock on top of the dipping succession. In summary, Beitstadfjorden is probably not suited for CO_2 disposal.

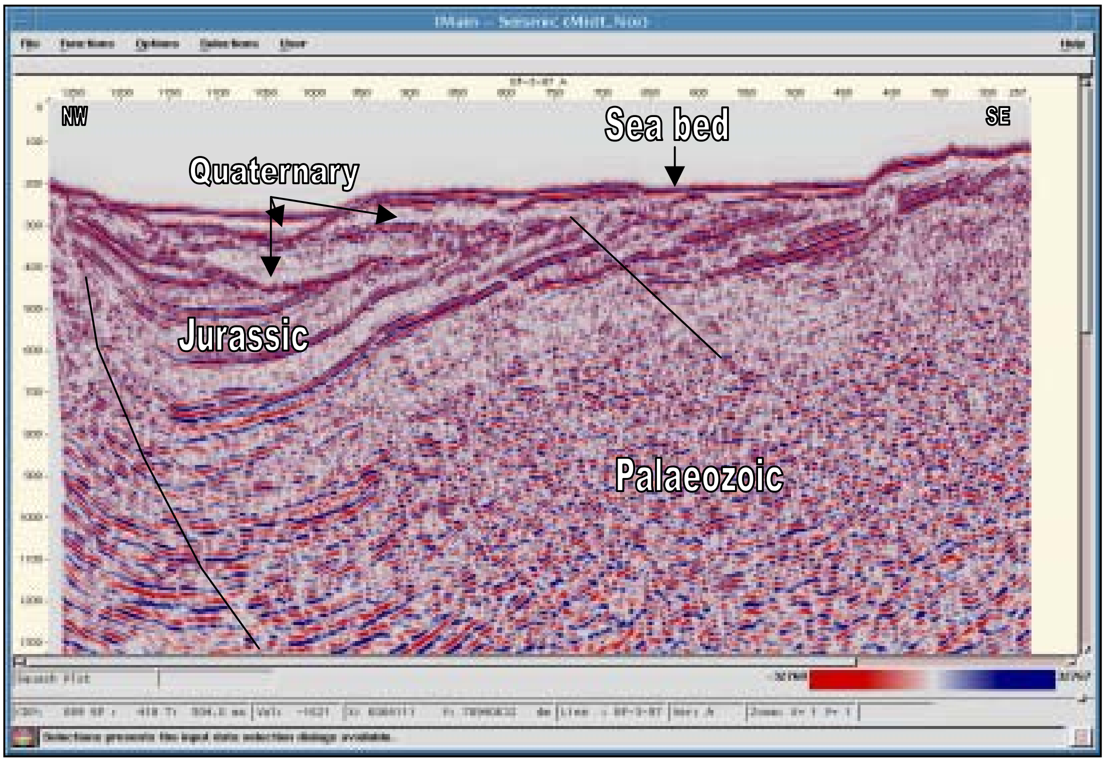

Figure 10. Seismic section illustrating downfaulted Jurassic rocks in Beitstadfjorden.

In Frohavet, on the Trøndelag coast (Fig. 3), lies a downfaulted sedimentary rock basin (half-graben) measuring ca. 15x60 km, which resembles the basin in Beitstadfjorden (Bøe 1991). The age of the sedimentary rocks has been determined from fossils in blocks scraped up by the ice, and deposited on a number of islands, during the last ice age. The rocks include calcareous sandstones, conglomerates and sedimentary breccias, and have been dated to Middle Jurassic (Bøe 1991). Recent seismic data from NPD shows that the Mesozoic package is >1000 m in its thickest part (Fig. 11) (Sommaruga and Bøe, submitted). In contrast to Beitstadfjorden, the sediments under the Frohavet cover a much larger area, and the volume of sediments deeper than 800 m below sea level is larger. However, the same uncertainties exist concerning the sedimentary succession as for Beitstadfjorden. It is unknown whether there are substantial developments of sandstones with the correct physical parameters, extent, thickness etc., which would be required for the storage of CO_2. The sedimentary layers dip in a manner that would allow gas to migrate towards the seabed, and it is unknown if there are closed sandstone aquifers, which would provide optimal storage. There is no tight cap rock on top of the dipping rock successsion.

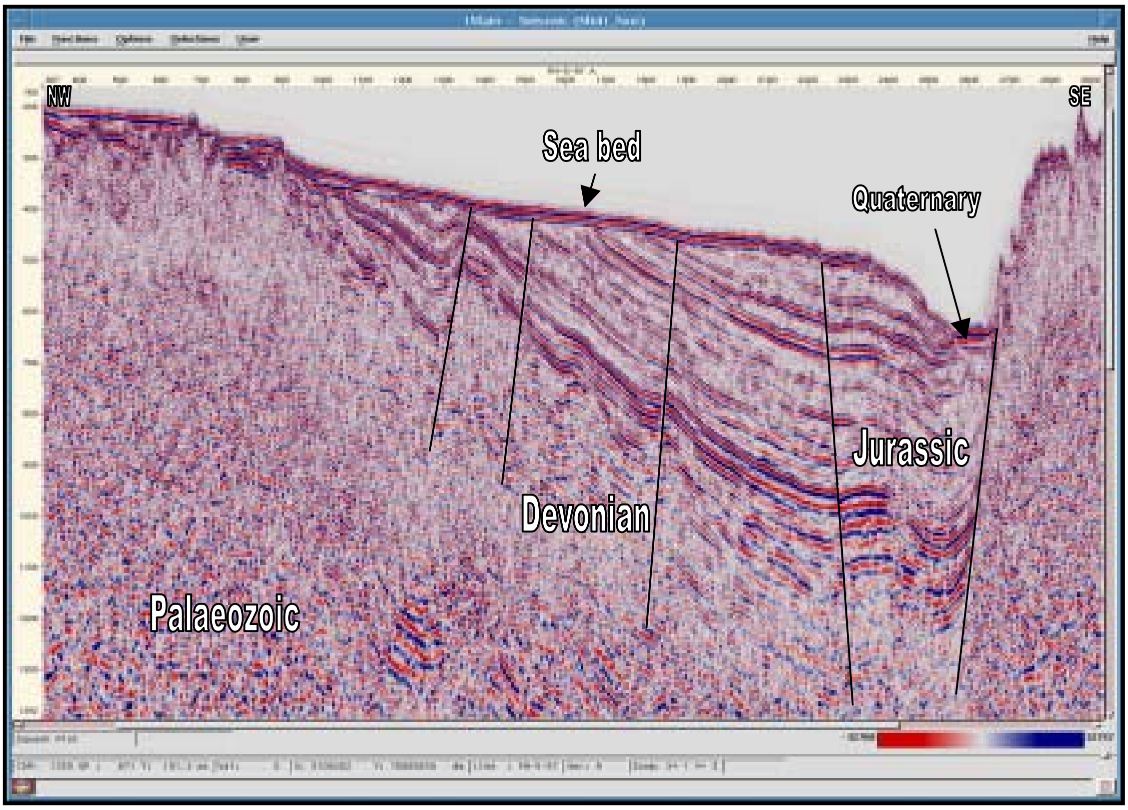

Figure 11. Seismic section illustrating downfaulted Jurassic rocks in Frohavet.

Apart from the coastal basins described above, the inner boundary of the Jurassic rocks is located 10-50 km from the coast. The nearest they come to land is soutwest of Smøla (Fig. 3), where they extend into the outermost shoals (Smelror et al. 1994, Bøe and Skilbrei 1998), west of Vikna (Gustavson and Bugge 1995, Solli et al. 1997), and at Træna (Gustavson & Gjelle 1991, Bugge et al. 2002). In the Griptarane area, southwest of Smøla, the base of the Jurassic is probably too shallow for the storage of CO_2.

Along the coast of Trøndelag and Nordland, the landward boundary of the eastward onlapping sedimentary rocks (Permian, Triassic and Jurassic) is generally poorly mapped, though there are certain exceptions (Gustavson and Blystad 1995, Gustavson and Bugge 1995, IKU 1995, Thorsnes 1995, Solli et al. 1997, Bugge et al. 2002).

The rocks which appear to have the greatest potential for storage of CO_2 are conglomerates and sandstones of the Lower Jurassic Åre and Tilje Formations, and the Middle Jurassic Ile and Garn Formations (Fig. 6, Dalland et al. 1988). Lateral equivalents of these formations subcrop and have been described in cores from shallow drilling along the coast (Bugge et al. 1984). Generally, the Jurassic rocks in the coastal zone dip away from land. This implies that CO_2 would migrate upwards towards the surface. It would thus be necessary to locate sandstones that are either encapsulated in shales, or sealed against tight faults.

In Andfjorden and Vestfjorden, respectively north and south of the Lofoten islands (Fig. 1), there are considerable thicknesses of sedimentary rocks, which could represent potential CO_2 storage volumes. The Jurassic succession at the base is several hundred metres thick and is overlain by Cretaceous and Tertiary (northern part of Andfjorden and southwestern part of Vestfjorden) deposits, which are several kilometres thick (Sigmond 1992, Gustavson & Blystad 1995, Henningsen & Tveten 1998, Zwaan et al. 1998). Along the western side of Andfjorden, Middle to Upper Jurassic rocks occur with a thickness of ca. 200 m on land on Andøya, beneath a ca. 600 m Cretaceous succession. The depth to the Jurassic sediments is less than the critical depth required for CO_2 storage. Detailed studies have been made of the Mesozoic succession on Andøya (Dalland 1979). The sediments comprise sandstones, siltstones, and shales. If similar rocks occur under Andfjorden and Vestfjorden, they could represent potential reservoirs for CO_2 storage. The most promising rocks would appear to be the Middle to Late Jurassic sandstones (Ramså and Dragnes Formations), which have porosities up to 30% on Andøya. In the central parts of the basins, the Jurassic rocks are too deep for CO_2 storage.

Jurassic rocks occur relatively close to the coast west of Lofoten and Troms, where the Nordmela and Stø Formations (Lower-Middle Jurassic) are either sandy and/or dominated by sandstones. The near-coastal equivalents of these formations may have a potential for CO_2 storage. The most promising area is from the northernmost point of Senja and northwards to ca. 71°N (Grogan and Zwaan 1997, Zwaan et al. 1998).

5.5 CO_2 storage potential in nearshore deposits older than the Jurassic

Fault basins with thick clastic successions of Triassic age occur along the coast of Western Norway, Trøndelag and Nordland. Similar fault basins with sediments deposited in the Permian and Carboniferous occur in the Skagerrak and outside Western Norway, Trøndelag and Nordland. In Karmsundet and south of Karmøy (Fig. 1), stratified sedimentary rocks (Bøe et al. 1992) may be either Jurassic-Triasssic or Permian-Carboniferous. The thickness of the deposits is only ca. 600 m, and with a water depth of less than 300 m this is not deep enough for the storage of CO_2. The layered succession also has a steep dip allowing gas migration up to the sea bed. Generally, we do not know the storage potential of these basins. In several cases they are very deep, and are thus not candidates for CO_2 storage. One should, however, expect significant volumes of sandstone in the succession, and porosities and permeabilities might be acceptable (e.g. Bugge et al. 2002).

Nearshore storage of CO_2 outside Finnmark would probably have to be made in Triassic rocks, which occur ca. 30 km north of the outhermost islands. Landward of the Triassic rocks are thick Permian and Carboniferous successions with carbonates and sandstones. On the Loppa High, reservoir properties in Permian and Carboniferous carbonates and Carboniferous sandstones are good (NPD 1996). A prospecting drill hole has shown that these rocks have a relatively high porosity.

6. CO2 STORAGE POTENTIAL OFFSHORE NORWAY

A large number of candidate aquifers for CO_2 storage have been identified in the Norwegian sector of the North Sea, the Norwegian Sea and in the Southern Barents Sea. The areal distribution of the various aquifers has been calculated from a number of public sources. Storage capacities have been calcualted for the depth interval 0.8-4 km below sea level. Descriptions of the aquifers and their cap rocks, summarized in the following chapters (starting with the youngest aquifers), are to a large degree taken from Deegan and Scull (1977), Vollset and Doré (1984), Dalland et al. (1988), and Isaksen and Tonstad (1989).

6.1 Norwegian North Sea

6.1.1 Utsira Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The late Middle Miocene to Early Pliocene (Eidvin et al. 2002) Utsira Formation of the Nordland Group is present in the Viking Graben area from ca. 58ºN to 62ºN (Fig. 12, Gregersen and Michelsen 1997, Eidvin et al. 2002). The formation is laterally continuous within the Viking Graben, and covers an area up to 470 km in N-S direction and up to ca. 100 km in E-W direction (Gregersen and Michelsen 1997, Eidvin et al. 2002). Two sand depocentres have been mapped, one in the north and one in the south. These are possibly separated by shale (P. Zweigel, pers. comm. 2001). The formation becomes thinner towards the east and eventually thins out between the Oseberg and Troll Fields. At the nearest, the formation lies some 60-70 km from the Norwegian coast.

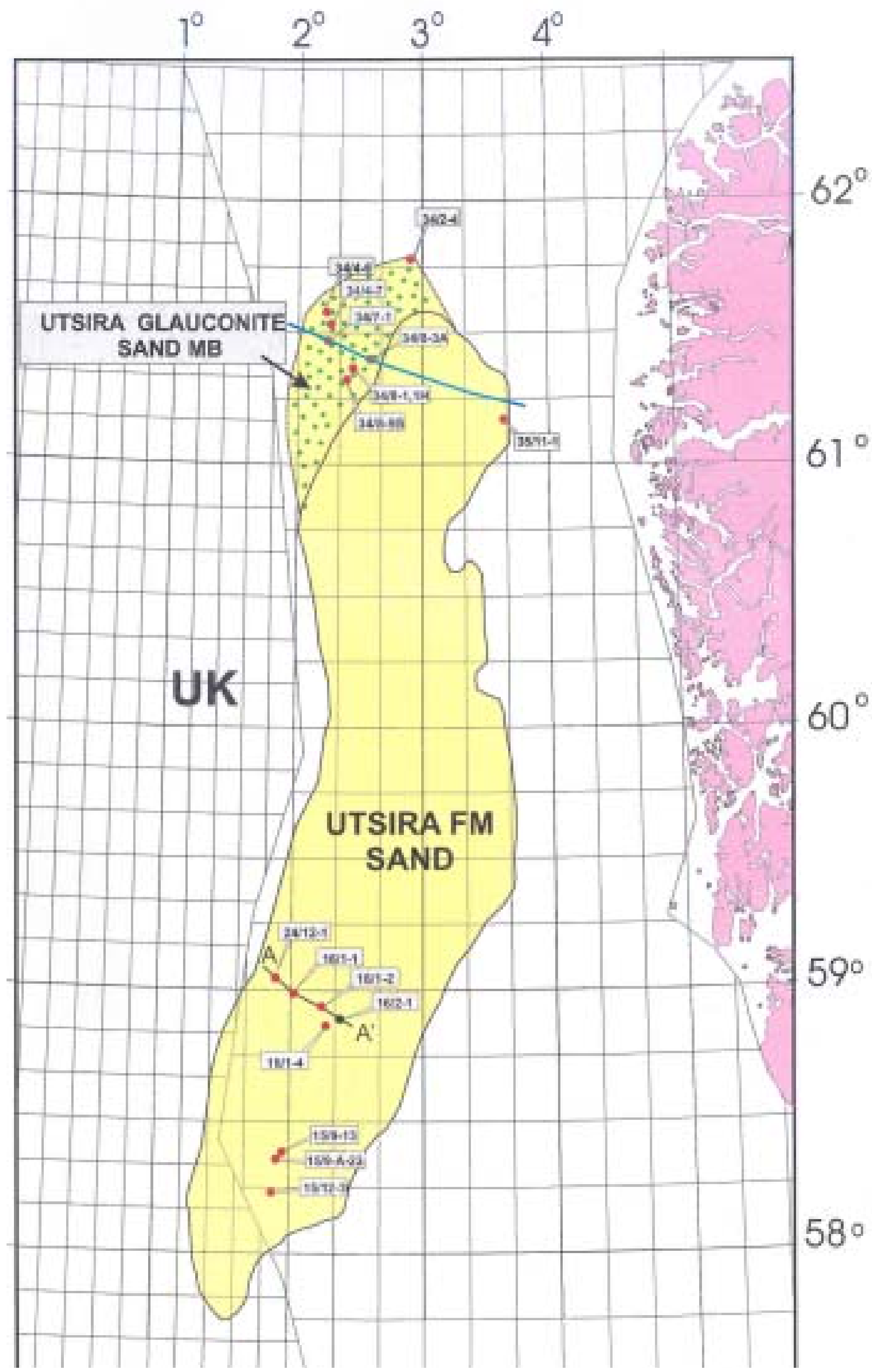

Figure 12. Map of the Utsira Formation. From Eidvin et al. (2002).

The formation is presently used for storage of CO_2 from the Sleipner Field (SACS-project), and it is therefore being extensively studied (e.g. Zweigel and Lindeberg 2000). The Utsira Formation has been interpreted in different ways. Gregersen and Michelsen (1997) interpreted the lower part of the formation to consist of stacked lowstand fan deposits, while the upper part consiststed of more clayey-silty intervals, indicative of an increased relative sea level. Rundberg (1989) and Galloway (2002) have interpreted the Utsira Formation as comprising predominantly shallow marine deposits. The sandstones are clear to white, often light greenish and normally very fine to fine-grained (Isaksen and Tonstad 1989). Occasionally lignite and rock fragments are found. The sandstones are separated by soft, plastic, light greenish claystones and minor siltstones. Glauconite and fossil fragments are common throughout. The source for the sediments of the Utsira Formation was probably located to the west.

Depth

The depth to the top of the Utsira Formation has been mapped in detail in the SACS-project, and varies from ca. 500 m to 1500 m. In the Central Viking Graben area the depth is 500-750 m (Eidvin et al. 2002).

Thickness

According to Isaksen and Tonstad (1989) the thickness of the Utsira Formation is 419.5 m in the type well (16/1-1) and 210 m in the reference well (15/9-13). The maximum thickness, according to Gregersen and Michelsen (1997), is 550 m. Due to errors in the original definition (in the south, the Utsira Formation was locally defined to include the Skade Formation, while in the north, many workers include Upper Pliocene deposits (Eidvin et al. 2001)) Eidvin et al. (2002) have suggested new candidate type wells, which significantly influences the interpreted thickness of the formation. The maximum thickness of the Utsira Formation is probably not much more than 250 m.

Percent shale

From well logs in Eidvin et al. (2002) it is estimated that 70% of the Utsira Formation is made of sand/sandstone.

Top seal

The Utsira Formation is overlain by Pliocene marine claystones of the upper part of the Nordland Group (Fig. 5a). The claystones are grey, sometimes greenish-grey and grey-brown, soft, sometimes silty and micaceous. The uppermost part of the Nordland Group consists of Pleistocene unconsolidated clays and sands, with glacial deposits uppermost (Isaksen and Tonstad 1989). The thickness of the seal is 500-1500 m. The seal on top of the Utsira Formation is assumed to be continuous across the area. In the east, the rocks are inclined such that stored CO_2 would migrate eastwards and up towards the Pleistocene boundary.

Hydrocarbon production

There is no hydrocarbon production from the Utsira Formation, however, it is a source of water for injection into oil fields to enhance oil recovery. Large-scale CO_2 injection would have to take this use of the formation water into account. The petroleum industry also injects waste, e.g. produced formation water, into the Utsira Formation.

CO_2 storage quality and capacity

In the ongoing SACS-project, where 1 million tonnes of CO_2 is stored in the Utsira Formation annually, it has been shown that the Utsira Formation has good storage quality with respect to porosity, permeability, mineralogy, bedding, depth, pressure and temperature (e.g. Zweigel and Lindeberg 2000). It is a very large aquifer with a thick and extensive claystone top seal. The aquifer is, however, unconfined along its margins, and the time before migrating CO_2 might reach the margins of the aquifer is unknown. The Utsira Formation is regarded as one of the most promising aquifers for CO_2 storage in Europe. It has both such a considerable thickness and extent that it alone could store the CO_2 emissions from all of the north European power stations and other large industrial plants for several hundred years (Torp & Christensen 1998).

It is here estimated that the Utsira Formation, below 800 m depth, has a pore volume of 918 km^3, a storage capacity in traps of 847 Mt (megatonnes) CO_2, and that the storage capacity of the entire aquifer is 42 356 Mt CO_2 (Table 6).

6.1.2 Skade Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Early Miocene (Eidvin et al. 2002) Skade Formation (Fig. 5a) of the Hordaland Group has been identified in the Viking Graben area between approximately 58º N and 60º30' N (Fig. 4, Isaksen and Tonstad 1989). The formation consists of marine sandstones with thin claystone interbeds. The sandstones are clear to light grey, usually fine to medium, occasionally coarse-grained, and are moderately to well sorted. Traces of fossils, shell fragments, mica and abundant glauconite occur. In some wells the sandstones are interbedded with silty claystones. The formation often interfingers with the unnamed claystones of the Hordaland Group. It is thought to have been deposited in an open marine environment as a response to a fall in sea level.

Depth

In the type well (24/12-1) the Skade Formation occurs at 1007-851 m depth, while in the reference well (15/9-13) it occurs at 1224-1143 m depth (Isaksen and Tonstad 1989).

Thickness

The thickness of the Skade Formation is 156 m in the type well and 81 m in the reference well (Isaksen and Tonstad 1989). It reaches nearly 300 m in Norwegian block 16/1 (Eidvin et al.

Table 6. Theoretical CO_2 storage potential in Nort Sea aquifers (0.8-4 km depth) in the Norwegian offshore area south of 62ºN (reservoir CO_2 densities partly after Lindeberg 1996)

Aquifer	Age	Range (km^2)	Average Thickness m	Net:Gross	Porosity %	Pore Volume (km^3)	Reservoir open (O) or closed (C)	Reservoir Density of CO_2 (kg/m^3)	Storage Capacity in Traps (Mt CO_2)	Storage Capacity of Entire Aquifer (Mt CO_2)
Utsira	Miocene-Pliocene	25 000	150	0.7	35	918	O	769	847	42 356
Skade	Miocene	13 000	120	0.7	32	349	O	719	301	15 055
Vade	Oligocene	1000	70	0.8	28	15	C	676	12	202
Grid	Eocene-Oligocene	10 000	140	0.6	28	235	O	623	175	8 784
Frigg	Eocene	2 000	90	0.8	29	42	O	695	35	1 751
Fiskebank	Paleocene	10 000	100	0.5	20	100	O	700	84	4 200
Hermod	Paleocene	1 600	100	0.9	20	28	O	658	22	1 105
Forties	Paleocene	500	70	0.7	25	6	O	716	5	258
Heimdal	Paleocene	13 000	180	0.6	28	393	O	652	307	15 374
Ty	Paleocene	6 000	180	0.8	20	172	O	664	137	6 852
Ekofisk*	Paleocene	30 000	100	0.2	20	120	C	737	106	1 769
Tor*	Late Cretaceous	40 000	300	0.2	20	480	C	712	295	6 835
Hod*	Late Cretaceous	40 000	300	0.1	20	240	C	700	202	3 360
Agat	Early Cretaceous	600	300	0.5	20	18	C	694	14	249
Sognefjord	Late Jurassic	8 000	100	0.9	25	180	C	700	151	2 520
Fensfjord	Late Jurassic	8 000	100	0.9	25	180	C	700	151	2 520
Krossfjord	Late Jurassic	4 000	100	0.9	25	90	C	700	75	1 260
Ula	Late Jurasssic	2 500	80	0.8	20	32	C	700	26	448
Hugin	Middle-Late Jur.	12 000	100	0.8	20	192	C	700	161	2 688
Sleipner	Middle Jurassic	12 000	40	0.5	20	48	C	700	40	672
Sandnes	Middle Jurassic	20 000	50	0.7	20	140	C	700	117	1 960
Bryne	Middle Jurassic	35 000	60	0.5	20	210	C	700	176	2 940[b]
Brent	Middle Jurassic	18 000	200	0.7	25	630	C	742	560	9 349
Cook	Early Jurassic	14 000	60	0.5	25	105	C	749	94	1 572
Johansen	Early Jurassic	5 000	100	0.8	20	80	C	700	67	1 120
Statfjord	Early Jurassic	25 000	200	0.5	22	550	C	761	502	8 371

Table 6 (continues)

Gassum	Early Jurassic	43 000	70	0.7	15	316	C	700	265	4 424 [b]
Skagerak[a]	Triassic	63 000	1000	0.7	15	6 615	-	-	-	-
Hegre[a]	Triassic	14 000	1500	0.7	15	2 205	-	-	-	
Total						**14 689**			**4927**	**147 994**

The calculation of storage capacity in traps (excluding hydrocarbon fields) is based on the assumption that 4% of the pore volume can be filled with CO_2, and that 3% of the aquifer volume is in a trap. The estimate of storage capacity of entire aquifers is based on a storage efficiency of 6% for open aquifers and 2% for closed aquifers (see Holloway 1996).

[a] Skagerrak and Hegre are not included in the total because of the permeability criterion.
[b] The Bryne and Gassum are open (subcrop) along the coast, and the storage capacities (entire aquifers) may be regarded as minimum values.
* Chalk/carbonate aquifers: storage potential only in the interval 0.8-3 km depth.

2002), but is usually around 50-100 m (Isaksen and Tonstad 1989). The formation shows a general eastward thinning.

Percent shale

From well logs in Isaksen and Tonstad (1989) and Eidvin et al. (2002) it is estimated that the Skade Formation consists of approximately 70% sandstone and 30% claystone.

Top seal

The Skade Formation is overlain by continuous claystones (ca. 100 m thick in the type well) of the Hordaland Group. In the Utsira High area, it is locally overlain by sand/sandstone of the Utsira Formation (Fig. 5a). In the north, the formation has a good top seal. In the Utsira High area, the Utsira and Skade formations may be regarded as one aquifer. The seal of the Skade Formation thus partly depends on that of the Utsira Formation (see previous section).

Hydrocarbon production

There is no hydrocarbon production from the Skade Formation.

CO_2 storage quality and capacity

The Skade Formation has good storage quality with respect to porosity, permeability, mineralogy, depth, and pressure. Numerous claystone interbeds separate the formation into several individual reservoir intervals, and may represent barriers inhibiting vertical CO_2 migration.

It is estimated that the Skade Formation, below 800 m depth, has a pore volume of 349 km^3, a storage capacity in traps of 301 Mt CO_2, and that the storage capacity of the entire aquifer is 15 055 Mt CO_2 (Table 6).

6.1.3 Vade Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Late Oligocene Vade Formation (Fig. 5a) of the Hordaland Group has only been penetrated in some wells in blocks 2/2 anf 2/3 (Fig. 4, Isaksen and Tonstad 1989). The formation consists of thinly interbedded, light green to grey, very fine-grained sandstones and siltstones. These are glauconitic, slighly micaceous, well sorted and fossiliferous. The formation interfingers with claystones of the Hordaland Group. The sandstones were deposited in a shallow marine environment. Their deposition can be seen as a response to an eustatic sea level fall or a tectonic uplift of the area. Regional considerations indicate a source area in the east or northeast.

Depth

In the type well (2/2-1) the Vade Formation occurs at 2172-2100 m depth, while in the reference well (2/3-2) it occurs at 1855-1795 m depth (Isaksen and Tonstad 1989).

Thickness

The thickness of the Vade Formation is 72 m in the type well and 60 m in the reference well (Isaksen and Tonstad 1989).

Percent shale

From well logs published by Isaksen and Tonstad (1989) it is estimated that the Vade Formation consists of approximately 80% sandstone and siltstone and 20% claystone.

Top seal

The Vade Formation is overlain by and embedded within claystones of the Hordaland Group (Fig. 5a). The thickness of the top seal is several hundred metres.

Hydrocarbon production

There is no hydrocarbon production from the Vade Formation.

CO_2 storage quality and capacity

The Vade Formation probably has good storage quality with respect to porosity, permeability and depth. It is totally embedded within shales of the Hordaland Group, and is thus well sealed. This may, however, cause rapid increase in pressure during CO_2 injection, especially because it is a relatively small aquifer.

It is here estimated that the Vade Formation has a pore volume of 15 km^3. The storage capacity in traps is 12 Mt CO_2 (may be higher, as the formation may be regarded as one stratigraphic trap), and the storage capacity of the entire aquifer is 202 Mt CO_2 (Table 6).

6.1.4 Grid Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Middle to Late Eocene (Early Oligocene in wells 25/6-1 and 24/12-2) Grid Formation (Fig. 5a) of the Hordaland Group is recognized in the Viking Graben area between approximately 58º30'N and 60º30'N (Fig. 4, Isaksen and Tonstad 1989, Bowman 1998). It thins eastwards and is not penetrated by wells on the Utsira High. It has been identified in some wells in the Oseberg area. In the Viking Graben north of 61ºN, several sandstone bodies occur in the Hordaland Group at the same level, but it is uncertain if they belong to the Grid Formation. It is possible that the Grid Formation can be divided into two units, a lower confined to the area south of 59ºN and probably of Middle Eocene age, and an upper, more widely distributed unit (Isaksen and Tonstad 1989). In some areas the lower unit is separated from the upper one by a sequence of claystones which is informally referred to as the Belton Member in the UK sector. The Grid Formation is widespread in the UK sector (Bowman 1998).

The formation consists of sandstones with interbeds of claystone and siltstone. Thicker claystone units of the Hordaland Group frequently interfinger with the sandstones of the Grid Formation. The sandstones often have a massive, "blocky" apparance. Individual sandstone beds show little or no evidence of fining-upwards or coarsening-upwards. The sandstones are very fine to fine, and occasionally medium to coarse. Sorting is generally moderate to good. Traces of mica, pyrite, glauconite and fossil fragments are common. A higher argillaceous content is found in distal areas. The formation was deposited in an open marine environment during a regressive period. Sands were derived from the East Shetland Platform and deposited in submarine fan systems, reaching eastwards into the present Norwegian sector (Bowman 1998).

Depth

In the type well (15/3-3) the Grid Formation occurs at 1840-1470 m depth, while in the reference wells it occurs at 1660-1502 m (24/12-1) and 1397-1282 m (24/12-2) depths (Isaksen and Tonstad 1989).

Permeability

The Grid Formation consists of relatively clean sandstones with high permeabilitiy. This is explained by extensive shelf reworking on the East Shetland Platform prior to resedimentation by mass movements into the basin (Bowman 1998).

Thickness

The thickness of the Grid Formation is 370 m in the well type section and 158 m and 115 m in the well reference sections (Isaksen and Tonstad 1989). There is a considerable increase in thickness from less than 200 m north of 59ºN, to nearly 400 m south of 59ºN, where there is a depocentre in Norwegian block 15/3. This is due to sand deposition having started earlier in the south than in the north. The formation thins eastwards, and is not penetrated by wells on the Utsira High.

Percent shale

From a well log published by Isaksen and Tonstad (1989) it is estimated that the Grid Formation consists of approximately 60% sandstone and 40% claystone and siltstone.

Top seal

The Grid Formation is overlain by and embedded within claystones of the Hordaland Group (Fig. 5a, Isaksen and Tonstad 1989). The thickness of the top seal is several hundred metres.

Hydrocarbon production

In the British sector, hydrocarbons are produced from the formation at the Alba and Chestnut Fields (UKCS Quadrant 16) (Bowman 1998, Brennand et al. 1998).

CO_2 storage quality and capacity

The Grid Formation has good storage quality with respect to porosity, permeability, mineralogy and depth. Numerous claystone interbeds and thicker claystone units divide the formation into separate stratigraphic traps, and may represent barriers inhibiting vertical CO_2 migration. The Grid Formation is embedded within shales of the Hordaland Group, and individual sandstone intervals may thus be well sealed. The Grid Formation continues into the British sector, where it is more widespread. Also there it is overlain by shales of the Hordaland Group. Injected CO_2 would probably migrate towards the west.

It is estimated that the Grid Formation, in the Norwegian sector, has a pore volume of 235 km^3, a storage capacity in traps of 175 Mt CO_2, and that the storage capacity of the entire aquifer is 8784 Mt CO_2 (Table 6).

6.1.5 Frigg Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Early Eocene Frigg Formation (Fig. 5a) of the Hordaland Group is found in the southwestern part of quadrant 30, the northwestern part of quadrant 25, and in adjacent areas of the UK sector (Fig. 4, Isaksen and Tonstad 1989). The Frigg sands of the Beryl and Bruce Fields just extend into the Norwegian sector at about 59º30'N. The formation consists of a series of stacked-channel, lobe and interchannel sandstones with some lenses and streaks of silty claystone, and other intervals of alternating sandstones and shales (Bowman 1998). The sandstones are poorly consolidated, light brown to buff, micaceous and carbonaceous, and very fine to medium, occasionally coarse grained. Some layers have a calcareous cement and traces of glauconite are present. The silty claystones are green to grey and carbonaceous. The Frigg Formation submarine fans were deposited by gravity flows. The mode of deposition led to the formation varying in thickness over short distances. The source was the East Shetland Platform to the west.

Depth

In the type well (25/1-1) the Frigg Formation occurs at 2115-1836 m depth, while in the reference well (30/7-6) it occurs at 1923-1783 m depth (Isaksen and Tonstad 1989).

Permeability

The sandstones of the Frigg Formation are relatively clean, with high permeabilitiy. This is related to extensive shelf reworking on the East Shetland Platform prior to resedimentation by mass movements into the basin (Bowman 1998).

Thickness

The thickness of the Frigg Formation is 279 m in the type well and 140 m in the reference well (Isaksen and Tonstad 1989). A depocentre with a maximum thickness of approximately 300 m lies in Norwegian block 25/1.

Percent shale

From well logs published by Isaksen and Tonstad (1989), it is estimated that the Frigg Formation consists of approximately 80% sandstone and 20% claystone.

Top seal

The Frigg Formation is overlain by several hundred metres of laterally continuous claystones of the Hordaland Group (Fig. 5a, Isaksen and Tonstad 1989).

Hydrocarbon production

In the Norwegian sector, there is/has been hydrocarbon production from the Frigg Formation at the Frigg and Odin Fields (Bowman 1998). In the British sector, several fields are producing from the Frigg Formation (Brennand et al. 1998).

CO_2 storage quality and capacity

The Frigg Formation has good storage quality with respect to porosity, permeability, mineralogy and depth. The Frigg Formation is embedded within shales of the Hordaland Group, and individual sandstone intervals may thus be well sealed. The aquifer is probably divided into many separate, stratigraphic traps. The Frigg Formation continues into the British sector, where it is more widespread. Also there it is overlain by shales of the Hordaland Group. Injected CO_2 is expected to migrate towards the west in sandstone bodies that are not comletely embedded within shales.

It is here estimated that the Frigg Formation, in the Norwegian sector, has a pore volume of 42 km^3, a storage capacity in traps of 35 Mt CO_2, and that the storage capacity of the entire aquifer is 1751 Mt CO_2 (Table 6).

6.1.6 Fiskebank Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Late Paleocene Fiskebank Formation (Fig. 5b) of the Rogaland Group is encountered in the Norwegian-Danish Basin (Fig. 4, Isaksen and Tonstad 1989). In the type section, the major lithology is very fine grained, well sorted, slightly silty sandstone, which occasionally has calcareous cement. The formation is probably a basin-margin deposit, and appears to be time-equivalent to the Sele Formation.

Depth

In the type well (9/11-1) the Fiskebank Formation occurs at 1483-1335 m depth, while in the reference well (8/9-1) it occurs at 1399-1307 m depth (Isaksen and Tonstad 1989).

Thickness

The thickness of the Fiskebank Formation is 148 m in the type well and 92 m in the reference well (Isaksen and Tonstad 1989).

Top seal

The Fiskebank Formation is overlain by the Balder Formation, which is mainly composed of fissile shales with interbedded sandy tuffs and occasional stringers of limestone, dolomite and siderite (Fig. 5b, Isaksen and Tonstad 1989). Sandstones are locally present. The Balder Formation is normally 40-60 m thick. The formation is distributed over most of the North Sea, and may correspond in part to the Mo Clay Formation in Denmark (Isaksen and Tonstad 1989). The Balder Formation is again overlain by thick claystones of the Hordaland Group.

Hydrocarbon production

There is no hydrocarbon production from the Fiskebank Formation.

CO_2 storage quality and capacity

The storage quality of the Fiskebank Formation is probably moderate to good with respect to porosity, permeability, mineralogy and depth.

It is here estimated that the Fiskebank Formation, in the Norwegian sector, has a pore volume of 100 km^3, a storage capacity in traps of 84 Mt CO_2, and that the storage capacity of the entire aquifer is 4200 Mt CO_2 (Table 6).

6.1.7 Hermod Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Late Paleocene Hermod Formation (Fig. 5b) of the Rogaland Group is found in the South Viking Graben, in the northwestern part of quadrant 25 and the southwestern part of quadrant 30 (Fig. 4, Isaksen and Tonstad 1989, Reynolds 1994). The formation may also be found in other parts of the South Viking Graben. The Hermod Formation consists of clean, basinal sandstones which are very fine to fine grained and clear to grey. The formation is to a limited extent interbedded with dark shales. It was deposited in submarine fan systems connected with the shelf-and-delta complex of the Sele Formation/Moray Group to the west (Bowman 1998).

Depth

In the type well (25/2-6) the Hermod Formation occurs at 2361-2221 m depth, while in the reference well (10/1-1A) it occurs at 2212-2127 m depth (Isaksen and Tonstad 1989).

Thickness

The thickness of the Hermod Formation is 140 m in the type well and 85 m in the reference well (Isaksen and Tonstad 1989). It thickens towards the centre of its distribution area.

Percent shale

From well logs published by Isaksen and Tonstad (1989), it is estimated that the Hermod Formation consists of approximately 90% sandstone and 10% claystone.

Top seal

The Hermod Formation occurs within/is overlain by the Sele Formation (Fig. 5b), which consists of tuffaceous, carbonaceous, montmorillonite-rich shales and siltstones with interbeds of glauconitic sandstones. The thickness is variable. The Sele Formation is again overlain by the Balder Formation, which is mainly composed of fissile shales (Isaksen and Tonstad 1989). The Sele Formation is widely distributed throughout the North Sea, but north of 60ºN it has only been penetrated in an area off Sognefjorden. It is not found west of there, into the Viking Graben, where the Lista Formation (predominantly shales) alone is present (Isaksen and Tonstad 1989).

Hydrocarbon production

There is no hydrocarbon production from the Hermod Formation, in the Norwegian sector of the North Sea.

CO_2 storage quality and capacity

The Hermod Formation has good storage quality with respect to porosity, permeability, mineralogy and depth. It is embedded within shales of the Rogaland Group, and may thus be well sealed. The sands of the Hermod Formation continue into the British sector. Injected CO_2 is expected to migrate towards the west in sandstone bodies that are not comletely embedded within shales.

It is estimated that the Hermod Formation, in the Norwegian sector, has a pore volume of 28 km^3, a storage capacity in traps of 22 Mt CO_2, and that the storage capacity of the entire aquifer is 1105 Mt CO_2 (Table 6).

6.1.8 Forties Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Late Paleocene Forties Formation (Fig. 5b) of the Rogaland Group extends as a large lobe from the area south of the Halibut Horst to the northwestern part of the Central Trough. Some small lobes also reach the Viking Graben (Fig. 4, Isaksen and Tonstad 1989, Reynolds 1994). The formation typically consists of interbedded sandstones, siltstones and claystones, becoming predominantly sandy higher in the section. The sand is fine to coarse grained, poorly to moderately sorted, and contains minor amounts of lignite, pyrite, glauconite and mica. The Forties Formation was deposited as aggrading submarine fans fed by deltaic systems to the west. The sands encountered in the Norwegian sector were deposited distally in lobes, and consists of very fine to fine, angular to subangular grains often with mica and calcareous cement.

Depth

In the type well (UK well 21/10-1) the Forties Formation occurs at 2370-2131 m depth, while in the reference well (7/11-1) it occurs at 3069-2904 m depth (Isaksen and Tonstad 1989).

Thickness

The thickness of the Forties Formation is 239 m in the UK type well and 165 m in the Norwegian reference well (Isaksen and Tonstad 1989). The thickness decreases eastwards and southwards into the Norwegian sector (Reynolds 1994).

Percent shale

From well logs published by Isaksen and Tonstad (1989) it is estimated that the Forties Formation consists of approximately 90% sandstones and siltstones and 10% claystone. In the Norwegian sector the content of sandstone and siltstone is ca. 70% and the clay content around 30%.

Top seal

The Forties Formation is overlain by the partially time equivalent Sele Formation (Fig. 5b), which consists of tuffaceous, carbonaceous, montmorillonite-rich shales and siltstones with interbeds of glauconitic sandstones and is widely distributed throughout the North Sea. The thickness is variable. The Sele Formation is in turn overlain by the Balder Formation, which is mainly composed of fissile shales (Isaksen and Tonstad 1989).

Hydrocarbon production

There are several hydrocarbon fields producing from the Forties Formation in the British sector of the North Sea (Brennand et al. 1998).

CO_2 storage quality and capacity

The Forties Formation has moderate storage quality with respect to porosity, permeability and mineralogy. It is embedded within shales of the Rogaland Group, and may thus be well sealed. The sands of the Forties Formation continue into the British sector. There is a wide range in number and thickness of interbedded lithologies, that might represent barriers to vertical CO_2 migration. Injected CO_2 is expected to migrate towards the west in sandstone bodies that are not comletely embedded within shales.

It is estimated that the Forties Formation, in the Norwegian sector, has a pore volume of 6 km^3, a storage capacity in traps of 5 Mt CO_2, and that the storage capacity of the entire aquifer is 258 Mt CO_2 (Table 6).

6.1.9 Heimdal Formation

General setting (age, distribution, correlations, lithology, depositional environment)

Sandstones of the Paleocene Heimdal Formation (Fig. 5b) of the Rogaland Group are distributed in a lobate pattern eastwards from the western margin of the Viking Graben (Fig. 4, Isaksen and Tonstad 1989, Reynolds 1994). The formation is dominated by thick units of poorly sorted fine to coarse grained, poorly cemented sandstones with variable amounts of mica, glauconite and detrital lignite. The sandstone units are interbedded with grey and black shales, limestones and sandy limestones. There is a wide range in number and thickness of interbedded lithologies. In general, the amount of carbonate increases towards the base of the formation. In a narrow belt extending from the eastern part of quadrant 15, the Heimdal Formation is developed as a clean sandstone without interbedded shales (Meile member).

In the westernmost areas (East Shetland Platform/Fladen Ground Spur), the Heimdal Formation was deposited on a shallow marine shelf under high-energy conditions. In the Viking Graben, the formation was deposited as aggrading submarine fans derived from the shallow shelf to the west. The shale layers consist of the fine fraction of the turbidity currents and of hemipelagic mud. The clean sandstones of the Meile member may have been derived by winnowing of the Heimdal Formation sands by submarine currents acting along highs.

Time-equivalent sandstones of the Andrew Formation, in the Central Trough, have a limited distribution and storage potential in the Norwegian sector, and are thus not discussed further here.

Depth

In the type well (24/4-1) the Heimdal Formation occurs at 2423-2067 m depth, while in the reference well (15/9-5) it occurs at 2684-2448 m depth (Isaksen and Tonstad 1989).

Thickness

The thickness of the Heimdal Formation is 356 m in the type well and 236 m in the reference well (Isaksen and Tonstad 1989). It thins rapidly south of the type and reference wells. The Meile Member is 140 m thick in the reference well (15/9-11), and has a relatively constant thickness.

Percent shale

From well logs published by Isaksen and Tonstad (1989) it is estimated that the Heimdal Formation consists of approximately 70% sandstones and 30% shales and limestones. The Meile member comprises more than 90% sandstone.

Top seal

The Heimdal Formation is overlain by the Lista Formation (Fig. 5b), which is widespread in the Norwegian North Sea. The Lista Formation varies in thickness from less than 50 m to several hundred metres (Isaksen and Tonstad 1989). It consists of shales with occasional stringers of limestone, dolomite and pyrite. Sandstones are locally developed, especially in the lower part of the formation, where they may be up to 5 m thick. The Lista Formation is itself overlain by the Sele and Balder formations, which are dominated by claystones.

Hydrocarbon production

In the Norwegian sector, hydrocarbons are produced from the Heimdal Formation at the Balder, Heimdal, Loke and Sleipner Fields (Brennand et al. 1998).

CO_2 storage quality and capacity

The Heimdal Formation has moderate storage quality with respect to porosity, permeability and mineralogy. It is overlain by shales of the Rogaland Group, and may thus be well sealed. Sands of the Heimdal Formation continue into the British sector. There is a wide range in number and thickness of interbedded lithologies that might represent barriers to vertical CO_2 migration. Injected CO_2 is expected to migrate towards the west in sandstone bodies that are not embedded within shales. The Heimdal Formation and the underlying Ty Formations can probably be regarded as one aquifer.

It is estimated that the Heimdal Formation, in the Norwegian sector, has a pore volume of 393 km^3, a storage capacity in traps of 307 Mt CO_2, and that the storage capacity of the entire aquifer is 15 374 Mt CO_2 (Table 6).

6.1.10 Vidar Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Early Paleocene Vidar Formation (Fig. 5b) of the Rogaland Group is present in the Central Trough (Fig. 4). A similar limestone, which may be an equivalent to the Vidar Formation, is found in well 16/1-1 (Isaksen and Tonstad 1989). Homogenous limestone is the dominant lithology, but streaks of skeletal detritus and clasts of sandstone occur. Presence of reworked Upper and Lower Cretaceous material indicates that the Vidar Formation represents reworked chalk from the Shetland Group chalk facies as well as reworked marls and claystones from the Cromer Knoll Group. Mass flows from each side of the Central Trough are the most probable transport mechanism for this reworked material. Submarine fans occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998).

Depth

In the type well (2/1-4) the Vidar Formation occurs at 3138-3075 m depth, while in the reference well (1/3-1) it occurs at 3147-3095 m depth (Isaksen and Tonstad 1989).

Permeability

Bioturbated hemipelagic chalk may have matrix permeabilities low enough to seal traps (Johnson and Fisher 1998). The storage potential might be good in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments. The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998). At 1000 m, 2000 m and 3000 m depths, permeabilities are typically reduced to 10-100 millidarcies (mD), 1-10 mD and <1 mD, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 1-10 mD, 0.1-1 mD and <0.01 mD.

Thickness

The thickness of the Vidar Formation is 63 m in the type well and 52 m in the reference well (Isaksen and Tonstad 1989).

Percent shale/mudstone

From well logs published by Isaksen and Tonstad (1989) it is estimated that the Vidar Formation consists of approximately 90% limestone and 10% other lithologies.

Top seal

The Vidar Formation is overlain by the Lista Formation (Fig. 5b), which is widespread in the Norwegian North Sea and varies in thickness from less than 50 m to several hundred metres (Isaksen and Tonstad 1989). It consists of shales with occasional stringers of limestone, dolomite and pyrite. Sandstones are locally developed, especially in the lower part of the formation, where they may be up to 5 m thick.

Hydrocarbon production

In the Norwegian sector of the North Sea, there is no hydrocarbon production from the Vidar Formation.

Porosity

The porosity of initial hemipelagic ooze may be 70-80%. At 1000 m, 2000 m and 3000 m depths, porosities are typically reduced to 50%, 30% and 20%, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 35%, 20% and 10%. Preservation of the higher depositional porosities is also a function of the subsequent burial, overpressure and hydrocarbon migration history (Johnson and Fisher 1998).

CO_2 storage quality and capacity

Homogenous limestone is the dominant lithology of the Vidar Formation, and we assume that the storage quality is generally poor because of low matrix permeability. In fact, bioturbated hemipelagic chalk may have permeabilities low enough to seal traps (Johnson and Fisher 1998). There may be a storage potential in areas of halokinesis and post-Jurassic inversion due to high fracture permeability. In the chalk submarine fans comprising reworked sediments there is probably poor connection between sediment blocks with acceptable permeabilities. The Vidar Formation is embedded within shales of the Lista Formation and is thus thought to be well sealed, however, due to the low permeabilities, we assume that the Vidar Formation has no storage potential for CO_2.

6.1.11 Ty Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Early Palaeocene Ty Formation (Fig. 5b) of the Rogaland Group has been identified in the southern Viking Graben, and is well developed in the northwestern part of quadrant 25 and the northernmost part of quadrant 15 (Fig. 4, Isaksen and Tonstad 1989). The Ty Formation consists of clean sandstones, generally massive and clear to light grey in colour. Distally, the sandstones are interbedded with dark grey shales, but the sandstone bodies tend to be clean. The Ty Formation was deposited in a deep marine fan system which built out from the west.

Time-equivalent sandstones of the Maureen Formation, in the Central Trough, have a limited distribution and storage potential in the Norwegian sector, and are thus not further discussed here.

Depth

In the type well (UK well 10/1-1A) the Ty Formation occurs at 2767-2421 m depth, while in the reference well (15/3-1) it occurs at 2715-2556 m depth (Isaksen and Tonstad 1989).

Thickness

The thickness of the Ty Formation is 346 m in the type well and 159 m in the reference well (Isaksen and Tonstad 1989). The depocenter lies west of the type well.

Percent shale

From well logs published by Isaksen and Tonstad (1989) it is estimated that the Ty Formation consists of approximately 80% sandstones and 20% shales and limestones.

Top seal

The Ty Formation is usually overlain by the Lista Formation (Fig. 5b), which is widespread in the Norwegian North Sea and varies in thickness from less than 50 m to several hundred metres (Isaksen and Tonstad 1989). The Lista Formation consists of shales with occasional stringers of limestone, dolomite and pyrite. Sandstones are locally developed, especially in the lower part of the formation, where they may be up to 5 m thick. In the southern Viking Graben, The Ty Formation may be overlain by the several hundred metres thick Heimdal Formation, which is dominated by thick units of poorly sorted fine to coarse grained, poorly cemented sandstones with variable amounts of mica, glauconite and detrital lignite. The sandstone units are interbedded with grey and black shales, limestones and sandy limestones. There is a wide range in number and thickness of interbedded lithologies. In general, the amount of carbonate increases towards the base of the formation. In a narrow belt extending from the eastern part of quadrant 15, the Heimdal Formation is developed as a clean sandstone without interbedded shales (Meile member). The Ty and Heimdal Formations can probably be regarded as one aquifer.

Hydrocarbon production

In the Norwegian sector of the North Sea, there is no hydrocarbon production from the Ty Formation.

CO_2 storage quality and capacity

The sandstones of the Ty Formation have good storage quality with respect to porosity, permeability, mineralogy and depth. The formation is overlain by shales of the Lista Formation or alternating sandstones, shales and limestones of the Heimdal Formation. Both formations continue westwards into the British sector of the North Sea. Injected CO_2 is expected to migrate towards the west in sandstone bodies that are not embedded within shales.

It is estimated that the Ty Formation, in the Norwegian sector, has a pore volume of 172 km^3, a storage capacity in traps of 137 Mt CO_2, and that the storage capacity of the entire aquifer is 6852 Mt CO_2 (Table 6).

6.1.12 Ekofisk Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Danian Ekofisk Formation (Figs. 5b and 7a) of the Shetland Group is widespread in the southern and central North Sea (Fig. 4, Ziegler 1990, Oakman and Partington 1998). In the Norwegian sector, the Ekofisk Formation is missing from parts of the Sørvestlandet High and the Lindesnes Ridge. In the type well the formation comprises white, tan or beige, hard, dense, sometimes finely crystalline limestones, although softer chalky textures are also present (Isaksen and Tonstad 1989). The formation usually consists of white to light grey, beige to brownish, mudstones or wackestones with occasional packstones/grainstones and pisolithic horizons, often alternating with argillaceous chalks, chalky limestones or limestones. Thin beds of grey, calcareous, often pyritic shales or clays are most common in the lower part, while brownish-grey cherts occur rarely to abundantly throughout the formation. The Ekofisk Formation was deposited in an open marine envrionment as calcareous debris flows, turbidites, and periodites.

Depth

In the type well (2/4-5) the Ekofisk Formation occurs at 3164-3258 m depth, while in the reference wells it occurs at 3354-3258 m (1/3-1) , 2982.5-2935 m (UK well 22/1-2A) and 3132-3041 m (2/5-1) depths (Isaksen and Tonstad 1989).

Permeability

Bioturbated hemipelagic chalk may have matrix permeabilities low enough to act as seal for traps (Johnson and Fisher 1998). The storage potential might be good in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments. The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998). At 1000 m, 2000 m and 3000 m depths, permeabilities are typically reduced to 10-100 mD, 1-10 mD and <1 mD, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 1-10 mD, 0.1-1 mD and <0.01 mD.

Thickness

The thickness of the Ekofisk Formation is 127 m in the type well and 96 m, 47.5 m and 91 m in the reference wells (Isaksen and Tonstad 1989). In the Norwegian sector, seismic interpretation indicates that a thickness of more than 150 m is found in the northwestern part of the Central Trough.

Top seal

In the central and northern North Sea, the Ekofisk Formation is usually overlain by the the Våle Formation (Fig. 5b). The Våle Formation may be absent at intrabasinal highs (Isaksen and Tonstad 1989). It typically consists of marls and claystones interbedded with limestone beds and stringers of sandstone and siltstone. In the Central Trough, the formation is developed as a light grey marl, but locally has chalk and limestone interbeds that probably were eroded from rising diapirs. It also contains carbonate layers in the southern Viking Graben. The formation is normally less than 100 m thick. In the west, the Våle formation becomes coarser grained and the Ekofisk Formation is overlain by the Maureen Formation in the Central Trough and the Ty Formation in the Southern Viking Graben, which are both dominated by sandstone.

Hydrocarbon production

In the Norwegian sector of the North Sea, there is hydrocarbon production from the Ekofisk Formation at several fields in the Central Trough (Brennand et al. 1998).

Porosity

The porosity of initial hemipelagic ooze may be 70-80%. At 1000 m, 2000 m and 3000 m depths, porosities are typically reduced to 50%, 30% and 20%, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 35%, 20% and 10%. Preservation of the higher depositional porosities is also a function of the subsequent burial, overpressure and hydrocarbon migration history (Johnson and Fisher 1998).

CO_2 storage quality and capacity

The varied lithology and low matrix permeability of the Ekofisk Formation suggests that it is not well suited for CO_2 storage. In fact, bioturbated hemipelagic chalk may have permeabilities low enough to act as a seal for traps (Johnson and Fisher 1998). The storage potential might be better in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments (which may comprise up to 50% of the total Chalk Group thickness). The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998). In the Norwegian sector of the North Sea, the Ekofisk Formation is overlain by shales of the Våle Formation and is thus thought to be well sealed. The Ekofisk Formation and the underlying Tor and Hod Formations are here regarded as one aquifer.

There is a storage potential in the Ekofisk Formation, but only in the reworked chalks at 800-3000 m depth, in overpressured zones, and in the oil and gas fields. It is estimated that the Ekofisk Formation has a pore volume of 120 km^3, a storage capacity in traps of 106 Mt CO_2, and that the storage capacity of the entire aquifer is 1769 Mt CO_2 (Table 6).

6.1.13 Tor Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Late Campanian to Maastrichtian Tor Formation (Figs. 7a, b) of the Shetland Group is present throughout the central North Sea (Fig. 4, Ziegler 1990, Oakman and Partington 1998). In the Norwegian sector, it is very thin or absent on the Lindesnes Ridge and Utsira High (Isaksen and Tonstad 1989). In the type well, the formation comprises white to light grey, tan to pink, hard, chalky limestones. The formation is generally homogenous, or consists of alternating white, grey or beige, moderately hard to very hard, rarely soft, mudstones or wackstones, rarely packstones, chalks, chalky limestones or limestones. Occasional fine layers of soft grey-green or brown marl occur and also rare stringers of grey to green calcareous shales.

The formation was deposited in an open marine environment as calcareous debris flows, turbidites and autochtonous periodites. It can be divided into a lower member (dominated by autochtonous periodite deposits interrupted by single or stacked minor debris flows), a middle member (showing an increase in slumps, slides and debris flows) and an upper member (consisting of high porosity, homogenous chalks representing debris flows).

The time-equivalent Hardråde Formation, which occurs on the Hordaland Platform (Figs. 7c, d), consists of interbedded limestones and mudstones. Although covering an area of ca. 16 000 km^2, it is here considered to have a small CO_2 storage potential, and is thus not further discussed.

Depth

In the type well (1/3-1) the Tor Formation occurs at 3828-3354 m depth, while in the reference wells it occurs at 3245-3982.5 m (UK well 22/1-2A), 2212-1869 m (UK well 29/25-1)) and 3312-3104 m (1/9-1) depths (Isaksen and Tonstad 1989).

Permeability

Bioturbated hemipelagic chalk may have matrix permeabilities low enough to act as a seal for traps (Johnson and Fisher 1998). The storage potential might be good in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments. The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998). At 1000 m, 2000 m and 3000 m depths, permeabilities are typically reduced to 10-100 mD, 1-10 mD and <1 mD, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 1-10 mD, 0.1-1 mD and <0.01 mD.

Thickness

The thickness of the Tor Formation is 474 m in the type well and 262.5 m, 143 m and 208 m in the reference wells (Isaksen and Tonstad 1989). In the Norwegian sector, seismic interpretation indicates that the thickness of the formation may exceed 600 m in the northwestern part of the Central Graben.

Top seal

The upper boundary of the Tor Formation represents an unconformity with a submarine hardground along the Lindesnes Ridge, and a change to clay-rich chalks or minor shales of the Ekofisk Formation (Figs. 7a, b, Isaksen and Tonstad 1989). The Ekofisk Formation (50-150 m thick) usually consists of mudstones or wackestones with occasional packstones/ grainstones and pisolithic horizons, often alternating with argillaceous chalks, chalky limestones or limestones. Thin beds of calcareous, often pyritic shales or clays are most common in the lower part, while cherts occur rarely to abundantly throughout the formation. The Ekofisk Formation is widespread in the southern and central North Sea (Isaksen and Tonstad 1989). In the Norwegian sector, it is missing from parts of the Sørvestlandet High and the Lindesnes Ridge. The Ekofisk, Tor and Hod Formations are here regarded as one aquifer.

Hydrocarbon production

In the Norwegian sector of the North Sea, hydrocarbons are produced from the Tor Formation at several fields in the Central Trough (Brennand et al. 1998).

Porosity

The porosity of initial hemipelagic ooze may be 70-80%. At 1000 m, 2000 m and 3000 m depths, porosities are typically reduced to 50%, 30% and 20%, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 35%, 20% and 10%. Preservation of the higher depositional porosities is also a function of the subsequent burial, overpressure and hydrocarbon migration history (Johnson and Fisher 1998).

CO_2 storage quality and capacity

Homogenous limestone is the dominant lithology of the Tor Formation, and we assume that the storage quality is generally poor because of low matrix permeability. In fact, bioturbated hemipelagic chalk may have permeabilities low enough to act as a seal for traps (Johnson and Fisher 1998). The storage potential might be better in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments (which may comprise up to 50% of the total Chalk Group thickness). The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998).

There is a storage potential in the Tor Formation, but only in the reworked chalks at 800-3000 m depth, in overpressured zones, and in the oil and gas fields. It is estimated that the Tor Formation has a pore volume of 480 km^3, a storage capacity in traps of 295 Mt CO_2, and that the storage capacity of the entire aquifer is 6835 Mt CO_2 (Table 6).

6.1.14 Hod Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Turonian to Campanian Hod Formation (Fig. 7a, b) of the Shetland Group is widely distributed in central and eastern parts of the central North Sea (Fig. 4, Ziegler 1990, Oakman and Partington 1998), passing laterally into sediments of the Herring and Flounder Formations to the west and the Tryggvason and Kyrre Formations to the northwest (Isaksen and Tonstad 1989). In the type well the formation consists of hard, white to light grey, crypto- to microcrystalline limestones which may become argillaceous or chalky in places. White, light grey to light brown, soft to hard chalk facies may dominate the formation or alternate with limestones. The limestones may be pink or pale orange. Thin, silty, white, light grey to green or brown, and soft grey to black, calcareous clay/shale laminae are occasionally present. Pyrite and glauconite may occur throughout the formation and the latter may be common the the lower part.

The formation was deposited in an open marine environment as cyclic pelagic carbonates (periodites) and distal turbidites. It can be divided into a lower member (comprising the largest part of the formation (including the Herring Formation), composed of bioturbated, laminated chalks with a low clay content), a middle member (mainly periodites with a higher content of terrigenous clay) and an upper member (dominated by perodites with minor allochtonous intercalations, but with a low clay content) (Isaksen and Tonstad 1989).

Depth

In the type well (1/3-1) the Hod Formation occurs at 4343-3828 m depth, while in the well reference sections it occurs at 2225-2012 m (UK well 29/25-1) and 2601-2494 m (2/8-8) depths (Isaksen and Tonstad 1989).

Permeability

Bioturbated hemipelagic chalk may have matrix permeabilities low enough to act as a seal for traps (Johnson and Fisher 1998). The storage potential might be good in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments. The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998). At 1000 m, 2000 m and 3000 m depths, permeabilities are typically reduced to 10-100mD, 1-10mD and <1 mD, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 1-10 mD, 0.1-1 mD and <0.01 mD.

Thickness

The thickness of the Hod Formation is 515 m in the type well and 213 m and 107 m in the reference wells (Isaksen and Tonstad 1989). In the Norwegian sector, seismic interpretation indicates that the thickness of the formation may exceed 700 m in the northwestern part of the Central Graben.

Top seal

The Hod Formation is overlain by the Tor Formation (Fig. 7a, b), which is up to 600 m thick (Isaksen and Tonstad 1989). The boundary may represent an unconformity in the Ekofisk area. The Tor Formation is generally homogenous, or consists of moderately hard to very hard, rarely soft, mudstones or wackstones, rarely packstones, chalks, chalky limestones or limestones. Occasional fine layers of soft marl occur and also rare stringers of calcareous shales. The Tor Formation is present throughout the central North Sea. In the Norwegian sector, it is very thin or absent on the Lindesnes Ridge and Utsira High (Isaksen and Tonstad 1989). The Ekofisk, Tor and Hod Formations are here regarded as one aquifer.

Hydrocarbon production

In the Norwegian sector of the North Sea, hydrocarbons are produced from the Hod Formation at several fields in the Central Trough (Brennand et al. 1998).

Porosity

The porosity of initial hemipelagic ooze may be 70-80%. At 1000 m, 2000 m and 3000 m depths, porosities are typically reduced to 50%, 30% and 20%, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 35%, 20% and 10%. Preservation of the higher depositional porosities is also a function of the subsequent burial, overpressure and hydrocarbon migration history (Johnson and Fisher 1998).

CO_2 storage quality and capacity

Alternating limestone, chalky limestone and chalk with shale laminae are the dominant lithologies of the Hod Formation, and we assume that the storage quality generally is poor because of low matrix permeability. In fact, bioturbated hemipelagic chalk may have permeabilities low enough to act as a seal for traps (Johnson and Fisher 1998). The storage potential might be better in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments (which may comprise up to 50% of the total Chalk Group thickness). The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998).

There is a theoretical storage potential in the Hod Formation, but only in the reworked chalks at 800-3000 m depth, in overpressured zones, and in the oil and gas fields. It is here estimated that the Hod Formation has a pore volume of 240 km^3, a storage capacity in traps of 202 Mt CO_2, and that the storage capacity of the entire aquifer is 3360 Mt CO_2 (Table 6).

6.1.15 Hidra Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Cenomanian Hidra Formation (Fig. 7a) of the Shetland Group is found in the southern and central North Sea (Fig. 4, Ziegler 1990, Oakman and Partington 1998). In the Norwegian sector, it is missing above highs such as the Sørvestlandet, Mandal, Jæren, Utsira and Sele Highs, the Grensen Ridge, as well as above many of the salt diapirs (Isaksen and Tonstad 1989). In the type well, the formation consists of white to light grey, hard chalks with thin interbeds of grey to black shale in the lower part of the formation. Locally the formation is more marly with interbedded marly chalk and marl. The chalks are occasionally softer with abundant glauconite and pyrite. At the base of the formation in UK well 22/1-2A, hard, black, carbonaceous and argillaceous limestones are present. Traces of pink waxy tuff occur in places. The formation is generally highly bioturbated. It was deposited in an open marine environment with a perioditic or turbiditic origin for the sediments.

Depth

In the type well (1/3-1) the Hidra Formation occurs at 4441-4371 m depth, while in the well reference sections it occurs at 3783-3738 m (UK well 22/1-2A)), 2258.5-2228 m (UK well 29/25-1)) and 2275.5-2220 m (Danish well BO-1) depths (Isaksen and Tonstad 1989).

Permeability

Bioturbated hemipelagic chalk may have matrix permeabilities low enough to act as a seal for traps (Johnson and Fisher 1998). The storage potential might be good in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments. The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998). At 1000 m, 2000 m and 3000 m depths, permeabilities are typically reduced to 10-100 mD, 1-10 mD and <1 mD, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 1-10 mD, 0.1-1 mD and <0.01 mD.

Thickness

The thickness of the Hidra Formation is 70 m in the type well and 45 m, 30.5 m and 55.5 m in the reference wells (Isaksen and Tonstad 1989). Seismic interpretation indicates that the formation reaches a maximum thickness of about 150 m in the northwestern part of the Central Trough in the Norwegian sector.

Top seal

The Hidra Formation is overlain by the Blodøks Formation (Fig. 7a), which is up to 20 m thick (Isaksen and Tondstad 1989). At the boundary, there may be a glauconitised hardground. The formation consists of shales and mudstones, which are non-calcareous to moderately calcareous. In the central North Sea, it may show a varied influx of marls, limestones and chalky limestones. The Blodøks Formation is present throughout the North Sea, lacking only on local highs such as the Sørvestlandet, Mandal, Jæren, Utsira and Sele Highs, the Grensen Ridge, as well as above many of the salt diapirs (Isaksen and Tonstad 1989). The Blodøks Formation is again overlain by the up to 700 m thick Hod Formation, which consists of chalk and limestone.

Hydrocarbon production

No hydrocarbons are produced from the Hidra Formation in the Norwegian sector of the North Sea.

Porosity

The porosity of initial hemipelagic ooze may be 70-80%. At 1000 m, 2000 m and 3000 m depths, porosities are typically reduced to 50%, 30% and 20%, respectively (Oakman and Partington 1998). For hemipelagic clean chalks, typical values are correspondingly 35%, 20% and 10%. Preservation of the higher depositional porosities is also a function of the subsequent burial, overpressure and hydrocarbon migration history (Johnson and Fisher 1998).

CO_2 storage quality and capacity

Chalk, marly chalk, and marl are the dominant lithologies of the Hidra Formation, and we assume that the storage quality is generally poor because of low matrix permeability. In fact, bioturbated hemipelagic chalk may have permeabilities low enough to act as a seal for traps (Johnson and Fisher 1998). There may be a storage potential in areas of halokinesis and post-Jurassic inversion due to high fracture permeability, and in chalk submarine fans comprising reworked sediments. The latter occur in connection with old Jurassic footwall crests, inversion pop-up structures and halokinetic features (Oakman and Partington 1998). The Hidra Formation is overlain by shales and mudstones of the Blodøks Formation, and is probably well sealed, however, due to the low permeabilities, we here assume that the Vidar Formation has no storage potential for CO_2.

6.1.16 Agat Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Aptian-Albian (possibly Early Cenomanian) Agat Formation (Fig. 7e) of the Cromer Knoll Group is encountered in the area around the Måløy fault blocks (Fig. 4) in Norwegian Blocks 35/3-36/1. It is expected to be present along the western boundary of the Fennoscandian Shield and around highs in the Møre and Vøring Basins (Vergara et al. 2001). Around the Måløy Fault Blocks, it is assumed to pass into shales towards the west (Isaksen and Tonstad 1989, Pegrum and Spencer 1990, Oakman and Partington 1998). In the type well, the formation consists of white to light grey, fine- to medium-grained, moderately to well-sorted sandstones alternating with grey claystones. The sandstones are usually micaceous and glauconitic and sometimes contain small amounts of pyrite. The sandstones in the type well are carbonate- and silica-cemented in zones. In the reference well, the upper part of the formation consists of medium- and coarse-grained to pebbly sandstones and conglomerates alternating with dark grey claystones. The conglomerates are both matrix- and grain-supported. The claystones are often found as 0.5-5 m thick layers between the sandstones. They are dark grey, usually calcareous and contain varying amounts of siltstone. They may occasionally pass into light grey, micaceous, calcareous and glauconitic siltstones. The sediments were deposited in a submarine fan/slope environment with gravity flows.

Depth

In the type well (35/3-4) the Agat Formation occurs at 3589-3345 m depth, while in the reference well (35/3-5) it occurs at 3620-3219 m depth (Isaksen and Tonstad 1989).

Thickness

The thickness of the Agat Formation is 244 m in the type well and 401 m in the reference well (Isaksen and Tonstad 1989).

Percent shale

From well logs published by Isaksen and Tonstad (1989) it is estimated that the Agat Formation consists of approximately 50% sandstone and 50% shale.

Top seal

Around the Måløy fault blocks, the Agat Formation is overlain either by the Rødby Formation (Cromer Knoll Group) or the Svarte Formation (Shetland Group) (Fig. 7e, Isaksen and Tonstad 1989). The Rødby Formation is generally 15-30 m thick and dominated by marlstones. Sandstones and siltstones are known to be present locally. The Svarte Formation, which may also overlie the Rødby Formation, may be more than 200 m thick. It generally consists of mudstones interbedded with limestones, but in the Agat area, sandstones occur. These are clear to light grey and often cemented by calcite. The Svarte Formation is again overlain by the Blodøks Formation, which consists of shales and mudstones, and which is up to 20 m thick. The Rødby, Svarte and Blodøks Formations are present around the Måløy fault blocks and form a tight seal above the Agat Formation, but are generally missing on the Horda Platform (Isaksen and Tonstad 1989).

Hydrocarbon production

Hydrocarbons occur in the Agat Field in the Agat Formation (Oakman and Partington 1998).

CO_2 storage quality and capacity

Sandstones of the Agat Formation are of poor quality in the shallowest areas (ca. 3 km depth) in the east. The reservoir quality improves downflank towards the southwest (Oakman and Partington 1998). The formation is overlain by marlstones, mudstones, limestones and sandstones of the Rødby, Svarte and Blodøks Formation, and is probably well sealed.

It is here estimated that the Agat Formation has a pore volume of 18 km^3, a storage capacity in traps of 14 Mt CO_2, and that the storage capacity of the entire aquifer is 249 Mt CO_2 (Table 6).

6.1.17 Sognefjord Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Callovian/Oxfordian to Kimmeridgian/Volgian Sognefjord Formation (Fig. 9c) of the Viking Group is encountered on the Horda Platform (Fig. 4), in the Troll Field Area, where it is the major reservoir interval (Vollset and Doré 1984, Gray 1987, Stewart et al. 1995, Spencer et al. 1996). It occurs in several fault blocks, downthrown towards the west (Fig. 13). The formation comprises very fine grained, highly micaceous to coarse grained sandstones and sands, grey-brown in colour, well sorted and friable to unconsolidated. The formation contains minor argillaceous and carbonaceous beds. Bioclastic material and occasional calcite-cemented bands occur locally. The formation was deposited in a shallow marine shelf to shoreface environment, and is characterized by both coarsening upwards and fining-upwards cycles at various scales, reflecting regressive-transgressive cycles. Sediments were derived from the Norwegian mainland to the east.

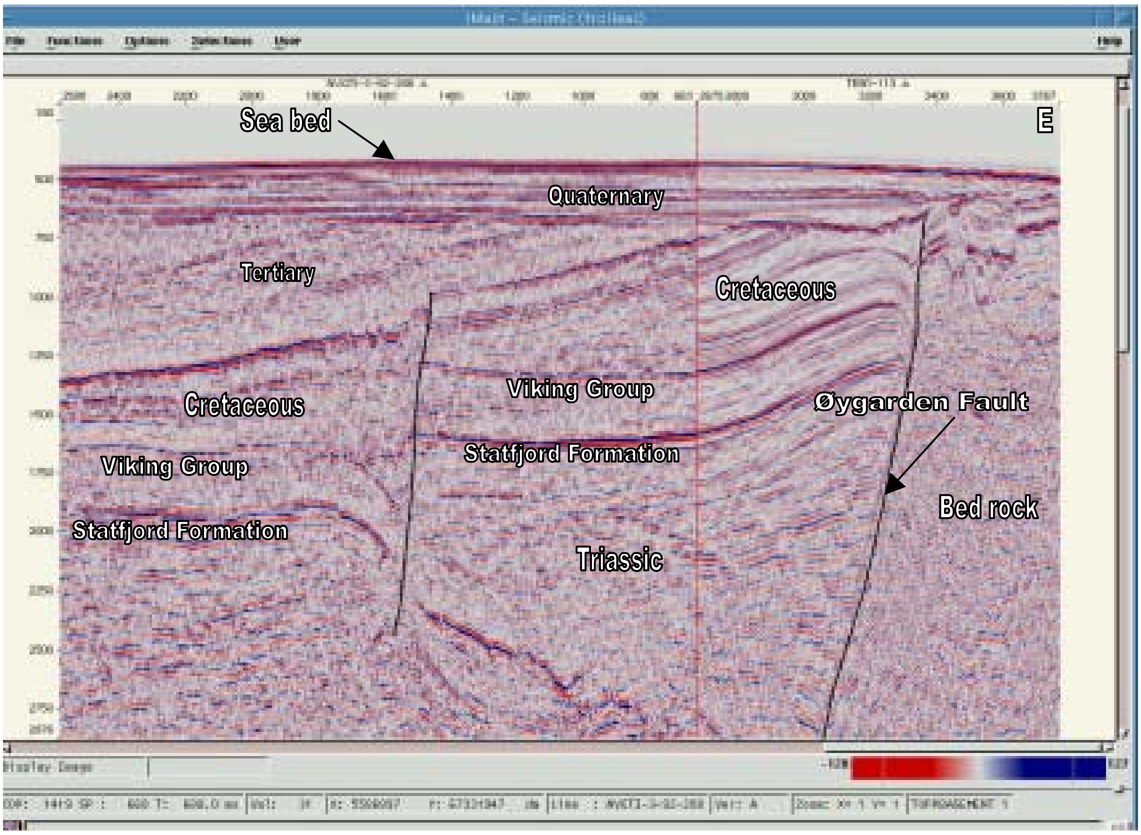

Figure 13. Seismic section east the Troll Field across the Øygarden Fault Zone.

Depth

In the type well (31/2-1) the Sognefjord Formation occurs at 1440-1531.5 m depth (Vollset and Doré 1984). A map of depths to the top of the Sognefjord Formation is shown in Fig. 14.

Permeability

The main reservoir units in the Troll Field consist of good quality shoreface sandstones with permeabilities that range from 1 mD to 10 D (Gray 1987). The fine-grained sediments within the Sognefjord Formation have permeabilities of 1-100 mD, while the coarse-grained, clean sandstones have permeabilities up to 20-30 D (Johnsen et al. 1995).

Thickness

The thickness of the Sognefjord Formation is 91.5 m in the type well (Vollset and Doré 1984).

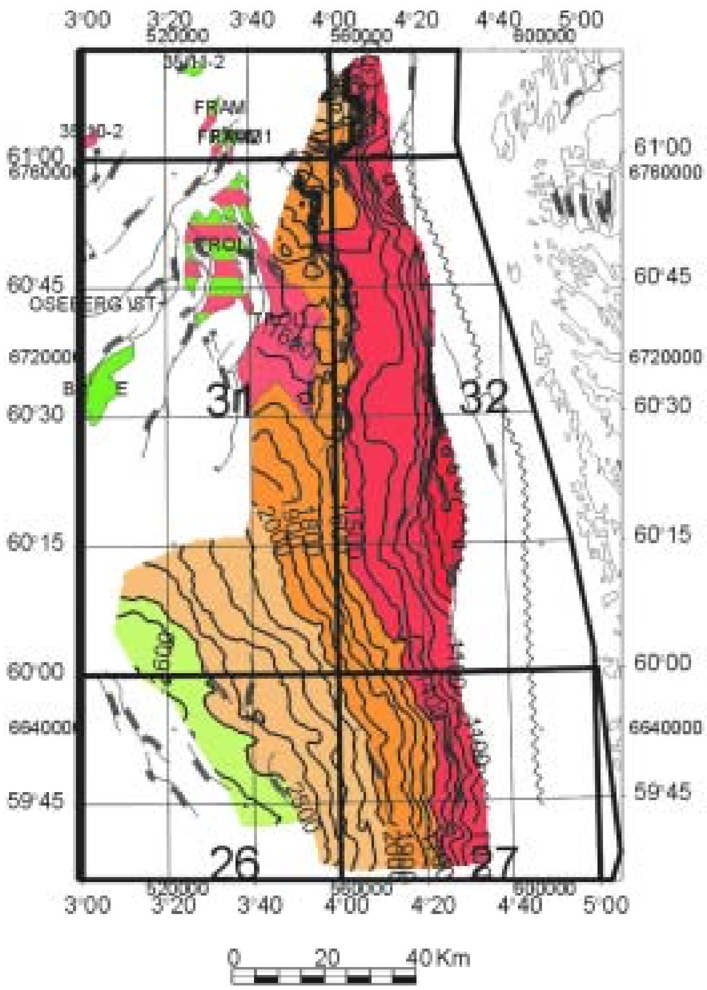

Figure 14. Depth in metres to the top of the Sognefjord Formation southeast of the Troll Field.

Percent shale

From a well log published by Vollset and Doré (1984) it is estimated that the Sognefjord Formation consists of approximately 90% sandstone and 10% shale.

Top seal

The Sognefjord Formation is overlain by the Draupne Formation (Fig. 9c), which is laterally continuous on the Horda Platform and consists of claystone. The Draupne Formation is locally several hundred metres thick (Vollset and Doré 1984). In some areas, the Sognefjord Formation is overlain by a siltstone (Heather "C"), followed by the Draupne Formation (Stewart et al. 1995). West of the Horda Fault Zone, southwest of Bergen, it is possible that there is a major coarse-grained interval of Volgian age in the Draupne Formation. Seismic data show a deltaic wedge sourced from the east in this area.

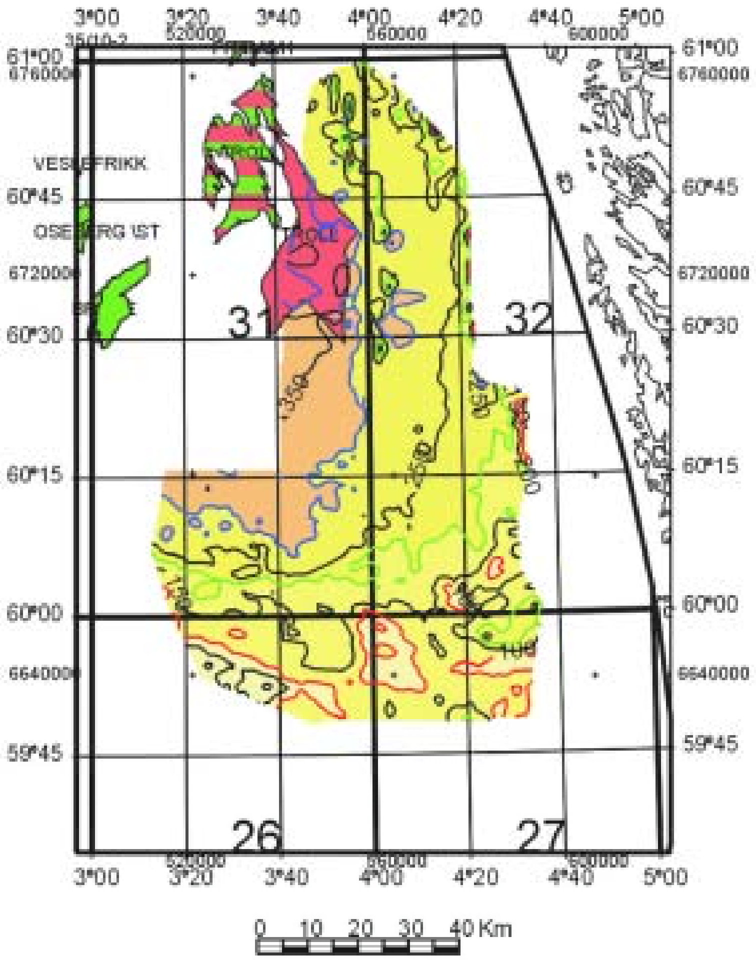

Figure 15. Isopach map of the Sognefjord-Fensfjord-Krossfjord-Brent aquifer in the area southeast of the Troll Field.

Hydrocarbon production

The Sognefjord Formation is the major reservoir interval in the Troll Field.

Porosity

The main reservoir units in the Troll Field consist of good quality shoreface sandstones with porosities ranging from 19% to 34% (Gray 1987). The fine-grained sediments within the Sognefjord Formation have porositites between 15 and 25%, while the coarse-grained, clean sandstones have porosities up to 38% (Johnsen et al. 1995).

CO_2 storage quality and capacity

The Sognefjord Formation comprises alternating intervals of good reservoir sands (upper shoreface) and micaceous sands and silts (shelf/lower shoreface). With regard to porosity, permeability, depth and top seal, the formation is well suited for CO_2 storage. North of the Troll Field, and possibly along parts of the Øygarden Fault Complex, east of the Troll Field, areas of possible neotectonic activity are interpreted (Dehls et al. 2000). Faults belonging to the Øygarden Fault Complex, along which the Sognefjord Formation is downfaulted, may reach the Quaternary erosion surface. The Sognefjord, Fensfjord and Krossfjord Formations are regared as one aquifer. Within several areas, the sands of the various formations are in direct contact, while in other areas, they are separated by more fine-grained intervals. The Sognefjord Formation is separated from the Fensfjord Formation by siltstones of the Heather Formation (Heather "B"), especially towards the west (Stewart et al. 1995).

It is here estimated that the Sognefjord Formation has a pore volume of 180 km^3, a storage capacity in traps of 151 Mt CO_2, and that the storage capacity of the entire aquifer is 2520 Mt CO_2 (Table 6). An isopach map of the Sognefjord-Fensfjord-Krossfjord (and into the Brent) aquifer, in the area southeast of the Troll Field, is shown in Fig. 15.

6.1.18 Fensfjord Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Callovian Fensfjord Formation (Fig. 9c) of the Viking Group is encountered on the Horda Platform, in the Troll Field Area (Fig. 4, Vollset and Doré 1984, Gray 1987, Stewart et al. 1995, Spencer et al. 1996). It occurs in several fault blocks, downthrown towards the west. The formation comprises very fine grained, highly micaceous to coarse grained sandstones and sands, grey-brown in colour, well sorted and moderately friable to consolidated. Calcite cemented sandstones occur in bands containing common bioclastic material. In the type well it is often carbonaceous and occasionally micaceous. Minor shale intercalations occur throughout. The formation was deposited in a shallow marine shelf to shoreface environment, and is characterized by coarsening upwards and fining-upwards cycles at various scales, reflecting regressive-transgressive cycles. Sediments were derived from the Norwegian mainland to the east.

Depth

In the type well (31/2-1) the Fensfjord Formation occurs at 1594.5-1741.5 m depth (Vollset and Doré 1984).

Permeability

The permeability of the Fensfjord Formation ranges from less than 1 mD in the fine-grained sections to several darcies in the coarse-grained sections (Johnsen et al. 1995). The main reservoir units in the Troll Field consist of good quality shoreface sandstones with permeabilities that range from 1 mD to 10 D (Gray 1987).

Thickness

The thickness of the Fensfjord Formation is 147 m in the type well (Vollset and Doré 1984).

Percent shale

From a well log published by Vollset and Doré (1984) it is estimated that the Fensfjord Formation consists of approximately 90% sandstone and 10% shale.

Top seal

The Fensfjord Formation is overlain by the Heather Formation (Heather "B") (Fig. 9c), which mainly consists of siltstone and silty claystone with thin streaks of limestone. The Heather Formation is highly variable in thickness, and may reach more than 1000 m in graben areas (Vollset and Doré 1984, Stewart et al. 1995). On the Horda Platform, where it interfingers with sandstones of the Krossfjord, Fensfjord and Sognefjord Formation, it becomes in places highly micaceous and grades into a sandy siltstone. On the easternmost part of the Horda Platform, it is probable that there is direct contact between the sandstones of the Fensfjord and Sognefjord Formations. The Sognefjord, Fensfjord and Krossfjord Formations are regared as one aquifer, overlain by the Draupne Formation (see description under Sognefjord Formation).

Hydrocarbon production

The Fensfjord Formation is a major reservoir interval in the Troll Field.

Porosity

The Fensfjord Formation has porositites between 15 and 35% (Johnsen et al. 1995). The main reservoir units in the Troll Field consist of good quality shoreface sandstones with porosities of 19-34% (Gray 1987).

CO_2 storage quality and capacity

The Fensfjord Formation comprises alternating intervals of good reservoir sands (upper shoreface) and micaceous sands and silts (shelf/lower shoreface). With regard to porosity, permeability and depth, the formation is well suited for CO_2 storage. North of the Troll Field, and possibly along parts of the Øygarden Fault Complex, east of the Troll Field, areas of neotectonic activity are interpreted (Dehls et al. 2000). Faults belonging to the Øygarden Fault Complex, along which the Fensfjord Formation is downfaulted, reach the Quaternary erosion surface. The Sognefjord, Fensfjord and Krossfjord Formations are regared as one aquifer. Within several areas, sands of the various formations are in direct contact, while in other areas, they are separated by more fine-grained intervals. The Sognefjord Formation is separated from the Fensfjord Formation by siltstones of the Heather Formation (Heather "B"), but possibly not in the easternmost areas (Stewart et al. 1995).

It is estimated that the Fensfjord Formation has a pore volume of 180 km^3, a storage capacity in traps of 151 Mt CO_2, and that the storage capacity of the entire aquifer is 2520 Mt CO_2 (Table 6).

6.1.19 Krossfjord Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Bathonian Krossfjord Formation (Fig. 9c) of the Viking Group is encountered on the eastern part of the Horda Platform (Fig. 4, Vollset and Doré 1984, Gray 1987, Stewart et al. 1995, Spencer et al. 1996). It occurs in several fault blocks, downthrown towards the west. The formation consists of sandstones, light grey-brown in colour, medium to coarse grained, well-sorted, and loose to very friable. Occasionally, calcite cemented streaks occur. The lower portion of the Krossfjord Formation is slightly argillaceous and carbonaceous with minor shale intercalations. The formation was deposited in a shallow marine shelf to shoreface environment, and is characterized by coarsening upwards and fining-upwards cycles at various scales, reflecting regressive-transgressive cycles. Sediments were derived from the Norwegian mainland to the east.

Depth

In the type well (31/2-1) the Krossfjord Formation occurs at 1741.5-1880 m depth (Vollset and Doré 1984).

Thickness

The thickness of the Krossfjord Formation is 138.5 m in the type well (Vollset and Doré 1984).

Percent shale

From a well log published by Vollset and Doré (1984) it is estimated that the Krossfjord Formation consists of approximately 90% sandstone and 10% shale.

Top seal

The Krossfjord Formation is overlain by the Fensfjord Formation (Fig. 9c), which is dominated by sandstone. The Fensfjord Formation is again overlain by the Heather Formation

(Heather "B"), which mainly consists of siltstone and silty claystone with thin streaks of limestone. The Heather Formation is highly variable in thickness, and may reach more than 1000 m in graben areas (Vollset and Doré 1984, Stewart et al. 1995). On the Horda Platform, where it interfingers with sandstones of the Krossfjord, Fensfjord and Sognefjord Formation, it becomes in places highly micaceous and grades into a sandy siltstone. The Sognefjord, Fensfjord and Krossfjord Formations are regared as one aquifer, overlain by the Draupne Formation (see description under Sognefjord Formation).

Hydrocarbon production

There is no hydrocarbon production from the Krossfjord Formation.

CO_2 storage quality and capacity

The Krossfjord Formation comprises alternating intervals of good reservoir sands (upper shoreface) and micaceous sands and silts (shelf/lower shoreface). With regard to porosity, permeability and depth, the formation is well suited for CO_2 storage. North of the Troll Field, and possibly along parts of the Øygarden Fault Complex, east of the Troll Field, areas of neotectonic activity are interpreted (Dehls et al. 2000). Faults belonging to the Øygarden Fault Complex, along which the Krossfjord Formation is downfaulted, locally reach the Quaternary erosion surface. The Sognefjord, Fensfjord and Krossfjord Formations are regared as one aquifer. Within several areas, the sands of the various formations are in direct contact, while in other areas, they are separated by more fine-grained intervals. On the eastern part of the Horda Platform, there is direct contact between sandstones of the Krossfjord Formation and the Fensfjord Formation (Stewart et al. 1995).

It is here estimated that the Krossfjord Formation has a pore volume of 90 km^3, a storage capacity in traps of 75 Mt CO_2, and that the storage capacity of the entire aquifer is 1260 Mt CO_2 (Table 6).

6.1.20 Eldfisk Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Kimmeridgian Eldfisk Formation (Fig. 9a) of the Tyne Group has its main development in the region of the Eldfisk Field, although thin, time equivalent sands are present in other parts of the Central Graben (Fig. 4, Vollset and Doré 1984, Bergan et al. 1989). The formation consists predominantly of sandstone but contains substantial interbeds of shale. In the type well the sandstone is dark yellowish brown, fine to coarse grained, poorly sorted and generally angular, while the shale is medium light grey to dark grey. Both the sandstone and the shale contain calcareous streaks. The Eldfisk Formation represents an influx of sand into the axial portions of the Central Graben at a time of regression. It is postulated that the formation is turbiditic in origin.

Depth

In the type well (2/7-3) the Eldfisk Formation occurs at 3626-3695 m depth, while in the reference well (1/9-3) it occurs at 4359.5-4386.5 m depth (Vollset and Doré 1984).

Thickness

The thickness of the Eldfisk Formation is 69 m in the type well and 27 m in the reference well (Vollset and Doré 1984).

Percent shale

From well logs published by Vollset and Doré (1984) it is estimated that the Eldfisk Formation consists of approximately 60% sandstone and 40% shale.

Top seal

The Eldfisk Formation is entirely enclosed within the thick upper Jurassic shale sequence of the Central Graben (Vollset and Doré 1984). It is overlain by the Farsund Formation (Fig. 9a), which is more than 200 m thick in the Central Graben (Bergan et al. 1989).

Hydrocarbon production

There is no hydrocarbon production from the Eldfisk Formation.

CO_2 storage quality and capacity

The Eldfisk Formation occurs at too great depths and has too small volume to be a well suited aquifer for CO_2 storage.

6.1.21 Ula Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Ula Formation (Fig. 9a) of the Vestlandet Group is developed around the eastern flanking highs of the Central Graben, in particular on the south-western flank of the Southern Vestland Arch (Fig. 4). It interfingers basinwards with marine shales of the Tyne Group (Haugesund, Farsund and Mandal Formations), which divide the formation into a lower and and upper unit (Bergan et al. 1989). The Ula Formation becomes thin or absent over the highs. Tongues of similar sands occur locally in the Tyne Group mudstones. Comparable formations in lithofacies and partly in age occur both in the Sleipner area (Hugin Formation) and in the Fiskebank and Egersund Sub-Basins (Sandnes Formation) (Vollset and Doré 1984). In the region of the Ula Field, the sands are Oxfordian to Early Volgian in age. Around the fringes of the Jæren and Mandal Highs and locally on the Southern Vestland Arch, developments of the formation are as young as Ryazanian (Bergan et al. 1989).

In the type well the Ula Formation is a generally massive, fine to medium grained, grey sandstone. A thin, dark grey siltstone is present in the basal part of the formation. The sandstones are arcosic, glauconitic and micaceous. Sorting and angularity vary between individual units of the formation. Bivalve shells and belemnite debris occur, often concentrated in thin lag deposits. Thin, nodular calcite-cemented bands are common. Within the Ula Field, the formation can be subdivided into a number of large scale upward fining and coarsening units. The sandstones are extensively bioturbated throughout. The sands of the Ula Formation are generally shallow marine in origin although the type of marine environment probably varies from area to area (Vollset and Doré 1984, Stewart 1993).

Depth

In the type well (7/12-2) the Ula Formation occurs at 3378-3531.5 m depth, while in the reference well (2/1-2) it occurs at 3316-3346.5 m depth (Vollset and Doré 1984).

Thickness

The thickness of the Ula Formation is 152 m in the type well and 30.5 m in the reference well (Vollset and Doré 1984).

Percent shale

From well logs published by Vollset and Doré (1984) it is estimated that the Ula Formation consists of approximately 80% sandstone and 20% shale.

Top seal

The Ula Formation interfingers with/is overlain by the Farsund and Mandal Formations (Fig. 9a), which are dominated by claystone but also contain frequent silty, sandy and calcareous horizons. In the axial regions of the Central Graben these formations are several hundred metres thick. Over intrabasinal highs and the Southern Vestland Arch the seal is only a few metres thick (Vollset and Doré 1984).

Hydrocarbon production

There is/has been hydrocarbon production from the Ula Formation at the Gyda, Mime and Ula Fields.

CO_2 storage quality and capacity

The Ula Formation has moderate storage quality with respect to porosity, permeability and mineralogy, and is well sealed by shales. It occurs at relatively great depths, and may thus not be among the best candidates for CO_2 storage. Generally, the Skagerrak, Gassum, Bryne, Sandnes and Ula Formations can be regarded as one aquifer, sealed by Upper Jurassic shales.

It is estimated that the Ula Formation has a pore volume of 32 km^3, a storage capacity in traps of 26 Mt CO_2, and that the storage capacity of the entire aquifer is 448 Mt CO_2 (Table 6).

6.1.22 Hugin Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Early Bathonian to Early Oxfordian Hugin Formation (Fig. 9b) of the Vestlandet Group is found in the Southern Viking Graben, north of the Jæren High (Fig. 4). The formation consists of light brown to yellow, very fine to medium grained sandstones. Occasional coarse grained layers are found. The sandstones have fair sorting, and the grains are subangular to subrounded. Shale and siltstone partings are common. Carbonaceous material and coal fragments are abundant. Occasional thin coal beds can be observed. The sandstones are often bioturbated, but cross-bedding can sometimes be observed. The sandstones are often calcareous and glauconitic. The Hugin Formation represents near shore, shallow marine sandstones with the occasional influence of continental fluviodeltaic conditions (Vollset and Doré 1984). These sediments were deposited during the northward progradation of the Vestland deltaic system (to ca. 60º30'N) in the Early Bathonian, and the following retreat of the delta, which started in Middle Bathonian times (Fjellanger et al. 1996).

Depth

In the type well (15/9-2) the Hugin Formation occurs at 3483-3657 m depth, while in the reference well (15/6-5) it occurs at 3627-3679 m depth (Vollset and Doré 1984).

Thickness

The thickness of the Hugin Formation is 174 m in the type well and 52 m in the reference well (Vollset and Doré 1984). Thickness variations are partly due to synsedimentary faulting.

Percent shale

From well logs published by Vollset and Doré (1984) it is estimated that the Hugin Formation consists of approximately 80% sandstone and 20% shale.

Top seal

The Hugin Formation is overlain by the Heather Formation (Fig. 9b), which mainly consists of silty claystone with thin streaks of limestone. The Heather Formation is highly variable in thickness, but may reach more than 1000 m in graben areas (Vollset and Doré 1984). It can be recognized over most of the northern North Sea north of 58ºN and east of the East Shetland Platform boundary faults.

Hydrocarbon production

In the Norwegin North Sea, there is hydocarbon production from the Hugin Formation at the Sleipner Field (Brennand et al. 1998).

CO_2 storage quality and capacity

The Hugin Formation comprises alternating intervals of good reservoir sands (delta front/upper shoreface/shore) and micaceous sands and silts (prodelta/lower-middle shoreface). With regard to porosity and permeability, the formation is well suited for CO_2 storage. Along the axis of the Viking Graben, the formation probably occurs at too great depths for storage. The Sleipner and Hugin Formations can be regarded as one aquifer.

It is estimated that the Hugin Formation has a pore volume of 192 km^3, a storage capacity in traps of 161 Mt CO_2, and that the storage capacity of the entire aquifer is 2688 Mt CO_2 (Table 6).

6.1.23 Sleipner Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Bajocian to Bathonian (locally as young as Callovian) Sleipner Formation (Fig. 9b) of the Vestlandet Group is found in the Southern Viking Graben (Fig. 4) between approximately 58ºN and 60ºN (Vollset and Doré 1984). The Ness Formation is broadly equivalent to the Sleipner Formation. The formation consists of a mixed sandstone and silty claystone lithology with coal measures. The sandstones are non-calcareous, light to medium brown, fine to medium grained, with occasional coarse and pebbly layers. The sandstones show a moderate to poor sorting with sub-angular to sub-rounded grains. The silty claystones are medium to dark grey or greyish brown, micromicaceous, hard and slighly fissile. Coal fragments, fossil leaves and root hairs are commonly found. The coals are mature, black and massive, often with thin laminations of silty claystone. The Sleipner Formation represents a continental, fluviodeltaic coaly sequence. These sediments were deposited during the northward progradation of the Vestland deltaic system (Fjellanger et al. 1996).

Depth

In the type well (15/9-2) the Sleipner Formation occurs at 3657-3699 m depth, while in the reference well (15/12-1) it occurs at 3152-3204 m depth (Vollset and Doré 1984).

Thickness

The thickness of the Sleipner Formation is 42 m in the type well and 52 m in the reference well (Vollset and Doré 1984). Thickness variations are partly due to synsedimentary faulting.

Percent shale and coal

From well logs published by Vollset and Doré (1984) it is estimated that the Sleipner Formation consists of approximately 50% sandstone and 50% claystone and coal.

Top seal

The Sleipner and Hugin Formations can be regarded as one aquifer. The Sleipner Formation is overlain by sandstones of the Hugin Formation or directly by the Heather Formation, which also overlies the Hugin Formation (Fig. 9b, Vollset and Doré 1984). The Heather Formation consists mainly of silty claystone with thin streaks of limestone. It is highly variable in thickness, but may reach more than 1000 m in graben areas. The Hugin Formation is found in the Southern Viking Graben, north of the Jæren High (Vollset and Doré 1984). The Heather Formation can be recognized over most of the northern North Sea north of 58ºN and east of the East Shetland Platform boundary faults.

Hydrocarbon production

In the Norwegin North Sea, there is no hydocarbon production from the Sleipner Formation (Brennand et al. 1998).

CO_2 storage quality and capacity

The Sleipner Formation comprises alternating intervals of good reservoir sands, claystone and coal, deposited in a fluviodeltacic system. With regard to mineralogy, porosity and permeability, the sandstones of the formation are well suited for CO_2 storage. Along the axis of the Viking Graben, the formation probably occurs at too great depths for storage.

It is estimated that the Sleipner Formation has a pore volume of 48 km^3, a storage capacity in traps of 40 Mt CO_2, and that the storage capacity of the entire aquifer is 672 Mt CO_2 (Table 6).

6.1.24 Sandnes Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Callovian Sandnes Formation (Fig. 9a) of the Vestlandet Group is developed in the Fiskebank Sub-Basin and in the Egersund Sub-Basin (Fig. 4, Vollset and Doré 1984). It is broadly comparable in lithofacies and partly in age with the Hugin Formation in the southern Viking Graben, the Ula Formation in the Central Trough and the Flyvbjerg Member of the Haldager Formation in the Danish Sub-Basin. In the type well, the Sandnes Formation consists of a massive white, very fine to coarse-grained glauconitic sandstone. It is firm to friable, poorly sorted and slightly silty. In other wells the formation comprises interbedded sandstones and shales. The shales are generally dark grey to brown, micaceous and occasionally carbonaceous. The Sandsnes Formation was deposited in a coastal/shallow marine environment.

Depth

In the type well (9/4-3) the Sandsnes Formation occurs at 2490-2507.5 m depth, while in the reference well (18/11-1) it occurs at 1878-1964 m depth (Vollset and Doré 1984).

Thickness

The thickness of the Sandnes Formation is 17.5 m in the type well and 86 m in the reference well (Vollset and Doré 1984).

Percent shale

From well logs in Vollset and Doré (1984) it is estimated that the Sandnes Formation consists of approximately 70% sandstone and 30% shale.

Top seal

The Sandnes Formation is overlain by siltstones and shales of the two lowest formations (Egersund and Tau Formations) of the Boknafjord Group (Fig. 9a, Vollset and Doré 1984). In the centres of the Fiskebank and Egersund Sub-Basins the thickness of the Boknafjorden Group is several hundred metres, but it thins considerable towards the basin margins. The Boknafjord Group is confined to the Fiskebank and Egersund Sub-Basins, although the upper formations extend further westward than those lying below (Vollset and Doré 1984).

Hydrocarbon production

There is no hydocarbon production from the Sandnes Formation (Brennand et al. 1998).

CO_2 storage quality and capacity

The Sandnes Formation comprises alternating intervals of sandstones and shales. With regard to porosity, permeability and depth, the sandstones of the formation are probably well suited for CO_2 storage. Generally, the Skagerrak, Gassum, Bryne, Sandnes and Ula Formations can be regarded as one aquifer, sealed by Upper Jurassic shales.

It is estimated that the Sandnes Formation has a pore volume of 140 km^3, a storage capacity in traps of 117 Mt CO_2, and that the storage capacity of the entire aquifer is 1960 Mt CO_2 (Table 6).

6.1.25 Bryne Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Bajocian to Bathonian (locally older in the Norwegian-Danish Basin) Bryne Formation (Fig. 9a) of the Vestlandet Group is present in the Norwegian-Danish Basin and in the Central Graben (Vollset and Doré 1984). The Bryne Formation is equivalent to the Haldager Sand Member of the Haldager Formation in Denmark, and also equivalent in age and lithofacies to the Sleipner Formation of the Southern Viking Graben. The Bryne Formation comprises interbedded sandstones, siltstones, shales and coals. The sandstones are white to grey, very fine to coarse grained, poorly sorted, friable to hard and occasionally kaolinitic. The shales are generally grey to brown, micacous, occasionally silty, non-calcareous and often carbonaceous. The Bryne Formation was deposited in a fluvial/continental environment.

Depth

In the type well (9/4-3) the Bryne Formation occurs at 2507.5-2613 m depth, while in the reference well (8/12-1) it occurs at 2710.5-2813 m depth (Vollset and Doré 1984).

Thickness

The thickness of the Bryne Formation is 105.5 m in the type well and 102.5 m in the reference well (Vollset and Doré 1984). It shows local variations in thickness which probably reflect both Middle Jurassic syndepositional structuring and later erosion. Two main Middle Jurassic depocentres are recognized; one in the Danish Sub-Basin and another in the Fiskebank-Sub-Basin.

Percent shale and coal

From well logs published by Vollset and Doré (1984) it is estimated that the Bryne Formation consists of approximately 50% sandstone and 50% siltstone, shale and coal.

Top seal

Generally, the Skagerrak, Gassum, Bryne, Sandnes and Ula Formations can be regarded as one aquifer, sealed by Upper Jurassic shales. The Bryne Formation is overlain by shales and siltstones of the Boknafjord and Tyne Groups, or by predominantly sandstones of the Sandnes (Norwegian Danish Basin) and Ula Formations (around the eastern flanking highs of the Central Graben) (Fig. 9a, Vollset and Doré 1984). The Sandnes and Ula Formations are again overlain by the Boknafjord and Tyne Groups, respectively. The thickness of the latter vary from a few metres above some highs to several hundred metres in the graben or basin areas. The Boknafjord Group is confined to the Fiskebank and Egersund Sub-Basins, although the upper formations extend further westward than those lying below (Vollset and Doré 1984). The Tyne Group is distributed throughout the Central Graben and over the Southern Vestland Arch. It passes northwards (in the Viking Graben) into the Viking Group. Due to the overall transgressive nature of the unit the higher formations of the group are more widely distributed.

Hydrocarbon production

In the Norwegian sector, there is no hydrocarbon production from the Bryne Formation.

CO_2 storage quality and capacity

The Bryne Formation comprises interbedded sandstones, siltstones, shales and coals. With regard to porosity, permeability and depth, the sandstones of the formation are probably suited for CO_2 storage, especially in the Norwegian-Danish Basin.

It is estimated that the Bryne Formation has a pore volume of 210 km^3, a storage capacity in traps of 176 Mt CO_2, and that the storage capacity of the entire aquifer is 2940 Mt CO_2 (Table 6). The storage capacity of the entire aquifer is probably a conservative estimate (see Table 6).

6.1.26 Brent Group

General setting (age, distribution, correlations, lithology, depositional environment)

The Bajocian to Early Bathonian (including Late Toarchian to the east) Brent Group (Fig. 9c) is recognizable over most of the East Shetland Basin, Northern Viking Graben and the northern part of the Horda Platform (Fig. 4, Fjellanger et al. 1996). It passes southwards into the Vestland Group, south of the Frigg Field. Northwards, the Brent Group shales out within the East Shetland Basin, between 61º30'N and 62ºN. The Group is divided into five formations. These are: the Broom (base), Rannoch, Etive, Ness and Tarbert (top) Formations. The Oseberg Formation is considered to be a Broom Formation time equivalent (Fjellanger et al. 1996). All formations are recognizable in the Brent-Statfjord area, but moving away from the type area, formations may be absent. The upper boundary of the Brent Group may vary in nature due to post-middle Jurassic tectonism and erosion. Variable amounts of the group may be missing, particularly towards the crests of tilted fault blocks.

The Group consists of grey to brown sandstones, siltstones and shales with subordinate coal beds and conglomerates. In the type well, the Broom Formation is a pale grey to brown, coarse-grained sandstone containing shale clasts. The Rannoch Formation is a light brown, fine-grained, well sorted, friable, very micaceous sandstone. The Etive Formation consists of massive grey-brown to clear, fine to coarse, occasionally pebbly and cross-bedded sandstones. The Ness Formation consists of an association of coals, shales, siltstones and very fine to medium grained sandstones. The formation is carbonaceous throughout and contains numerous rootlet horizons. Small scale cross-bedding and horizontal bedding are common. Synsedimentary deformation is frequently observed. Shales within the formation are silty, fissile and frequently pyritic. Coarsening and fining upward sequences are common features. In the type well section, the Tarbert Formation consists of grey to brown relatively massive fine to medium grained sandstone with subordinate thin siltstone, shale and coal beds and some calcareous bands.

The Broom Formation is a shallow marine deposit, and is a precursor of the regression which characterizes the overlying Rannoch Formation, which is generally interpreted as delta front sheet sands and/or prograding shoreface sands (Vollset and Doré 1984). The Etive Formation has been interpreted as upper shoreface, barrier bar, mouth bar and distributary channel deposits. The Ness Formation is thought to represent delta plain or coastal plain deposits, while the Tarbert Formation was deposited in a marginal marine environment. The phases of lowstand, progradation, aggradation, retrogradation and drowning of the Brent deltaic system has been described by Fjellanger et al. (1996).

Depth

In the type well (UK well 211/29-3) and reference wells (33/9-1, 30/6-7 and 31/4-4) the formations of the Brent Group occur at depths between 2464 m and 2879 m (Vollset and Doré 1984). The depth to the Brent Group varies from a few hundred metres to more than 5000 m, in the Viking Graben (Fjellanger et al. 1996).

Thickness

The thickness of the group varies from zero to more than 400 m, in the Viking Graben (Fjellanger et al. 1996). In UK well 211/29-3 (Brent Field) it is 226.5 m, while the Norwegian well 33/9-1, in the Statfjord Field, has 204 m of Brent Group sediments (Vollset and Doré 1984). Wells used to illustrate the group on and around the Horda Platform have thicknesses between 159 m (30/6-7) and 78 m (31/4-4). Thicknesses of 200 m or more are present to the north in quadrant 35.

The thickness of the Broom Formation is 11 m in the type well and 4 m in the reference well (Vollset and Doré 1984). In the Brent-Statfjord area it varies from a few metres to about fifteen meters in thickness. The thickness of the Rannoch Formation is 35 m in the type well and 62 m in the reference well. The thickness of the Etive Formation is 11 m in the type well and 27 m, 59 m and 37 m in the reference wells. The thickness of the Ness Formation is 138.5 m in the type well and 66 m, 81 m and 26 m in the reference wells, while the thickness of the Tarbert Formation is 31 m in the type well and 45 m, 15 m and 14 m in the reference wells (Vollset and Doré 1984).

Percent shale and coal

From well logs published by Vollset and Doré (1984) it is estimated that the Brent Group consists of approximately 75% sandstone, siltstone and conglomerate and 25% shale and coal.

Top seal

The upper boundary of the Brent Group may vary in nature due to post-middle Jurassic tectonism and erosion. In the Tampen Spur and Northern Viking Graben, the Brent Group is overlain by up to 1000 m of shales of the Heather Formation, which can be recognized over most of the northern North Sea north of 58ºN and east of the East Shetland Platform boundary faults (Fig. 9c, Vollset and Doré 1984). In the Troll Field area, on the Horda Platform, the Brent Group may be directly overlain by sandstones of the Krossfjord and Fensfjord Formations (Stewart et al. 1995), and these formations, along with the Sognefjord Formation and the Brent Group can be regarded as one aquifer.

Hydrocarbon production

The Brent Group is the major reservoir interval for many of the major hydrocarbon fields in the Northern North Sea, both in the Norwegian sector and the British sector (Brennand et al. 1998).

CO_2 storage quality and capacity

The Brent Group comprises interbedded sandstones, siltstones, shales and coals. With regard to porosity, permeability and depth (except in the deep parts of the Viking Graben), the sandstones of the group are well suited for CO_2 storage. However, in many areas there may be major conflicts of use (hydrocarbon exploitation). On the eastern part of the Horda Platform, the Brent Group and the overlying Krossfjord, Fensfjord and Sognefjord Formations may be regarded as one aquifer.

It is estimated that the Brent Group has a pore volume of 630 km^3, a storage capacity in traps of 560 Mt CO_2, and that the storage capacity of the entire aquifer is 9349 Mt CO_2 (Table 6).

6.1.27 Cook Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Pliensbachian to Toarchian Cook Formation (Fig. 9c) of the Dunlin Group is present throughout the East Shetland Basin and on the northern part of the Horda Platform (Fig. 4, Vollset and Doré 1984). In the UK type well section, the formation is dominantly a marine siltstone with minor grey, silty claystone intercalations. The siltstones and claystones may contain sandy streaks, becoming more prominent away from the type well, especially in Norwegian waters. On the Horda Platform and along its western margin, sandstone is the dominant lithology in the formation. The sands are white to greyish brown, very fine to fine grained, subangular to subrounded and well sorted. Occasionally thin layers of medium to coarse grained sandstones are found. The sandstones are hard to friable. Silica is the most common cement. Mica, glauconite, carbonaceous material and calcareous cement may be present.

The sandstones can be divided into three types, related to depositional environment and basin geometry (Vollset and Doré 1984). In the Statfjord Field area the sandstones are belived to represent marine shoal sands. On the Horda Platform and along its western margin the sandstones represent prograding shelf sands and several cycles can be recognized within the formation. In the graben area, the sands are thinner bedded, and the shale intercalations show no gradations into the sands. These sandstones are belived to represent redeposited sands from the edge of the shelf (the Horda Platform and the East Shetland Basin west of the graben area). The formation is devided into Cook A, B and C, of which the Cook A and C units are interpreted as prograding, shallow marine sandbodies, separated by a transgressive mudstone in areas where it has not been eroded by incision of the Cook C unit (Underhill 1998).

Depth

In the type well (UK well 211/29-3) the Cook Formation occurs at 2887-2950.5 m depth, while in the reference wells it occurs at 2715-2801 m (33/9-1), 2975-3023 m (30/6-7), 2093-2134 m (31/2-1) and 4735-4801 m (30/-7) depths (Vollset and Doré 1984).

Thickness

The thickness of the Cook Formation is 63.5 m in the type well and 86 m, 66 m, 48 m and 41 m in the reference wells (Vollset and Doré 1984).

Percent shale

From well logs published by Vollset and Doré (1984) it is estimated that the Cook Formation, in the Norwegian North Sea, consists of approximately 50% sandstone and 50% siltstone and shale.

Top seal

The Cook Formation is overlain by the Drake Formation (Fig. 9c), which consists of claystone and shale and which is widely distributed throughout the East Shetland Basin and northern Horda Platform. On the Horda Platform, sandstones are found within the Drake Formation (Vollset and Doré 1984) and it is not known if there is a tight seal immediately above the Cook Formation everywhere. The thickness of the Drake Formation varies from 19 m to 189 m in the type and reference wells.

Hydrocarbon production

In the Norwegian sector of the North Sea, there is hydrocarbon production from the Cook Formation at the Statfjord Field (Brennand et al. 1998).

CO_2 storage quality and capacity

The dominant lithology of the Cook Formation, on the Horda Platform, is sandstone. With regard to porosity, permeability, depth and top seal, the sandstones of the Cook Formation, in this area, are probably well suited for CO_2 storage. The Cook Formation and the underlying Johansen Formation may be regarded as one aquifer.

It is estimated that the Cook Formation has a pore volume of 105 km^3, a storage capacity in traps of 94 Mt CO_2, and that the storage capacity of the entire aquifer is 1572 Mt CO_2 (Table 6).

6.1.28 Johansen Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Sinemurian to Pliensbachian Johansen Formation (Fig. 9c) of the Dunlin Group is restricted to an area extending from the eastern part of the Horda Platform northwards to the Måløy fault blocks (Fig. 4, Vollset and Doré 1984). In the type well, the formation consists of a sequence of sandstones with thin calcite cemented streaks throughout. The lower part is a medium to fine-grained, micacous, well-sorted sandstone which grades downwards into light grey, silty, micaceous claystone. The main section of the formation is composed of medium grained, friable sandstones, with angular to subrounded, well sorted quartz grains. The uppermost part is composed of medium to fine-grained, micacous sandstones, which are moderately sorted, silty and argillaceous. The sandstones form a clastic wedge consisting mainly of fining-up, sharp-based nearshore and inner-shelf deposits, but there is a suggestion that more brackish water and alluvial environments existed in the eastern areas (Underhill 1998).

Depth

In the type well (31/2-1) the Johansen Formation occurs at 2176-2272.5 m depth (Vollset and Doré 1984).

Thickness

The thickness of the Johansen Formation is 95.5 m in the type well (Vollset and Doré 1984).

Percent shale

From a well log published by Vollset and Doré (1984) it is estimated that the Johansen Formation consists of approximately 80% sandstone and 20% claystone.

Top seal

In the type well area, the Johansen Formation splits the Amundsen Formation (Fig. 9c), which consists of siltstones and shales, but which also contains sandstone beds in the marginal areas of the basin (Vollset and Doré 1984). Where the Amundsen Formation is not present above the Johansen Formation (in the east) the latter may be directly overlain by the Cook

Formation, which on the Horda Platform consists of sandstones, and the Johansen Formation and the Cook Formation may be regarded as one aquifer. The Cook Formation is overlain by the Drake Formation (Fig. 9c), which consists of claystone and shale and which is widely distributed throughout the East Shetland Basin and northern Horda Platform. On the Horda Platform, sandstones are found within the Drake Formation (Vollset and Doré 1984).

Hydrocarbon production

There is no hydrocarbon production from the Johansen Formation.

CO_2 storage quality and capacity

The dominant lithology of the Johansen Formation is sandstone. With regard to porosity, permeability and depth, the formation is probably suited for CO_2 storage.

It is estimated that the Johansen Formation has a pore volume of 80 km^3, a storage capacity in traps of 67 Mt CO_2, and that the storage capacity of the entire aquifer is 1120 Mt CO_2 (Table 6).

6.1.29 Statfjord Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Rhaetian to Sinemurian Statfjord Formation (Fig. 9c) can be recognized in the entire area between the East Shetland Platform to the west and the bounding fault zone of the Fennoscandian Shield to the east (Fig. 4). The formation is identified in the Viking Graben as far south as Norwegian blocks 25/8 and 25/11 (Vollset and Doré 1984). The Statfjord Formation was divided in the type well area (Statfjord Field and west of the Viking Graben) into three members; the Raude Member (base), the Eiriksson Member and the Nansen Member (top) (Deegan and Scull 1977). In the British sector, the Nansen has now been raised to formation status (Underhill 1998).

The Statfjord Formation exhibits a transition from continental to shallow marine sediments (Vollset and Doré 1984). In the type well area, it is a transitional coarsening upward sequence in the basal parts (Raude Member, ca. 60 m thick) consisting of grey, green and sometimes red shale interbedded with thin siltstones, sandstones and dolomitic limestones (Fisher and Mudge 1998). Above are massive white to grey sandstone bodies interbedded with greenish-grey to red-brown shales (Eiriksson Member). The Eiriksson Member is overlain by thick, white to grey, fossiliferous and glauconitic sandstones (Nansen Member). On the Horda Platform, east of the Viking Graben, the Statfjord Formation consists of massive, white, fine to coarse grained sandstones interbedded with light grey, and sometimes red, silty micaceous, lignitic shales. Towards the east the frequency of black, coaly shales and coal layers increases.

The lower transitional unit in the type well area appears to represent an upward passage from the dominantly continental deposits of the Lunde Formation of the Hegre Group to lower alluvial plain and braided stream deposits which make up most of the Statfjord Formation (Vollset and Doré 1984, Underhill 1998). Towards the top of the formation coarse sandstones with pebble beds, crossbedding and channel structures appear to have been deposited in a coastal environment. Sandstones of the overlying Nansen Member/Formation are interpreted as a time-transgressive shallow-marine deposit that records the retreat and local ravinement of the Statfjord alluvial system.

Depth

In the type well (33/12-2) the Statfjord Formation occurs at 2700-2951 m depth, while in the reference wells it occurs at 3112-3434 m (UK well 211/24-1), 2712-3003 m (30/6-1) and 3652-3847 m (25/2-5) depths (Vollset and Doré 1984).

Permeability

Permeabilities of the Statfjord sandstones at the type locality average 470 mD at depths in excess of 2.5 km (Underhill 1998), and 300-2000 mD in the Brent Field (Johnson and Fisher 1998).

Thickness

The thickness of the Statfjord Formation is 251 m in the type well and 322 m, 291 m and 195 m in the reference wells (Vollset and Doré 1984). The formation is thinner on the crest of fault blocks and thicker on the downthrown side. It attains its fullest development in the central part of the Viking Graben. To the east, towards the bounding fault zone of the Fennoscandian Shield, the formation is reduced to tens of meters in thickness.

Percent shale

From well logs published by Vollset and Doré (1984) it is estimated that the Statfjord Formation consists of approximately 60% sandstone and and 40% shale, coal and limestone.

Top seal

The Statfjord Formation is overlain by several hundred metres of shales and siltstones of the Dunlin Group (Fig. 9c), which is recognizable over most of the East Shetland Basin and the northern part of the Horda Platform. The lowermost formation of the Dunlin Group (Amundsen Formation) is dominated by siltstones and shales, in part carbonaceous and pyritic. Thin sandstone beds are present in marginal areas. Variation in thickness on tilted fault blocks probably reflects syndepositional movements during deposition of the Dunlin Group.

Hydrocarbon production

The Statfjord Formation is the major reservoir interval for many of the major hydrocarbon fields in the Northern North Sea, both in the Norwegian sector and the British sector (Brennand et al. 1998).

Porosity

Porosities in the Statfjord sandstones of the type locality average 22% (Underhill 1998), and 20-24% in the Brent Field (Johnson and Fisher 1998).

CO_2 storage quality and capacity

The Statfjord Formation comprises interbedded sandstones, siltstones, shales, limestones (lower part) and coals (especially on the Horda Platform). With regard to porosity, permeability and depth (except in the deep parts of the Viking Graben), the sandstones of the formation are probably suited for CO_2 storage. The Statfjord Formation is well sealed by the Amundsen Formation, except where it is faulted. The Hegre Group and Statfjord/Nansen Formations can be regarded as one aquifer.

It is estimated that the Statfjord Formation has a pore volume of 550 km^3, a storage capacity in traps of 502 Mt CO_2, and that the storage capacity of the entire aquifer is 8371 Mt CO_2 (Table 6).

6.1.30 Gassum Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Rhaetian to Early Sinemurian Gassum Formation (Fig. 9a) is encountered in the Norwegian-Danish Basin and in the Skagerrak, and in several areas extends almost to the Norwegian coast, where it crops out at the sea bed (Figs. 1 and 4, Fisher and Mudge 1998). It is acknowledged that the Gassum and Statfjord Formations are part of the same suite of late Triassic to early Jurassic continental/paralic deposits and that there may have been depositional continuity between the two units (Vollset and Doré 1984). The connection may have been via the Stord Basin or southern Viking Graben. The term Gassum Formation should be restricted to the area south of the Ling Graben (Vollset and Doré 1984). In the Egersund Basin, the Gassum Formation comprises grey, fine to medium-grained sandstones with minor conglomerates interbedded with grey-brown silty shales and coals. This suggests that a system of large meandering rivers with an extensive flood plain replaced the previously braided ephemeral stream deposits of the Skagerrak Formation as a marine transgression entered the basin from the south (Jacobsson et al. 1980, Fisher and Mudge 1998).

Depth

Offshore southern Norway, the Gassum Formation probably extends to the sea bed. In the Norwegian-Danish Basin it generally occurs shallower than 3000 m, extending to more than 4000 m in the Central Trough. In the type well (Danish well Gassum no. 1) the Gassum Formation occurs at 1613-1643 m depth, while in the reference wells it occurs at 2682-2825 m (17/10-1) and 2601-2609 m (7/9-1) depths (Vollset and Doré 1984).

Thickness

It is estimated that the average thickness of the Gassum Formation is 70 m.

Percent shale

It is estimated that the Gassum Formation comprises 80% sandstone and 20% shale and coal.

Top seal

The Gassum Formation is overlain by the shale-dominated Fjerritslev Formation (Fig. 9a), which can be correlated in age, lithologhy and depositional environment with the Dunlin Formation of the Northern North Sea, north of the Ling Graben (Vollset and Doré 1984). Where the Fjerritslev Formation is absent due to erosion, the Gassum Formation is overlain by the Bryne Formation of the Vestland Group, which comprises interbedded sandstones, siltstones, shales and coals. The Fjerritslev Formation of the Norwegian-Danish Basin and the Southern Vestland Arch area is patchily distributed as a result of the mid-Jurassic erosional episode (Vollset and Doré 1984). Generally, the Skagerrak, Gassum, Bryne, Sandnes and Ula Formations can be regarded as one aquifer, sealed by Upper Jurassic shales.

Hydrocarbon production

In the Norwegian sector of the North Sea, there is no hydrocarbon production from the Gassum Formation.

CO_2 storage quality and capacity

The Gassum Formation comprises sandstones with interbedded shales and coals. With regard to depth, the sandstones of the formation are well suited for CO_2 storage. However, many

Triassic sandstone reservoirs in the Central North Sea show significant diagenetic deterioration, and the reservoir quality may be marginal to non-productive. Sandstones are typically highly feldspathic, fine-grained and tightly cemented (Johnson and Fisher 1998). This implies that porosities and permeabilities are relatively low.

It is estimated that the Gassum Formation has a pore volume of 316 km^3, a storage capacity in traps of 264 Mt CO_2, and that the storage capacity of the entire aquifer is 4424 Mt CO_2 (Table 6).

6.1.31 Skagerrak Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Middle and Late Triassic Skagerrak Formation (Fig. 9a) is present throughout the eastern part of the Central North Sea and the western Skagerrak (Figs. 1 and 4, Deegan and Scull 1977, Fisher and Mudge 1998). It may be missing over certain structures because of erosion or halokinesis. Westward from the type well (10/8-1), the formation interfingers with and progrades over the associated claystone sequence (Smith Bank Formation). In the southern Central Trough, the Skagerrak Formation has been subdivided into three sandstone and three mudstone members (Fisher and Mudge 1998).

The formation consists of interbedded conglomerates, sandstones, siltstones and shales. Various shades of reds and browns are the dominant colours but light to dark grey beds are also present. Sandstones may be orthoquartzitic, arkosic or highly lithic. Anhydrite, dolomite and limestone are subordinate lithologies. The bulk of the Skagerrak Formation was probably deposited in a coalescing and prograding system of alluvial fans along the eastern and southern flanks of a structurally controlled basin. The limited areal extent and poorly preserved faunal components suggest that some of the dark shale, carbonate and anydrite beds were deposited in lakes. Better preserved microfossils and other indicators such as glauconite show that some beds were deposited when minor marine incursions occurred between floods of continental clastics. In the Egersund Basin, Jakobsen et al. (1980) interpreted the sedimentary succession to comprise tectonically induced, coarsening-upward cycles, dominated by ephemeral braided streams (Fisher and Mudge 1998).

Depth

In the type well (10/8-1), the Skagerrak Formation occurs at 1567-2749 m depth, while in the reference well (17/10-1) it occurs at 2684-3398 m depth (Deegan and Scull 1977). In the Norwegian-Danish Basin, it generally occurs shallower than 3000 m, extending to more than 4000 m in the Central Trough.

Thickness

The thickness of the Skagerrak Formation is 1182 m in the type well and 714 m in the reference well (Deegan and Scull 1977). In the western parts of the Skagerrak, the thickness of the formation is more than 3000 m. Westward from the type well (10/8-1), the formation interfingers with and progrades over the associated claystone sequence (Smith Bank Formation). The maximum thickness at the north-west limit of well control (Deegan and Scull 1977) is 660 m and at the south-west limit 250 m.

Percent shale

From well logs (Deegan and Scull 1977, Jakobsen et al. 1980) it is estimated that the Skagerrak Formation consists of approximately 70% sandstone and conglomerate and 30% siltstone, shale and sabkha deposits.

Top seal

The Skagerrak Formation is usually overlain unconformably by Jurassic or younger sediments (Deegan and Scull 1977). Most frequently, these belong to the Gassum or Bryne Formations, which comprise interbedded sandstones, siltstones, shales and coals, or the shaly Fjerritslev Formation (Fig. 9a). Generally, the Skagerrak, Gassum, Bryne, Sandnes and Ula Formations can be regarded as one aquifer, sealed by Upper Jurassic shales.

Hydrocarbon production

There is no hydrocarbon production from the Skagerrak Formation in the Norwegian sector of the North Sea.

CO_2 storage quality and capacity

The Skagerrak Formation comprises sandstones and conglomerates with interbedded siltstone, shale, anhydrite, dolomite and limestone. Considering depth, the formation is well suited for CO_2 storage, outside the Central Trough. However, many Triassic sandstone reservoirs in the Central North Sea show significant diagenetic deterioration, and the reservoir quality may be marginal to non-productive. Sandstones are typically highly feldspathic, fine-grained and tightly cemented (Johnson and Fisher 1998). This implies that porosities and permeabilities may be relatively low.

It is here estimated that the Skagerrak Formation has a pore volume of 6615 km^3. This is approximately 40% of the total pore volume calculated for the aquifers in the Norwegian North Sea (Table 6). However, the storage capacity of the Skagerrak Formation is not included in the total storage capacity because the permeability of these rocks is thought to be generally low.

6.1.32 Hegre Group

General setting (age, distribution, correlations, lithology, depositional environment)

The Early to Late Triassic Hegre Group (Fig. 9c) is apparently present in the whole Northern North Sea area north of 60ºN (Fig. 4, Vollset and Doré 1984). It is terminated to the west by major faults along the east flank of the East Shetland Platform and to the east by the Øygarden Fault Zone. In the northeastern part of the North Sea area, where Precambrian/Caledonian basement dips gently to the west, progressively younger Triassic sediments onlap basement in an easterly direction. In the east, on the Måløy fault blocks, Triassic strata are probably missing, but may have been preserved from erosion in N-S elongated basins to the east of the structural highs.

West of the Viking Graben, in the Tampen Spur area, the Hegre Group is divided into three formations; the (basal) Teist Formation, the Lomvi Formation and the Lunde Formation (top). A similar subdivision can possibly be used for the Horda Platform. The Teist and Lomvi Formations have been recognized in all deep wells between the Brent Field and the southern edge of the Møre Basin. The Lunde Formation is assumed to be present throughout the northern North Sea area, although major parts may be missing on structural highs owing to erosion or non-deposition.

The Hegre Group consists of intervals of interbedded sandstones, claystones and shales. Shales and claystones usually have reddish colours whereas the sandstones show a range in colour from white, light grey, orange to brick red. The grain size varies from very fine to coarse and the sediments are in parts of a pebbly nature. The Hegre Group also has subordinate white limestone, anhydrite and brownish-red marl. The Teist Formation consists of interbedded sandstone, claystone and marl. The sandstones are dominantly very fine to fine-grained, dark red brown and calcareous. In addition white and pink, medium to coarse sandstone is present in the upper levels of the succession. Red marl forms the main argillaceous lithology with green and dark grey claystone as subordinate constituents. The Lomvi Formation consists of fine to coarse-grained, brown, grey or white kalolinitic sandstone with subordinate and thin red marls and claystones. The Lunde Formation is an interbedded sequence of very fine to very coarse-grained sandstones (2-10 m thick), claystones, marls and shales (Vollset and Doré 1984, Fisher and Mudge 1998). The sandstones are mainly white, pink or grey and cemented to a variable degree by kaolinite, anhydrite and carbonate. The interbedded argillaceous units are dominantly red-brown claystones, siltstones and shales with thin limestones. Tuff horizons are present in the lower half of the formation in the Statfjord Field area, where the lowermost 300 m consist of brick red to brown red calcareous claystones grading to marls.

The Teist Formation is probably of continental origin, and the sandstones may include both fluvial and eolian depostis. The finer-grained lithologies are assigned to overbank and lacustrine environments. The Lomvi Formation most probably consists of fluvial deposits. The Lunde Formation is dominantly of continental origin, deposited in lacustrine and fluvial environments.

Depth

In the type well (33/12-5) , the Teist Formation occurs from 3867 m to total depth of 4573 m, while in the reference well (33/5-1), it occurs at 3298 m to total depth of 3829 m (Vollset and Doré 1984). In the type well (33/12-5), the Lomvi Formation occurs at 3747-3867 m depth, while in the reference well (33/5-1), it occurs at 3220-3298 m depth. In the type well (33/12-2), the Lunde Formation occurs at 2951-4048 m depth, while in the reference well (UK well 211/29-5), it occurs at 3003-4055 m depth (Deegan and Scull 1977).

Thickness

The thickness of the Hegre Group, within the East Shetland Basin, shows a general increase from the western flank towards the centre of the basin. On the eastern flank, thick Triassic deposits are found just west of the Øygarden Fault Zone. The maximum drilled sequence by 1984 was 1839 m (Vollset and Doré 1984). The maximum thickness of the Teist Formation is 706 m in the type well and 531 m in the reference well. For the Lomvi Formation, the thickness is 120 m in the type well and 78 m in the reference well, while for the Lunde Formation it is 1079 m in the type well and 1052 m in the reference well.

Percent shale

From well logs published by Vollset and Doré (1984) and Fisher and Mudge (1998) it is estimated that the Hegre Group consists of approximately 70% sandstone/siltstone and and 30% claystone, shale, limestone, anhydrite and marl.

Top seal

The Hegre Group is directly overlain by Cretaceous strata on some of the structural highs. Where Jurassic is present, the top of the Hegre Group is normally placed at the change from interbedded sandstones and shales of the Hegre Group to the relatively massive, clean sandstones of the Statfjord Formation (Fig. 9c). In addition, the upper boundary of the Hegre Group is often close to the top of abundant red beds in the section (Vollset and Doré 1984). The thickness of the Statfjord Formation is 251 m in the type well and 322 m, 291 m and 195 m in the reference wells (Vollset and Doré 1984). The formation is thinner on the crest of fault blocks and thicker on the downthrown side. It attains its fullest development in the central part of the Viking Graben. To the east, towards the bounding fault zone of the Fennoscandian Shield, the formation is reduced to tens of meters in thickness. The Hegre

Group and Statfjord Formation can be regarded as one aquifer, generally sealed by Lower Jurassic shales.

Hydrocarbon production

In the Norwegian sector of the North Sea, there is hydrocarbon production from the Hegre Group (Lunde Formation) at the Snorre and Visund Fields (Brennand et al. 1998).

CO_2 storage quality and capacity

The Hegre Group comprises sandstones, claystones and shales with subordinate anhydrite, limestone and marl. The formation comprises thick sandstone units that may possibly be suitable for CO_2 storage. With regard to depth, the formation is suited for storage on the Horda Platform, however, it probably has low porosities and permeabilities.

It is here estimated that the Hegre Group has a pore volume of 2205 km^3. This is almost 15% of the total pore volume calculated for the aquifers in the Norwegian North Sea (Table 6). However, the storage capacity of the Hegre Group is not included in the total revenue because the permeability of these rocks is thought to be generally low.

6.2 Norwegian Sea

Nine formations with a potential storage capacity for CO_2 are included in this inventory. Some units with sandstones are not included, either because they occur too far offshore/too deep, because they are not properly investigated/understood, or because they are not properly sealed. One of the units not included is the Santonian-Campanian Nise Formation of the Shetland Group (Fig. 6). This is extensively developed in the Vøring Basin, where it has very large sandstone thicknesses (Vergara et al. 2001). Neither are the Paleocene Egga Member (Våle Formation/lower Tang Formation) nor sandstones of the Ryazanian-Turonian Lange Formation included. These are present along the eastern Møre Basin Margin and have probably extensive sandstone developments in the Møre and Vøring Basins (Vergara et al. 2001). The informally named Molo formation (deltaic complex time equivalent with the Kai Formation, see below) is not included because it occurs too shallow and without a seal.

6.2.1 Naust Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Late Pliocene-Pleistocene Naust Formation (Fig. 6) of the Nordland Group is laterally continuous across the Mid-Norwegian shelf. The formation consists of interbedded claystone, siltstone and sand, occasionally with very coarse clastics in the upper part. The sand content in the Naust Formation varies locally, but there is no significant regional variation (Dalland et al. 1988). The formation was deposited in a predominantly marine/glaciomarine environment in a subsiding basin, characterised by major westerly prograding wedges. Thick debris flows and slide deposits occur in the succession, as well as contourites and other marine and glaciomarine deposits. In the uppermost part, moraine predominates.

Depth

In the type well (6507/12-1) the base of the Naust Formation is at 1342 m (Dalland et al. 1988). In several areas of the Møre and Vøring Basins the base of the formation is at ca. 2000 m.

Thickness

The Naust Formation is several hundred metres thick in the Haltenbanken-Trænabanken area (Dalland et al. 1988). The thickness increases from zero along the coast to a maximum of ca. 1500 m along the shelf break. An average thickness of 1000 m is estimated here.

Percent shale

From well logs published by Dalland et al. (1988) it is estimated that the Naust Formation consists of approximately 70% clay/claystone and 30% sand/sandstone.

Top seal

The Naust Formation occurs at the sea bed, without a top seal. Within the formation there may be tight reservoirs, but this has not been studied.

Hydrocarbon production

There is no hydrocarbon production from the Naust Formation.

CO_2 storage quality and capacity

The Naust Formation comprises interbedded claystone, siltstone and sand. It has a very large range and volume, and probably contains sands that would be well suited for CO_2 storage. However, the formation has no top seal, and it is presently regarded as poorly suited for CO_2 storage. It is estimated that the Naust Formation has a pore volume of 12 600 km^3, which is 73% of the total pore volume calculated for the aquifers in the Norwegian Sea (Table 7). However, because the formation has no top seal, and the quality and extent of individual sands within the formation are poorly known, the storage capacity of the formation is not included in the total revenue.

Table 7. Theoretical CO_2 storage potential in aquifers (0.8-4 km depth) in the Norwegian Sea off Mid Norway (62ºN-69º30'N)

Aquifer	Age	Range (km^2)	Average Thickness m	Net:Gross	Porosity %	Pore Volume (km^3)	Reservoir open (O) or closed (C)	Reservoir Density of CO_2 (kg/m^3)	Storage Capacity in Traps (Mt CO_2)	Storage Capacity of Entire Aquifer (Mt CO_2)
Naust[a]	Pliocene-Pleistocene	140 000	~1000	0.3	30	12 600	O	-	-	-
Kai[a]	Miocene-Pliocene	160 000	250	0.2	30	2 400	O	-	-	-
Lysing[b]	Late Cretaceous	5 000	50	0.8	25	50	C	700	42	700
Rogn[c]	Late Jurassic	2 000	50	0.8	30	24	C	700	20	336
Garn	Middle Jurassic	30 000	80	0.9	25	540	C	700	453	7 560[d]
Ile	Middle Jurassic	40 000	70	0.8	20	448	C	700	376	6 272[d]
Tilje	Early Jurassic	40 000	100	0.6	15	360	C	700	302	5 040[d]
Åre	L. Triassic-E. Jur.	40 000	400	0.3	15	720	C	700	604	10 080[d]
Total						**17 142**			**1 759**	**29 988**

The calculation of storage capacity in traps (excluding hydrocarbon fields) is based on the assumption that 4% of the pore volume can be filled with CO_2, and that 3% of the aquifer volume is in a trap. The estimate of storage capacity of entire aquifers is based on a storage efficiency of 6% for open aquifers and 2% for closed aquifers (see Holloway 1996).

[a] The presence of aquifers and tight cap rocks has not been documented, and storage capacities are thus not calculated
[b] The theoretical range of Cretaceous hydrocarbon plays/aquifers may be several times larger
[c] The theoretical range of Late Jurassic hydrocarbon plays/aquifers may be up to 7000 km^2
[d] The formations are open (subcrop) along the coast, and the storage capacities (entire aquifers) may be regarded as minimum values.

6.2.2 Kai Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Early Miocene to Late Pliocene Kai Formation (Fig. 6) of the Nordland Group is present throughout the Haltenbanken area (Fig. 1) apart from the crest of the Nordland Ridge. The formation consists of alternating claystone, siltstone and sandstone with limestone stringers. The sand content varies locally within the Kai Formation, but there is no significant regional variation (Dalland et al. 1988). The Kai Formation was deposited in marine environments with varying water depths in a rapidly subsiding basin characterised by major westerly prograding wedges (Dalland et al. 1988).

Depth

In the type well (6407/1-2), the Kai Formation occurs at 1690-1419 m depth (Dalland et al. 1988). In several areas of the Møre and Vøring Basins the base of the formation is at more than 2000 m.

Thickness

The thickness of the Kai Formation is 271 m in the type well (Dalland et al. 1988). An average thickness of 250 m is estimated here.

Percent shale

From well logs published by Dalland et al. (1988) it is estimated that the Kai Formation consists of approximately 80% clay/claystone and 20% sand/sandstone.

Top seal

The Kai Formation is overlain by the several hundred to thousand metres thick Naust Formation, which consists of alternating claystone, siltstone and sand (Fig. 6, Dalland et al. 1988).

Hydrocarbon production

There is no hydrocarbon production from the Kai Formation.

CO_2 storage quality and capacity

The Kai Formation comprises interbedded claystone, siltstone and sandstone. It has a very large volume, and probably contains sands that would be well suited for CO_2 storage.

However, the formation is generally poorly studied. It is probably heterogeneous, and due to the lack of a tight and extensive top seal, it is presently regarded as poorly suited for storage. It is estimated that the Kai Formation has a pore volume of 2400 km^3, which is 14% of the total pore volume calculated for the aquifers in the Norwegian Sea (Table 7). However, the presence of a tight and estensive top seal has not been documented, and the quality and extent of individual sands within the formation are poorly known. The storage capacity of the Kai Formation is thus not included in the total revenue.

6.2.3 Lysing Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Late Cenomanian to Turonian/Coniacian Lysing Formation (Fig. 6) of the Cromer Knoll Group is widely distributed over the Halten Terrace (Fig. 3), but is absent on the Trøndelag Platform (Dalland et al. 1988, Vergara et al. 2001). It thins to the south and north of the type well. Koch and Heum (1995) have shown that the formation is especially thick and continuous in the Grinna Graben, and probably on the northwestern part of the Halten Terrace and on the Dønna Terrace. The formation predominantly consists of fine to medium, occasionally coarse-grained, white-grey sandstones, partly carbonate-cemented and interbedded with shales (Dalland et al. 1988). The formation was deposited in a marine environment as submarine fans, with the sandstones representing turbidites (Koch and Heum 1995).

Depth

In the type well (6507/7-1) the Lysing Formation occurs at 3000-2926 m depth, while in the reference well (6506/12-4) it occurs at 3150-3132.5 m depth (Dalland et al. 1988).

Thickness

The thickness of the Lysing Formation is 74 m in the type well and 17.5 m in the reference well (Dalland et al. 1988). An average thickness of 50 m is estimated here.

Net sand thickness

The net sand thickness in the type well is 60 m (Koch and Heum 1995).

Percent shale

From well logs published by Dalland et al. (1988) it is estimated that the Lysing Formation consists of approximately 80% sandstone and 20% shale. Koch and Heum (1995) has shown a net/gross ratio of 0.83 in the type well.

Top seal

The Lysing Formation is overlain by almost 1000 m of claystones interbedded with minor amounts of carbonates and sandstones of the Shetland Group (Fig. 6, Dalland et al. 1988).

Hydrocarbon production

There is hydrocarbon production from the Lysing Formation at the Åsgard (Smørbukk Sør) Field (Koch and Heum 1995).

CO_2 storage quality and capacity

The Lysing Formation comprises sandstones interbedded with thinner shales. With regard to depth, top seal, porosity, permeability and mineralogy it is probably well suited for CO_2 storage. However, sandstones occur as separated submarine fan deposits in an area far offshore, and the formation may thus not be very well suited for storage.

It is here estimated that the Lysing Formation has a pore volume of 50 km^3, a theoretical storage capacity in traps of 42 Mt CO_2, and that the theoretical storage capacity of the entire aquifer is 700 Mt CO_2 (Table 7).

6.2.4 Rogn Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Oxfordian to Kimmeridgian Rogn Formation (Fig. 6) of the Viking Group is mainly developed in the Draugen Field area and along the eastern margin of the Frøya High (Fig. 3, Dalland et al. 1988, Koch and Heum 1995). It occurs in several separate areas, to the east of the highs in the Haltenbanken area (Koch and Heum 1995). The formation shows a coarsening upward sequence from siltstones and shales to sandstones which constitute the bulk of the unit. The formation's sandstones are interpreted as shallow marine offshore bars and shoreline deposits. Similar Rogn Formation sandstones are found along the eastern margins of the Sklinna High and the Nordland Ridge (Koch and Heum 1995).

Depth

In the type well (6407/9-1), the Rogn Formation occurs at 1670-1621 m depth (Dalland et al. 1988). East of the Frøya High and south of the Nordland Ridge, it occurs around 2 km depth, while east of the Sklinna High, it occurs at depths down to 4-5 km (Koch and Heum 1995).

Thickness

The thickness of the Rogn Formation is 49 m in the type well (Dalland et al. 1988). An average thickness of 50 m is estimated here.

Percent shale

From well logs published by Dalland et al. (1988) it is estimated that the formation consists of approximately 80% sandstone and 20% shale.

Top seal

The Rogn Formation is developed within the Spekk Formation, which consists of shale (Fig. 6, Dalland et al. 1988, Koch and Heum 1995). The Rogn Formation is overlain by several hundred metres of shale and claystone, and is thus well sealed.

Hydrocarbon production

There is hydrocarbon production from the Rogn Formation at the Draugen Field (Koch and Heum 1995).

CO_2 storage quality and capacity

The Rogn Formation comprises mainly sandstones, with siltstones and shales near the base. Considering depth, top seal, porosity, permeability and mineralogy it is probably well suited for CO_2 storage. However, it has a small storage capacity, and there is oil production from the formation at the Draugen Field. This might cause conflicts of use.

It is estimated that the Rogn Formation has a pore volume of 24 km^3, a theoretical storage capacity in traps of 20 Mt CO_2, and that the theoretical storage capacity of the entire aquifer is 336 Mt CO_2 (Table 7).

6.2.5 Garn Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Bajocian to Bathonian Garn Formation (Fig. 6) of the Fangst Group is encountered across most of Haltenbanken (Figs. 1 and 3). It may be over 100 m thick on the Halten Terrace, but in structurally high positions the entire unit may be eroded. Time-eqivalent sandstone-dominated sequences subcrop on the sea-floor along the inner part of the Trøndelag Platform (Bugge et al. 1984), and outliers of Middle Jurassic sediments are present in the Frohavet Basin (Bøe 1991) and in the Beitstadfjord Basin (Bøe and Bjerkli 1989). The latter probably represent a continental facies eqivalent of the predominantly marine Fangs Group. Along the southern margin of the Nordland Ridge (e.g. the Heidrun Field) the succession is much thinner than on the Halten Terrace. In the Trænabanken area, shaly sediments are lateral equivalents of the Garn Formation sandstones (Dalland et al. 1988). The formation is time eqivalent to parts of the Brent Group in the North Sea and to the upper part of the Stø Formation in the Hammerfest Basin.

The Garn Formation consists of medium to coarse-grained, moderately to well-sorted sandstones. Mica-rich zones are present. The sandstone is occasionally carbonate-cemented. The formation may represent progradations of braided delta lobes. Delta top and delta front facies with active fluvial and wave-influenced processes are recognized (Dalland et al. 1988).

Depth

In the type well (6407/1-3), the Garn Formation occurs at 3704-3600 m depth, while in the reference well (6507/11-3)it occurs at 2457-2412 m depth (Dalland et al. 1988). Time-eqivalent sandstone-dominated sequences subcrop on the sea-floor along the inner part of the Trøndelag Platform (Bugge et al. 1984), and shallow outliers of Middle Jurassic sediments are present in the Frohavet Basin (Bøe 1991) and in the Beitstadfjord Basin (Bøe and Bjerkli 1989) (Fig. 3). On the Trøndelag Platform, the Garn Formation generally occurs shallower than 3 km.

Permeability

The Garn Formation has excellent primary reservoir quality which, however, decreases with depth due to quartz cementation and illitization. The illitization is reducing the permeability of the Garn Formation drastically when it is buried deeper than 3600 m below sea level, and the formation is practically impermeable when buried below 4200 m. The permeability is better than 1000 millidarcies at less than 3000 m depth (Koch and Heum 1995).

Thickness

The thickness of the Garn Formation is 104 m in the type well and 45 m in the reference well (Dalland et al. 1988). Along the southern margin of the Nordland Ridge (e.g. the Heidrun Field), the succession is much thinner than on the Halten Terrace. An average thickness of 80 m is estimated here.

Percent shale

From well logs in Dalland et al. (1988) it is estimated that the Garn Formation consists of approximately 90% sandstone and 10% shale. At depths shallower than ca. 3000 m, the net/gross ratio is generally >0.9, while there is a drastic reduction below ca. 3600 m (Koch and Heum 1995).

Top seal

The Garn Formation is overlain by the Viking Group, which is totally dominated by shales and mudstones (Fig. 6, Dalland et al. 1988). The Viking Group is up to 1000 m thick. The Viking Group is present in most wells on Haltenbanken and Trænabanken, but with only a thin partial development on the Nordland Ridge (Dalland et al. 1988). 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, Aarhus et al. 1986).

Hydrocarbon production

There is hydrocarbons in the Garn Formation in several fields, e.g. at Heidrun, Åsgard, Tyrihans Sør, Tyrihans Nord, Trestakk and Mikkel (Koch and Heum 1995).

Porosity

The Garn Formation has excellent primary reservoir quality which, however, decreases with depth due to quartz cementation and illitization. The porosity of the Garn Formation is gradually reduced with depth of burial, from ca. 30% at 1500 m depth, to 8-17% around 4000 m depth (Koch and Heum 1995).

CO_2 storage quality and capacity

The Garn Formation comprises mainly sandstones. With regard to depth, top seal, porosity, permeability and mineralogy it is well suited for CO_2 storage. This formation is assumed to be among the best candidates for storage off mid-Norway.

It is estimated that the Garn Formation has a pore volume of 540 km^3, a theoretical storage capacity in traps of 453 Mt CO_2, and that the theoretical storage capacity of the entire aquifer is 7560 Mt CO_2 (Table 7).

6.2.6 Ile Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Late Toarcian to Aalenian Ile Formation (Fig. 6) of the Fangst Group generally varies in thickness from 50 m to 100 m over most of Haltenbanken (Fig. 1). It is also encountered in wells on Trænabanken (Dalland et al. 1988). Sandstone-dominated successions of similar age have been located by sea bottom sampling and shallow drilling on the eastern part of the Trøndelag Platform (Fig. 3, Bugge et al. 1984). No comparable time equivalent formations are known from the North Sea area. In the Hammerfest Basin, the middle part of the Stø Formation may be correlated to the Ile Formation. Fine to medium and occasionally coarse grained sandstones with varying sorting are interbedded with thinly laminated siltstones and shales. Mica rich intervals are common. Thin carbonate-cemented stringers occur, particularly in the lower part of the unit. The formation represents various tidal-influenced delta or coastline settings.

Depth

In the type well (6507/11-3) the Ile Formation occurs at 2536-2471.5 m depth, while in the reference well (6407/1-3) it occurs at 3813-3741 m depth (Dalland et al. 1988). 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), and shallow outliers of Middle Jurassic sediments are present in the Frohavet Basin (Bøe 1991) and in the Beitstadfjord Basin (Bøe and Bjerkli 1989) (Fig. 3).

Permeability

The Ile Formation has excellent primary reservoir quality, which decreases with depth due to quartz cementation and illitization. The illitization is reducing the permeability of the Ile Formation drastically when it is buried deeper than ca. 4000 m below sea level, at which depth it is typically 10 mD (varying from 1-100 millidarcies). Around 3000 m depth, the permeability is ca. 1000 mD (Koch and Heum 1995).

Thickness

The thickness of the Ile Formation is 64.5 m in the type well and 72 m in the reference well (Dalland et al. 1988). The formation generally varies from 50 m to 100 m over most of

Haltenbanken, with a general thickening to the west and a marked thinning to the northeast. An average thickness of 70 m is estimated here.

Percent shale

From well logs in Dalland et al. (1988) it is estimated that the Ile Formation consists of approximately 80% sandstone and 20% shale. At depths shallower than ca. 3000 m, the net/gross ratio is generally >0.6, while there is a drastic reduction below ca. 4000 m (Koch and Heum 1995). There is, however, a large spread in net/gross values.

Top seal

The Ile Formation is overlain by the Not Formation of the Fangst Group (Fig. 6). The Not Formation consists of claystones with micronodular pyrite, which coarsen upwards into bioturbated fine-grained sandstones which are locally mica-rich and sandstone-cemented (Dalland et al. 1988). The formation may be up to 50 m thick, but is locally removed by erosion. The Not Formation is recognized over the entire Haltenbanken area, if not eroded. The thickest development is seen on the southwestern part of the Halten Terrace and the unit generally thins eastwards on the Trøndelag Platform. On Trænabanken, a time-equivalent succession dominated by mudstone is assigned to the Viking Group (Dalland et al. 1988).

Hydrocarbon production

Hydrocarbons are produced from the Ile Formation in several fields, e.g. at Heidrun, Åsgard, Njord and Mikkel (Koch and Heum 1995).

Porosity

The Ile Formation has excellent primary reservoir quality, which however decreases with depth due to quartz cementation and illitization. The porosity of the sandstones of the Ile Formation is gradually reduced with depth of burial, from almost 30% at 1500 m depth, to 12-17% between 4000 m and 5000 m depth (Koch and Heum 1995).

CO_2 storage quality and capacity

The Ile Formation comprises mainly sandstones, interbedded with thinly laminated siltstones and shales. With regard to depth, top seal, porosity, permeability and mineralogy it is well suited for CO_2 storage. This formation is assumed to be among the best candidates for storage off mid-Norway.

It is estimated that the Ile Formation has a pore volume of 448 km^3, a theoretical storage capacity in traps of 376 Mt CO_2, and that the theoretical storage capacity of the entire aquifer is 6272 Mt CO_2 (Table 7).

6.2.7 Tofte Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Pliensbachian to Toarcian Tofte Formation (Fig. 6) of the Båt Group is only recognized on the northwestern part of the Halten Terrace (Fig. 3), where it consists of a continuous succession of coarse-grained sandstones. The sandstones wedge out eastwards and interfinger with the Ror Formation. No known time-equivalent lithostratigraphic units in surrounding areas are similar to the Tofte Formation (Dalland et al. 1988). The Tofte Formation consists of modertely to poorly sorted coarse-grained sandstones which often show large-scale cross bedding. In the type section the quartz content is generally higher than 90%, although the sediment is texturally immature. Bioturbation occurs throughout the cored intervals, especially in zones of very poor sorting and high clay content. The sandstones were deposited by eastwards prograding fan deltas which reflect tectonic uplift to the west.

Depth

In the type well (6506/12-1), the Tofte Formation occurs at 4229-4164 m depth. In the reference well (6407/4-1), it occurs at 4208.5-4150 m depth (Dalland et al. 1988), with 40 m of the section belonging to the Tofte Formation. The rest comprises fine-grained deposits of the interfingering Ror Formation.

Permeability

The Tofte Formation is deeply buried in the Åsgard (Smørbukk and Smørbukk Sør) area, and has retained only limited permeability (Koch and Heum 1995).

Thickness

The thickness of the Tofte Formation is 65 m in the type well and approximately 40 m in the reference well (Dalland et al. 1988). The formation thins rapidly eastwards across the Halten Terrace.

Percent shale

From well logs published by Dalland et al. (1988) it is estimated that the Tofte Formation consists of approximately 80% sandstone and 20% shale.

Top seal

The Tofte Formation occurs within (interfingers with), or is overlain by the Ror Formation (Fig. 6). The Ror Formation is dominated by grey to dark grey mudstones containing interbedded silty and sandy coarsening upward sequences, commonly a few metres thick. Such sequences become more frequent towards the top of the formation, giving the unit an overall coarsening upwards trend over most of Haltenbanken. The Ror Formation varies from 70 m to 170 m in thickness (Dalland et al. 1988). The Ror Formation is present in all wells on Haltenbanken. There is a general thinning to the northeast. To the west, it interfingers with sandstones of the Tofte Formation, and the oldest part of the Ror Formation is often absent. The Ror Formation is also present in some Trænabanken wells, but has been removed by erosion over large parts of the Nordland Ridge (Dalland et al. 1988).

Hydrocarbon production

There is hydrocarbons in the Tofte Formation at the Åsgard Field (Koch and Heum 1995).

CO_2 storage quality and capacity

The Tofte Formation comprises mainly sandstones. It is probably too deeply buried and has too low permeability to be well suited for CO_2 storage.

6.2.8 Tilje Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Sinemurian to Pliensbachian Tilje Formation (Fig. 6) of the Båt Group is present both on Haltenbanken and Trænabanken, although it is absent on the Nordland Ridge, due to erosion. The formation is uniformly developed throughout the Halten Terrace, but it thins northeastwards on the Trøndelag Platform (Fig. 3, Dalland et al. 1988). Shallow drilling close to the coast (Bugge et al. 1984) indicates time equivalent deposits dominated by coarse-grained clastics. The Tilje Formation is comparable in age to the lower part of the Stø Formation in the Hammerfest Basin. The formation consists of very fine to coarse-grained sandstones interbedded with shales and siltstones. The sandstones are commonly moderately sorted with a 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. Nearshore marine to intertidal environments are typical of the formation. Subcrops near the coast indicate a gradual transition to continental environments eastwards.

Depth

In the type well (6507/11-1) the Tilje Formation occurs at 2596-2498 m depth, while in the reference well (6609/10-1) it occurs at 1733-1642 m depth (Dalland et al. 1988). Shallow drilling close to the coast (Bugge et al. 1984) indicates time equivalent deposits dominated by coarse-grained clastics at the sea bed. Fig. 16 is a map of depth to the top of the Tilje Formation, interpreted from seismic data.

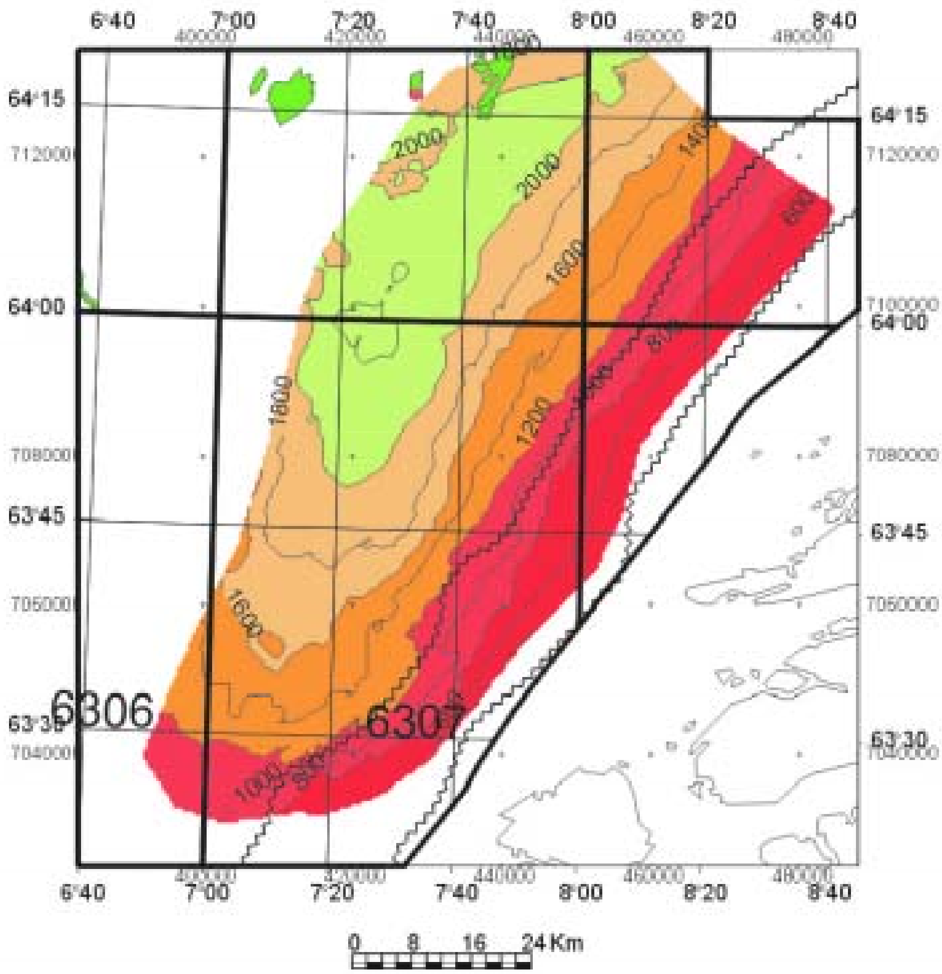

Figure 16. Depth in metres to the top of the Tilje Formation, Froan Basin off Mid-Norway.

Permeability

In the Tilje Formation, thin zones with clorite coating have retained good reservoir quality at great depth throughout Haltenbanken, but individual sandstones show great variablility in reservoir quality (Koch and Heum 1995). Around 3000 m depth, the permeability is generally 100-1000 mD (Koch and Heum 1995). Between 4000 m and 5000 m depth, permeabilities are 0.5-300 mD (Koch and Heum 1995).

Thickness

The thickness of the Tilje Formation is 98 m in the type well and 91 m in the reference well (Dalland et al. 1988). It is absent on the Nordland Ridge due to erosion. The formation is uniformly developed throughout the Halten Terrace, where it is from 100 m to 150 m thick, but it thins northeastwards to less than 100 m on the Trøndelag Platform. Fig. 17 is an isopach map showing thickness of the Tilje Formation, interpreted from seismic data.

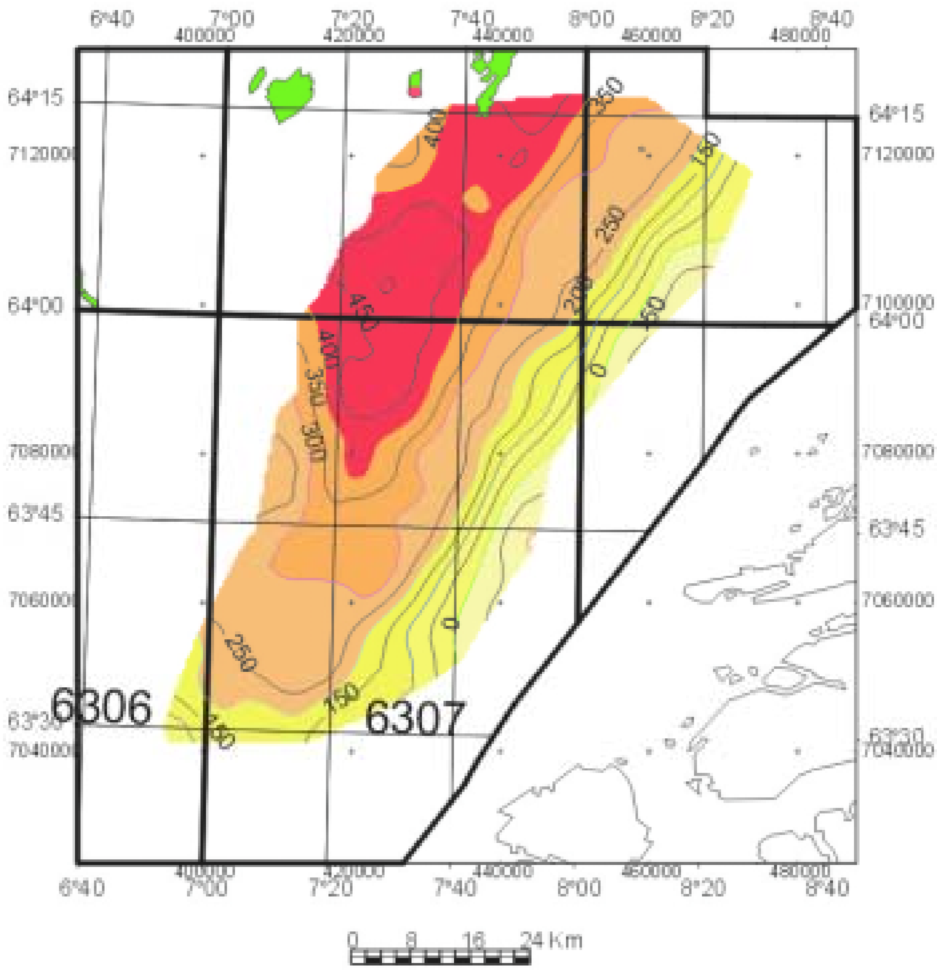

Figure 17. Isopach map of the Tilje Formation, Froan Basin off Mid-Norway.

Percent shale

From well logs published by Dalland et al. (1988), it is estimated that the Tilje Formation consists of approximately 60% sandstone and 40% sandy and silty shale. At depths shallower than 3000 m, there is a range in net/gross values from 0.4-0.9, while between 4000 m and 5000 m depth, the values range from 0-0.5 (Koch and Heum 1995).

Top seal

The Tilje Formation is overlain by the Ror Formation (Fig. 6) of the Båt Group. The Ror Formation is dominated by grey to dark grey mudstones containing interbedded silty and sandy coarsening upward sequences, commonly a few metres thick. Such sequences become more frequent towards the top of the formation, giving the unit an overall coarsening upwards trend over most of Haltenbanken. The Ror Formation varies from 70 m to 170 m in thickness (Dalland et al. 1988). In several areas, the shaly formations of the Båt Group (Ror Formation) and Fangst Group (Not Formation) may not act as good cap rocks. However, the overlying, 1000 m thick shale succession of the Viking Group is most probably tight.

The Ror Formation is present in all wells on Haltenbanken. There is a general thinning to the northeast. To the west it interfingers with sandstones of the Tofte Formation, and the oldest part of the Ror Formation is often absent. The Ror Formation is also present in some Trænabanken wells, but has been removed by erosion over large parts of the Nordland Ridge (Dalland et al. 1988).

Hydrocarbon production

Hydrocarbons are produced from the Tilje Formation at the Heidrun, Åsgard and Njord Fields (Koch and Heum 1995).

Porosity

The porosity of the sandstones of the Tilje Formation is gradually reduced with depth of burial, from around 30% at 1500 m depth, to 17-22% at 3000 m, and 9-18% between 4000 m and 5000 m depth (Koch and Heum 1995).

CO_2 storage quality and capacity

The Tilje Formation comprises sandstones interbedded with siltstones and shales. With regard to depth and top seal it is probably suited for CO_2 storage, especially on the Trøndelag Platform, where also porosities and permeabilities are assumed to be acceptable due to shallower depths of burial.

It is estimated that the Tilje Formation has a pore volume of 360 km^3, a theoretical storage capacity in traps of 302 Mt CO_2, and that the theoretical storage capacity of the entire aquifer is 5040 Mt CO_2 (Table 7).

6.2.9 Åre Formation

General setting (age, distribution, correlations, lithology, depositional environment)

The Rhaetian to Pliensbachian Åre Formation (Fig. 6) of the Båt Group is present in all areas drilled in the Haltenbanken-Trænabanken region, but seismic data indicate that it is truncated in positive areas such as the Nordland Ridge (Dalland et al. 1988). The upper part of the formation contains a laterally continuous mudstone interval; this has a generally uniform thickness, but thins slightly to the north. Shallow drilling close to the coast (Bugge et al. 1984) shows conglomerates which are probably lateral equivalents to the Åre Formation. The formation is partially equivalent to the Statfjord Formation in the North Sea and to the combined upper Fruholmen, Tubåen and Nordmela Formations in the Hammerfest Basin. The Åre Formation has a lower sand content than the Statfjord Formation in the northern North Sea. It consists of alternating sandstones and claystones interbedded with coals and coaly claystones. The claystones are greyish or locally red brown and noncalcareous to very calcareous. The sandstones are greyish, very fine to coarse-grained and predominantly moderately to poorly sorted. The coals in the type well are dark brown to black, vitreous, brittle and locally pyritic. The interpretation of the formation is that coastal plain and delta plain deposits with swamps and channels pass upwards into marginal marine facies. Individual coals can be up to 8 m thick. More proximal lithofacies contain less coal and coarser sandstones.

Depth

In the type well (6507/12-1), the Åre Formation occurs at 2920-2412 m depth, while in the reference well (6407/1-2) it occurs at 4548-4221 m depth (Dalland et al. 1988). Shallow drilling close to the coast (Bugge et al. 1984) shows conglomerates which are probably lateral equivalents to the Åre Formation. Fig. 18 is a map of depth to the top of the Åre Formation, interpreted from seismic data.

Permeability

Channel sands in the Åre Formation have good reservoir quality at shallow depths (Koch and Heum 1995). When buried deeper, the reservoir quality decreases rapidly.

Thickness

The thickness of the Åre Formation is 508 m in the type well and 327 m in the reference well (Dalland et al. 1988). It is generally between 300 m and 500 m thick. Seismic data indicate that the formation is truncated in positive areas such as the Nordland Ridge.

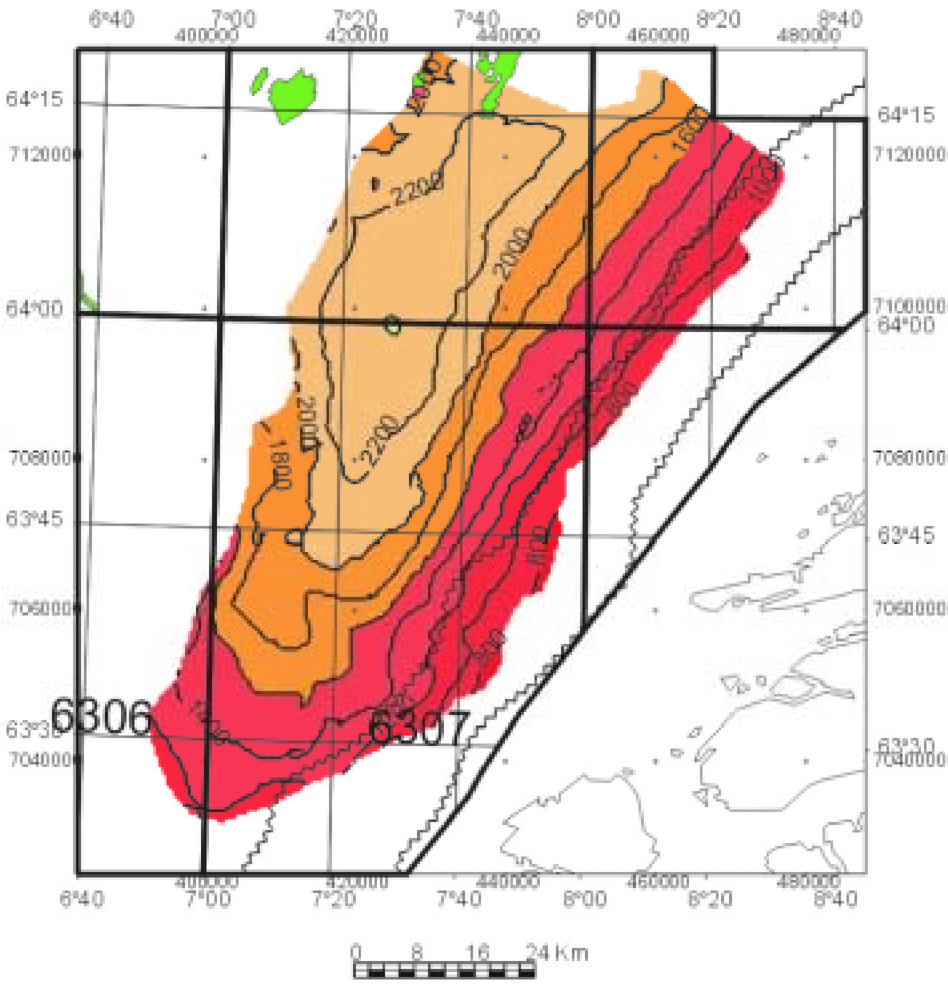

Figure 18. Depth in metres to the top of the Åre Formation, Froan Basin off Mid-Norway.

Percent shale

From well logs published by Dalland et al. (1988) it is estimated that the Åre Formation consists of approximately 30% sandstone and 70% claystones, coals and coaly claystones.

Top seal

The Åre Formation is overlain by the 100-150 m thick Tilje Formation (Båt Group), which consists of very fine to coarse-grained sandstones interbedded with shales and siltstones (Fig. 6, Dalland et al. 1988). The sandstones are commonly moderately sorted with a 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. In several areas, especially in Trænabanken, the shaly formations of the Båt Group (Ror Formation) and Fangst Group (Not Formation) may not act as good cap rocks. However, the overlying, 1000 m thick shale succession of the Viking Group is most probably tight. The Viking Group is present in most wells on Haltenbanken and Trænabanken, but with only a thin partial development on the Nordland Ridge (Dalland et al. 1988). 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, Aarhus et al. 1986).

Hydrocarbon production

Hydrocarbons are produced from the Åre Formation at the Heidrun Field (Koch and Heum 1995).

CO_2 storage quality and capacity

The Åre Formation comprises sandstones and claystones interbedded with coals and coaly claystones. On the the Trøndelag Platform, where the formation does not occur too deep, it's sandstones are probably suited for CO_2 storage. In this region, porosities and permeabilities are assumed to be acceptable due to shallower depths of burial. There is a laterally continuous mudstone interval in the upper part of the Åre Formation (Dalland et al. 1988), and the Åre Formation and the overlying Tilje Formation are thus regarded as separate aquifers. The Åre Formation is strongly subdivided by coal beds and claystones, however, relatively thick sandstone units occur.

It is estimated that the Åre Formation has a pore volume of 720 km^3, a theoretical storage capacity in traps of 604 Mt CO_2, and that the theoretical storage capacity of the entire aquifer is 10 080 Mt CO_2 (Table 7).

6.3 Southern Barents Sea

For the Southern Barents Sea, aquifers are not described in detail. However, Table 8 summarizes the theoretical CO_2 storage potential of various groups and formations in this region. Much of the information used for calculation of pore volumes has been obtained from NPD (1996).

7. EVALUATION OF AQUIFERS RELATIVE TO CO_2 EMISSION SOURCES

The largest CO_2 point sources in Norway are all located onland along the coast or in the offshore area. Also the aquifers suited for CO_2 storage are located in the offshore area, generally more than 20 km from the coastline.

Table 8. Theoretical CO_2 storage potential in aquifers (0.8-4 km depth) in the Norwegian part of the Southern Barents Sea.

Aquifer	Age	Range (km^2)	Average Thickness m	Net:Gross	Porosity %	Pore Volume (km^3)	Reservoir open (O) or closed (C)	Reservoir Density of CO_2 (kg/m^3)	Storage Capacity in Traps (Mt CO_2)	Storage Capacity of Entire Aquifer (Mt CO_2)
Sotbakken/Nordland[b]	Tertiary	43 000	~1000	0.05	30	645	-	-	-	-
Knurr	Early Cretaceous	18 000[a]	70[e]	0.6	17	128	C	700	107	1 792[g]
Stø	Early-Middle Jur.	88 000[a]	70	0.9	21	1164	C	700	978	16 296[g]
Nordmela	Early Jurassic	88 000[a]	100	0.5	17	748	C	700	628	10 472[g]
Tubåen	L. Triassic-E. Jur.	44 000	90	0.7	18	998	C	700	838	13 972[g]
Fruholmen	Late Triassic	88 000[a]	200	0.6	18	1900	C	700	1596	26 600[g]
Snadd	Middle- Late Tr.	112 000	~1000	0.07[h]	17	1332	C	700	1120	18 648[g]
Kobbe	Middle Triassic	120 000	200	0.3[h]	15	1080	C	700	907	15 120[g]
Klappmyss[c]	Early-Middle Tr.									
Havert[c]	Early-Middle Tr.									
Tempelfjorden equivalent[d]	Early-Late Perm.									
Gipsdalen equivalent[d]	Early Permian									
Gipsdalen equivalent[d]	L. Carb. - E. Perm.									
Gipsdalen equivalent[f]	Early-Late Carb.									
Total						**7995**			**6174**	**102 900**

The Southern Barents Sea is bounded in the north by latitude 74º30'N, in the east ny longitude 32ºE, in the south by latitude 69º30'N and the baseline marking the limit of the northern Norwegian coast. In the west, the area is bounded by longitude 16ºE between latitudes 69º30'N and 72ºN, and by longitude 15ºE between latitudes 72ºN and 74º30'N. The calculation of storage capacity in traps (excluding hydrocarbon fields) is based on the assumption that 4% of the pore volume can be filled with CO_2, and that 3% of the aquifer volume is in a trap. The estimate of storage capacity of entire aquifers is based on a storage efficiency of 6% for open aquifer, and 2% for closed aquifers (see Holloway 1996).

[a] Range calculated for hydrocarbon play area as interpreted by NPD (1996)
[b] The presence of aquifers and tight cap rocks has not been documented, and storage capacities are thus not calculated
[c] Aquifers may be present in coarse grained basin margin deposits along the Finnmark Platform
[d] Carbonate aquifers with a possible storage potential along the Finnmark Platform
[e] Average net reservoar thickness of sandstones that locally occur along palaeobasin margins (NPD 1996)
[f] Serpukhovian-Moscovian conglomerates and sandstones with a possible storage potential along the Finnmark Platform (NPD 1996)
[g] The formations are open (subcrop) along the Finnmark Platform, and the storage capacities (entire aquifers) may be regarded as minimum values.
[h] The net:gross has been reduced by ca. 25% due to the presence of many thin sandstone horizons.

7.1 Northern Viking Graben/Tampen Spur area

There is a concentration of large CO_2 point sources in the Northern Viking Graben/Tampen Spur area (Tables 1 and 4), with the Statfjord Field having the largest emissions in Norway in 1999 (1.34 Mt CO_2). Several aquifers could be used for storage of CO_2 (Table 9). For the northernmost fields (Gullfaks, Snorre, Statfjord and Visund), local aquifers include Utsira, Brent, Cook and Statfjord-Hegre. Due to its large volume and shallow depth, the most promising aquifer would be the Utsira Formation, but also Brent is a good candidate.

For the southernmost fields in the Northern Viking Graben (Veslefrikk, Oseberg, Brage), local aquifers include Utsira, Skade, Grid, Frigg, Heimdal-Ty, Brent, Cook and Statfjord-Hegre. Due to large volumes and shallow depths, the Utsira, Skade, Grid and Heimdal are the most promising, but also Brent is a candidate (Table 9).

For fields on the Northern Horda Platform (Troll), local aquifers include Utsira, Agat, Sognefjord-Fensfjord-Krossfjord-Brent, Cook-Johansen and Statfjord-Hegre. Because of large volumes and shallow depths, the most promising are Utsira and Sognefjord-Fensfjord-Krossfjord.

7.2 Southern Viking Graben

For the oil and gas fields in the northern part of the Southern Viking Graben (Frigg, Heimdal, Jotun, Balder), local aquifers include Utsira-Skade, Grid, Frigg, Hermod, Heimdal-Ty, Hugin-Sleipner, Brent, Cook and Statfjord-Hegre (Table 9). The most promising formations for storage of CO_2 in this area are Utsira-Skade, Grid, Frigg, Hermod, Heimdal-Ty and Hugin.

For the oil and gas fields in the southern part of the Southern Viking Graben (Sleipner, Varg), local aquifers include Utsira, Skade, Grid, Heimdal, Ty, Ekofisk-Tor-Hod and Hugin-Sleipner. The most promising formations for storage of CO_2 appear to be Utsira, Skade, Grid, Heimdal and Hugin.

7.3 Central Trough/Norwegian Danish Basin

For the oil and gas fields in the Central Trough (Ekofisk, Gyda, Valhall), local aquifers include Vade, Forties, Ekofisk-Tor-Hod and Ula-Bryne-Skagerrak (Table 9). The most promising formations for storage of CO_2 in this area are Vade and Ula.

Table 9. Regions with large CO_2 point sources in relation to potential storage aquifers. The aquifers with the best storage potential are in yellow, while the most promising formations are in bold.

Northern Viking Graben/Northern Horda Platform/ Tampen Spur	Southern Viking Graben	Central Trough/ Norwegian-Danish Basin	Halten and Dønna Terraces	Oslofjord Region and Porsgrunn Area	Southern Norway from Egersund to Arendal	Western Norway from Boknafjorden to Sunnmøre	Nordmøre and Trond-heimsfjorden area	Nordland from Mosjøen to Kjøpsvik
Northern Viking	Southern Viking	Central Trough	Naust	Bryne-	**Fiskebank**	Utsira	**Garn**	**Ile**
Graben, north, and	Graben, north	**Vade**	Kai	**Gassum**	Ekofisk-Tor-Hod	Agat	**Ile**	**Tilje**
Tampen Spur area	**Utsira-Skade**	Forties	**Lysing**		**Sandnes-**	**Sognefjord-**	**Tilje**	**Åre**
Utsira	**Grid**	Ekofisk-Tor-Hod	**Rogn**		**Bryne-**	**Fensfjord-**	**Åre**	
Brent	**Frigg**	**Ula**-Bryne-	**Garn**		**Gassum-**	**Krossfjord-**		
Cook	**Hermod**	Skagerrak	**Ile**		**Skagerrak**	Brent		
Statfjord-Hegre	**Heimdal-Ty**		Tilje			Cook-Johansen		
	Hugin-Sleipner	Norwegian-	Åre			Statfjord-Hegre		
Northern Viking	Brent	Danish Basin						
Graben, south	Cook	**Fiskebank**						
Utsira	Statfjord-Hegre	Ekofisk-Tor-Hod						
Skade		**Sandnes-Bryne-**						
Grid	Southern Viking	**Gassum-**						
Frigg	Graben, south	Skagerrak						
Heimdal-Ty	**Utsira**							
Brent	**Skade**							
Cook	**Grid**							
Statfjord-Hegre	**Heimdal**							
	Ty							
Northern Horda	Ekofisk-Tor-Hod							
Platform	**Hugin**-Sleipner							
Utsira								
Agat								
Sognefjord-								
Fensfjord-								
Krossfjord-								
Brent								
Cook-Johansen								
Statfjord-Hegre								

For the oil and gas fields in the Norwegian Danish Basin (Yme), local aquifers include Fiskebank, Ekofisk-Tor-Hod and Sandnes-Bryne-Gassum-Skagerrak. The most promising aquifers for storage of CO_2 appear to be Fiskebank and Sandnes-Bryne-Gassum-(Skagerrak).

7.4 Halten and Dønna Terraces

For the oil and gas fields offshore Mid-Norway (Norne, Heidrun, Åsgard, Draugen and Njord), local aquifers include (Naust), (Kai), Lysing, Rogn, Garn, Ile, Tofte, Tilje and Åre (Table 9). The most promising aquifers for storage of CO_2 in this area are Lysing, Rogn, Garn and Ile.

7.5 Oslofjord region and Porsgrunn area

In the Oslofjord Region and Porsgrunn area there are several large CO_2 point sources that could be candidates for carbondioxide storage (Tables 1 and 3). The ones with emissions >200 000 tonnes/year are Esso Norge AS at Slagentangen (oil refinery), Hydro Polymers AS at Rafnes (vinyl chloride monomer), Hydro Porsgrunn Industripark in Porsgrunn (ammonia and magnesium), Norcem AS in Brevik (cement) and Globe Norge AS Hafslund Metall in Sarpsborg (iron and steel).

For the point sources located in the Oslofjord region and the Porsgrunn area, there are no local aquifers available for the storage of CO_2. The nearest aquifer would probably be the Lower Jurassic Bryne and Gassum Formations in the Skagerrak (Table 9), which are located more than 60 km southwest of the Porsgrunn area. The storage potential of the Bryne and Gassum Formations, in this area is, however unknown.

7.6 Southern Norway from Egersund to Arendal

Between Egersund and Arendal, Elkem AS Fiskaa Silikon in Kristiansand (iron and steel) is the only CO_2 source emitting more than 200 000 tonnes/year (Tables 1 and 3). Aquifers include Fiskebank, Ekofisk-Tor-Hod and Sandnes-Bryne-Gassum-Skagerrak (Table 9). The most promising aquifers for storage of CO_2 appear to be the Fiskebank and Sandnes-Bryne-Gassum-Skagerrak. Aquifers in this area are generally located more than 30 km off the coast, except for in the Varnes Graben, where storage may theoretically be possible ca. 15 km from the coast, in the Gassum Formation.

7.7 Western Norway from Boknafjorden to Sunnmøre

In this region, there are several large CO_2 point sources (Tables 1 and 3). The ones with emissions >200 000 tonnes/year are Statoil Kårstø (oil and gas terminal), Hydro Aluminium AS Karmøy Fabrikker (aluminium), Bjølvefossen AS in Ålvik (iron and steel), Eramet Norway AS in Sauda (iron and steel), Tinfos Titan & Iron AS in Tyssedal (iron and steel), Statoil Mongstad (oil refinery), Hydro Aluminium AS Årdal Metallverk (aluminium) and Elkem AS Bremanger Smelteverk (iron and steel). In addition, two gas-fired power stations (each with emissions of ca. 1 Mt CO_2 per year) are at the planning stages, one at Kårstø, and one at Kollsnes west of Bergen.

The Horda and Øygarden Fault Zones are major structures that trend in N-S direction some 40-50 km from the coast southwest of Bergen, and some 20-30 km off the coast between Bergen and Nordfjord. West of these structures, there are thick sedimentary successions which are probably well suited for the storage of CO_2. Aquifers include Agat, Sognefjord-Fensfjord-Krossfjord-Brent, Cook-Johansen and Statfjord-Hegre. The most promising aquifer appear to be the Sognefjord-Fensfjord-Krossfjord-Brent (Table 9), located in the area of the Troll Field. It is also possible that there is a major sandstone interval of Volgian age in the Draupne Formation southwest of Bergen, but this has to be verified by drilling. Pipelines from Kollsnes and Mongstad to storage sites in the Sognefjord Formation, west of the major fault zones, would have to be of the order of 35 and 45 km long, respectively.

East of the major fault zones, Jurassic rocks occur at a distance of some 20 km from the outermost skerries west of Rogaland, and ca. 10 km off the coast of Hordaland (at Utsira, Late Jurassic rocks occur only 2-3 km from the island). The details of these successions, which partly occur in small fault-bounded basins, are not known, but aquifers may include the Brent Group and lateral equivalents of the Krossfjord, Fensfjord and Sognefjord Formations.

From point sources in Western Norway, it would also be possible to transport CO_2 to storage sites in the Utsira Formation, 70-100 km from the coast.

7.8 Nordmøre and Trondheimsfjorden area

CO_2 point sources >200 000 tonnes/year in this region include Statoil Tjeldbergodden (methanol), Hydro Aluminium AS Sunndal Verk at Sunndalsøra (aluminium) and Elkem Thamshavn Verk AS in Orkanger (iron and steel) (Tables 1 and 3). In addition, a gas-fired power station is being planned at Skogn at Trondheimsfjorden. The CO_2 emissions will be in the order of 2.2 Mt/year.

Aquifers suited for storage of CO_2 from this area are located on the Trøndelag Platform, and include the Garn, Ile, Tilje and Åre (Table 9). The closest these formations come to land is ca.

10 km off Smøla and Frøya, and 20 km off the Froan Islands. However, storage of CO_2 would have to take place above the central parts of the Froan Basin, some 30-40 km off the outermost skerries. A pipeline from Tjeldbergodden would be the order of 80 km long.

There is also a possibility that CO_2 may be stored in shallow Jurassic fault basins in the coastal zone. The largest and most promising of these is the Frohavet Basin, but very few details of the sedimentary succession are known. This basin could possibly be an alternative for CO_2 point sources in the Trondheimsfjorden area. The straight distance from Skogn to the Frohavet Basin is ca. 90 km; along the fjords the distance is ca. 140 km.

7.9 Nordland from Mosjøen to Kjøpsvik

CO_2 point sources >200 000 tonnes/year along this stretch of Norway include Elkem Aluminium AS in Mosjøen (aluminium), FESIL Rana Metall in Mo i Rana (iron and steel), Elkem AS Salten Verk in Valljord (iron and steel) and Norcem AS in Kjøpsvik (cement) (Tables 1 and 3).

Aquifers suited for storage of CO_2 are probably the Ile, Tilje and Åre (Table 9). The landward boundary of these formations is generally located 40-50 km from the Norwegian mainland (although it is in many places very close to the outermost skerries). This implies that CO_2 for storage from Mo i Rana (which has 4 point sources with a total emission of 521 000 tonnes in 1999) would have to be transported ca. 150 km to a storage site offshore. CO_2 from the cement factory Norcem AS in Kjøpsvik would probably have to be stored in Vestfjorden, in rocks possibly equivalent to the Ramså or Dragnes Formations on Andøya.

7.10 Troms and Western Finnmark

The aquifers outside Troms and Finnmark are not described in any detail in this report; we have, however, tried to summarize the approximate storage potential in the Southern Barents Sea (Table 8) and to give a short description of the geology along the coast. The only large point source in this large region is Finnfjord Smelteverk AS at Finnsnes (iron and steel). In addition, if Statoil decides to start production of LNG from the Snøhvit field in the Southern Barents Sea, several million tons of CO_2 per year (separated from the natural gas at a landbased plant at Melkøya) will have to be disposed of in the underground somewhere to the north of Hammerfest. CO_2 from Finnfjord Smelteverk AS could possibly be stored in Andfjorden or outside Senja, in rocks equivalent to the Ramså or Dragnes Formations, on Andøya. There is also a theoretical storage potential in the Tertiary deposits west of Senja. North of Hammerfest, the most promising aquifers are the Tubåen and Stø Formations, but there are probably several other alternatives.

8. STORAGE SECURITY

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

In Norway, there are no aquifers suitable for CO_2 storage on land. Aquifers that might be candidates for nearshore (closer to land than ca. 15 km) storage of CO_2 are possibly present outside Western Finnmark and Troms, around Lofoten and Vesterålen, locally along the coasts of Nordland and Hordaland, and in the Frohavet Basin and the Varnes Graben. None of the storage possibilities, except for the Frohavet Basin and the Varnes Graben, are located closer to the coast than ca. 5 km. In Norway, all the large aquifers that are well suited for CO_2 storage are located far (more than 20 km) offshore.

This implies that there is no immediate danger of suffocation for people living on land due to a sudden release of CO_2. For people on ships and offshore installations, the situation may be different. Away from a blow-out area, the concentration of carbondioxide in the air will diminish.

We do not regard slow leakages of carbondioxide from a subsurface storage reservoir beneath the ocean (for example along an open fracture) as a threat to humans. In the open ocean, released CO_2 will be mixed with air and diluted rapidly.

A blow-out may represent a physical threat to ship traffic and floating installations due to the loss of buoyancy, or cause damage to installations on the sea bed, for example pipe-lines.

9. CONFLICTS OF USE

For several aquifers it is possible that there might be conflicts of use, especially in relation to the oil and gas industry within the major oil and gas provinces, in the Central Trough, in the Southern and Northern Viking Grabens and in Haltenbanken. This industry might want to use individual aquifers as a source of water for injection and enhanced oil recovery, or for disposal of produced formation water. The latter is presently done. CO_2 storage might interfere with the efficient production of oil and gas and increase corrosion of the subsurface production facilities. Migration of CO_2 into hydrocarbon fields may also contaminate discovered/undiscovered oil or gas resources or unintendedly reduce the CO_2 storage capacity of hydrocarbon fields. If carbondioxide is stored in oil or gas bearing formations one has to ensure that the CO_2 will not migrate into hydrocarbon reservoirs, unless this is wanted. Injected CO_2 might, however, make oil less viscous, and thus have a positive effect on the recovery of oil (EOR).

In Norway, there is no offshore mining or mineral exploitation, except for hydrocarbons. It is possible, but not very likely, that conflicts will arise in relation to exploitation of other resources (e.g. coal or heat), in the future. There is a theoretical possibility that aquifers could be used for storage of natural gas. However, Norway has a large production and export of both oil and gas. It is thus more likely that gas will not be produced (will be kept in its original reservoir) than that it will be transferred to another site for storage. In the future, it is possible that aquifers will be needed for storage of chemical or radioactive wastes. Contamination of potable water associated with CO_2 storage will not occur, as all aquifers are situated offshore.

10. SUMMARY

The GESTCO project comprises a study of the distribution and coincidence of thermal CO_2 emission sources and location/quality of geological storage capacity.

In 1998, the largest CO_2 process emissions from point sources on land came from manufacturing of iron, steel and ferro alloys (4 Mt) and aluminium (1.7 Mt), but also process emissions from manufacturing of chemicals and mineral products contributed significantly. The largest emissions from stationary combustion came from refining (2 Mt), and from the manufacturing of chemicals and mineral products.

The industrial point sources on land are spread over much of Norway, but 6 regions with clusters of CO_2 point sources can be mapped. These are the Oslofjord area (1.2 Mt in 1999), the Porsgrunn area (2.4 Mt, with 3 point sources larger than 0.5 Mt in 1999), Agder (0.8 Mt in 1999), Western Norway (4.6 Mt, with 2 point sources larger than 0.5 Mt in 1999), Nordmøre-Trondheimsfjorden (1.4 Mt in 1999) and Mosjøen-Kjøpsvik (1.6 Mt in 1999). According to SFT, by 2010 there will be significant increases in CO_2 emissions from Statoil Mongstad and Statoil Kårstø (Western Norway), Statoil Tjeldbergodden (Nordmøre) and Hydro Porsgrunn Industripark (Porsgrunn area). Three gas-fired power plants are at the planning stages. Kårstø and Kollsnes, which are located in Western Norway, might increase annual CO_2 emissions by approximately 2.1 mill tons CO_2, while a plant at Skogn (Trondheimsfjorden area) is planned to release 2.2 mill tons CO_2 annually.

In 1999, approximately 9.4 Mt CO_2 were emitted by the offshore petroleum industry. These emissions were mainly from point sources (platforms) located at the various oil and gas fields in production, and are predominantly related to stationary combustion. In 1998, combustion of natural gas produced 6.8 Mt of CO_2, flaring 1.2 Mt and diesel combustion 0.5 Mt. The area with the largest emissions (4.55 Mt in 1999) is the Northern Viking Graben/Tampen Spur with 3 point sources emitting more than 0.5 Mt in 1999. Other areas with large emissions are the Central Graben (1.8 Mt in 1999), the southern Viking Graben (1.1 Mt in 1999) and Haltenbanken (1.7 Mt in 1999). For the next 15 years, NPD expects an increase in CO_2 emissions from the offshore oil and gas industry to a maximum of 14 Mt/year in 2006-2007, and then a gradual reduction to the year 2000 level.

There are no rock formations suitable for the storage of CO_2 on land in Norway. In the offshore area, however, a large number of candidate aquifers for CO_2 storage have been identified in the Norwegian part of the North Sea, in the Norwegian Sea and in the Southern Barents Sea. The storage capacity in geological traps (outside hydrocarbon fields) is estimated to be ca. 13 000 Mt CO_2, while the storage capacity in aquifers not confined to traps is estimated to be at least 280 000 Mt CO_2. In a separate Gestco project report (Schuppers et al. 2002), it is estimated that the total future storage capacity in Norwegian hydrocarbon fields is ca. 15 000 Mt CO_2.

It is here estimated that the storage capacity in aquifers in the Norwegian North Sea is at least 150 000 Mt CO_2. The aquifers with the largest theoretical capacities are the Tertiary Utsira, Skade, Frigg, Heimdal and Ty Formations, the Cretaceous Tor Formation, and the Jurassic Brent Group and Statfjord Formation. Triassic rocks have very large volumes, but are possibly not well suited for the storage of CO_2 in the Norwegian North Sea, due to low permeabilities. Along the coast, the most promising aquifers are the Fiskebank, Sandnes-Bryne-Gassum and Sognefjord-Fensfjord-Krossfjord.

The storage capacity in aquifers in the Norwegian Sea area is estimated to be at least 30 000 Mt CO_2. These figures do not include the Tertiary Naust and Kai Formations, which have very large theoretical storage potential, but which have poor top seals. The aquifers with the largest theoretical storage capacities are the Jurassic Garn, Ile, Tilje and Åre Formations.

In the Southern Barents Sea, we have estimated a storage capacity in aquifers of approximately 100 000 Mt CO_2. The aquifers with the largest theoretical storage capacities are the Jurassic Stø and Nordmela Formations, the Triassic-Jurassic Tubåen Formation and the Triassic Fruholmen, Snadd and Kobbe Formations.

Table 9 summarises regions with large CO_2 point sources in relation to potential storage aquifers offshore. In Norway, all the large aquifers that are well suited for CO_2 storage are located far (more than 20 km) offshore. This implies that there is no immediate danger of suffocation for people living on land due to a sudden release of CO_2. For people on ships and offshore installations, the situation may be different. Away from a blow-out area, the concentration of CO_2 in the air will diminish. We do not regard slow leakages of CO_2 from a subsurface storage reservoir beneath the ocean as a threat to humans. In the open ocean, released CO_2 will be mixed with air and diluted rapidly.

For several aquifers, it is possible that there might be conflicts of use, especially in relation to the oil and gas industry. This industry might want to use individual aquifers as a source of water for injection and enhanced oil recovery, or for disposal of produced formation water. CO_2 storage might interfere with the efficient production of oil and gas, increase corrosion of subsurface production facilities or contaminate discovered/undiscovered oil or gas resources. In the future, it is also possible that aquifers will be needed for storage of other chemical or radioactive wastes.

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12. REFERENCES

Aarhus, N., Verdenius, J. & Birkelund, T. 1986: Biostratigraphy of a Lower Cretaceous section from Sklinnabanken, Norway with som comments on the Andøya exposure. *Norsk Geologisk Tidsskrift 66*, 17-43.

Askvik, H. & Rokoengen, K. 1985: Geologisk kart over Norge, berggrunnskart KRISTIANSUND - M. 1:250 000. *Norges geologiske undersøkelse.*

Bergan, M., Tørudbakken, B. & Wandås, B. 1989: Lithostratigraphic correlation of Upper Jurassic sandstones within the Norwegian Central Graben: sedimentological and tectonic implications. *In* Collinson, J.D. (ed): *Correlation in Hydrocarbon exploration*. Graham & Trotman, London, 243-251.

Bowman, M.B.J. 1998: Cenozoic. *In* Glennie, K.W. (ed.): *Petroleum Geology of the North Sea. Basic concepts and recent advances. Fourth Edition*. Blackwell Science, Oxford, 350-375.

Brekke, H., Kalheim, J.E. Riis, F., Egeland, B., Blystad, P., Johnsen, S. & Ragnhildstveit, J. 1992: Two-way time map of the unconfomity at the base of the Upper Jurassic (north of 69°N) and the unconfomity at the base of the Cretaceous (south of 69°N), offshore Norway, including the main geological trends onshore. Scale 1:2 mill. NPD Continental Shelf Map No. 1. *The Norwegian Petroleum Directorate/The Geological Survey of Norway.*

Brennand, T.P., Van Hoorn, B., James, K.H. & Glennie, K.W. 1998: Historical Review of North Sea Exploration. *In* Glennie, K.W. (ed.): *Petroleum Geology of the North Sea. Basic concepts and recent advances. Fourth Edition*. Blackwell Science, Oxford, 1-41.

Bugge, T., Knarud, R. & Mørk, A. 1984: Bedrock geology on the mid-Norwegian continental shelf. *In* Norwegian Petroleum Society (ed.): *Petroleum Geology of the North European Margin*. Graham & Trotman, London, 271-283.

Bugge, T., Ringås, J.E., Leith, D.A., Mangerud, G., Weiss, H.M. & Leith, T.L. 2002: Upper Permian as a new play model on the Mid-Norwegian continental shelf; investigated by shallow stratigraphic drilling. American Association of Petroleum Geologists Bulletin (in press).

Bøe, R. 1991: Structure and seismic stratigraphy of the innermost mid-Norwegian continental shelf: an example from the Frohavet area. *Marine and Petroleum Geology 8*, 140-151.

Bøe, R. & Bjerkli, K. 1989: Mesozoic sedimentary rocks in Edøyfjorden and Beitstadfjorden, central Norway: implications for the structural history of the Møre-Trøndelag Fault Zone. *Marine Geology 87*, 287-299.

Bøe, R., Sørensen, S. & Hovland, M. 1992: The Karmsundet Basin, SW Norway: stratigraphy, structure and neotectonic activity. *Norsk Geologisk Tidsskrift 72*, 281-283.

Bøe, R. & Skilbrei, J.R. 1998: Structure and seismic stratigraphy of the Griptarane area, Møre Basin margin, mid-Norway continental shelf. *Marine Geology 147*, 85-107.

Bøe, R., Sand, M. & Sturt, B. 1998: Muligheter for undergrunnsdeponering av CO_2 i kystnære områder - en forstudie. *NGU Report 98.149*, 43 pp.

Bøe, R., Rise, L. & Brekke, H. 2000: Berggrunnsgeologisk kart over den norske delen av Skagerrak og Nordsjøen mellom Kristiansand og Karmøy. *NGU Report 2000.010*, 10 pp.

Christensen, N.P. 1998: Reducing carbon dioxide emissions - the European Upstream Oil Industry i taking the initiative. *GEO ENeRGY 5*, February 1998, 1-2.

Czernichowski-Lauriol, I., Sanjuan, B., Rochelle, C., Bateman, K., Pearce, J. & Blackwell, P. 1996: Analysis of the geochemical aspects of the underground disposal of CO_2. *In Deep injection disposal of hazardous and industrial waste*. Academic press, 565-583.

Dalland, A. 1979: The Sedimentary Sequence of Andøy, Northern Norway - Depositional and Structural History. Proceedings, Norwegian Sea Symposium, Tromsø 1979. *Norwegian Petroleum Society NNS/26*, 1-31.

Dalland, A., Worsley, D. & Ofstad, K. 1988: A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. *Norwegian Petroleum Directorate Bulletin No. 4*, 65 pp.

Deegan, C.E. & Scull, B.J. 1977: A standard lithostratigraphic nomenclature for the Central and Northern North Sea. *Rep. Inst. Geol. Sci., No. 77/25: Bull. Norw. Petrol. Direct., No. 1., HMSO, London*. 36 pp.

Dehls, J.F., Olesen, O., Bungum, H., Hicks, E.C., Lindholm, C.D. & Riis, F. 2000: Neotectonic map: Norway and adjacent areas. *Geological Survey of Norway*, Trondheim.

Dons, J.A. & Larsen, B.T. 1978: The Oslo Paleorift - A review and Guide to Excursions. *Norges Geologiske Undersøkelse 337, Bulletin 45*, 199 pp.

Eidvin, T. & Rundberg, Y. 2001: Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. *Norsk Geologisk Tidskrift 81*, 119-160.

Eidvin, T., Rundberg, Y. & Smelror, M. 2002: Revised chronology of Neogene sands (Utsira and Skade Formations) in the central and northern North Sea. *In* NGF/NPF (eds.): Onshore-offshore relationships on the North Atlantic Margin, Trondheim, 13th-15th May 2002. Extended Abstract.

Fisher, M.J. & Mudge, D.C. 1998: Triassic. *In* Glennie, K.W. (ed.): *Petroleum Geology of the North Sea. Basic concepts and recent advances. Fourth Edition*. Blackwell Science, Oxford, 212-244.

Fjellanger, E., Olsen, T.R. & Rubino, L. 1996: Sequence stratigraphy and palaeogeography of the Middle Jurassic Brent and Vestland deltaic systems, Northern North Sea. *Norsk Geologisk Tidsskrift 76*, 75-106.

Fossen, H. 1998: Advances in understanding the post-Caledonian structural evolution of the Bergen area, West Norway. *Norsk Geologisk Tidsskrift 78*, 33-46.

Fossen, H., Mangerud, G., Hesthammer, J., Bugge, T. & Gabrielsen, R.H. 1997: The Bjorøy Formation: a newly discovered occurrence of Jurassic sediments in the Bergen Arc System. *Norsk Geologisk Tidsskrift 77*, 269-287.

Galloway, W.E. 2002: Seismic Expressions of Deep-Shelf Depositional and Erosional Morphologies, Miocene Utsira Formation, North Sea Basin. *In* Rebesco, M. and Stow, D.A.V. (eds.): *Seismic expression of contourites and related deposits*. Marine Geophysical Researches Special issue, Kluwer Academic Publishers, The Netherlands.

Gee, D. & Sturt, B.A. 1985 (eds.): *The Caledonide Orogen - Scandinavia and related areas*. John Wiley & Sons, Chichester. 1266 pp.

Gray, D.I. 1987: Troll. *In* Spencer, A.M., Campell, C.J., Hanslien, S.H., Nelson, P.H., Nysæther, E. & Ormaasen, E.G. (eds): *Geology of the Norwegian Oil and Gas Fields*. Graham and Trotman, London, 389-401.

Gregersen, U., Michelsen, O. & Sørensen, J.C. 1997: Stratigraphy and facies distribution of the Utsira Formation and Pliocene sequences in the northern North Sea. *Marine and Petroleum Geology 14*, 893-914.

Grogan, P. & Zwaan, K.B. 1997: Geologisk kart over Norge, berggrunnskart HELGØY, M 1:250 000. *Norges geologiske undersøkelse*.

Gustavson, M. & Gjelle, S.T. 1991: Geologisk kart over Norge. Berggrunnskart MO I RANA, M 1:250 000. *Norges geologiske undersøkelse*.

Gustavson, M. & Blystad, P. 1995: Geologisk kart over Norge, berggrunnskart BODØ, M 1:250 000. *Norges geologiske undersøkelse*.

Gustavson, M. & Bugge, T. 1995: Geologisk kart over Norge, berggrunnskart VEGA, M 1:250 000. *Norges geologiske undersøkelse*.

Henningsen, T. og Tveten, E. 1998: Geologisk kart over Norge. Berggrunnskart ANDØYA, M: 1:250 000. *Norges geologisk undersøkelse*.

Holloway, S. (editor) 1996: The underground disposal of carbon dioxide. Contract No JOU2 CT92-0031, Final Report. *British Geological Survey*, Keyworth, Nottingham, UK.

Holtedahl, H. 1988: Bedrock geology and Quaternary sediments in the Lista basin, S. Norway. *Norsk Geologisk Tidsskrift 68*, 1-20.

IKU 1995: Shallow Drilling Helgeland 1992. *IKU Information sheet no.: 15, Project No. 23.1684.00*. Shallow Drilling, February 1995.

Isaksen, D. & Tonstad, K. 1989: A revised Cretaceous and Tertiary lithostratigraphic nomenclature for the Norwegian North Sea. *NPD-Bulletin no. 5*, 59 s.

Jacobsen, K.H., Hamar, G.P., Ormaasen, O.E. & Skarpnes, O. 1980: Triassic facies in the North Sea north of the Central Highs. *In* NPF (ed.): *The sedimentation of the North Sea reservoir rocks*. Geilo XVIII, NPF, 1-10.

Johnsen, J.R., Rutledal, H. & Nilsen, D.E. 1995: Jurassic reservoirs; field examples from the Oseberg and Troll Fields: Horda Platform area. *In* Hanslien, S. (ed.): *Petroleum Exploration and Exploitation in Norway*. NPF Special Publication 4, 199-234, Elsevier, Amsterdam.

Johnson, H.D. & Fisher, M.J. 1998: North Sea Plays: Geological Controls on Hydrocarbon Distribution. *In* Glennie, K.W. (ed.): *Petroleum Geology of the North Sea. Basic concepts and recent advances. Fourth Edition*. Blackwell Science, Oxford, 463-547.

Jorde, K., Sigmond, E.M.O. & Thorsnes, T. 1995: STAVANGER, Berggrunnsgeologisk kart 1:250 000. *Norges geologiske undersøkelse*.

Koch, K.-O. & Heum, O.R. 1995: Exploration trends of the Halten Terrace. *In* Hanslien, S. (ed.): *Petroleum Exploration and Exploitation in Norway*. NPF Special Publication 4, 235-251, Elsevier, Amsterdam.

NPD 1996: Geology and Petroleum Resources in the Barents Sea. *The Norwegian Petroleum Directorate*, October 1996.

Oakman, C.D. & Partington, M.A. 1998: Cretaceous. *In* Glennie, K.W. (ed.): *Petroleum Geology of the North Sea. Basic concepts and recent advances. Fourth Edition*. Blackwell Science, Oxford, 294-349.

Pegrum, R.M. & Spencer, A.M. (eds) 1990: Hydrocarbon plays in the North Sea. *In* Brooks, J. (ed.): *Classic Petroleum Provinces*. Special Publication No. 50, Geological Society, London, 441-470.

Ragnhildstveit, J. & Helliksen, D. 1997: Geologisk kart over Norge, berggrunnskart Bergen - 1:250 000. *Norges geologisk undersøkelse*.

Ragnhildsteveit, J., Naterstad, J., Jorde, K. & Egeland, B. 1998: Geologisk kart over Norge; berggrunnskart Haugesund - M 1:250 000. *Norges geologiske undersøkelse*.

Reynolds, T. 1994: Quantitative analysis of submarine-fans in the Tertiary of the North Sea Basin. *Marine and Petroleum Geology 11*, 202-207.

Rise, L., Sættem, J., Fanavoll, S., Thorsnes, T., Ottesen, D. & Bøe, R. 1999: Sea-bed pockmarks related to fluid migration from Mesozoic bedrock strata in the Skagerrak offshore Norway. *Marine and Petroleum Geology 16*, 619-631.

Rokoengen, K. & Sørensen, S. 1990: Late Jurassic sedimentary bedrock north of Utsira, offshore western Norway. *Norsk Geologisk Tidsskrift 70*, 61-63.

Rundberg, Y. 1989: Tertiary sedimentary history and basin evolution of the Norwegian North Sea between 60°-62° - An intergrated approach. Dr. ing. Thesis, University of Trondheim, 308 pp, (reprinted 1991 in Report 25 Institute of Geology and Rock Mechanics, University of Trondheim).

Sigmond, E.M.O. 1992: Bedrock map, Norway and adjacent ocean areas. M 1:3 000 000. *Norges geologiske undersøkelse.*

Sigmond, E.M.O., Gustavson, M. & Roberts, D. 1984: Berggrunnskart over Norge - M. 1:1 million. *Norges geologiske undersøkelse*.

Smelror, M., Jacobsen, T., Rise, L., Skarbø, O., Verdenius, J.G. & Vigran, J.O. 1994: Jurassic to Cretaceous stratigraphy of shallow cores on the Møre Basin Margin, Mid-Norway. *Norsk Geologisk Tidsskrift 74*, 89-107.

Solli, A., Bugge, T. & Thorsnes, T. 1997: Geologisk kart over Norge, berggrunnskart NAMSOS, M 1:250 000. *Norges geologiske undersøkelse*.

Sommaruga, A. & Bøe, R. 2002: Shallow Jurassic basins along the coast of Mid-Norway. *In* NGF/NPF (eds.): Onshore-offshore relationships on the North Atlantic Margin, Trondheim, 13th-15th May 2002. Extended Abstract.

Spencer, A.M., Leckie, G.G. & Chew, K.J. 1996: North Sea hydrocarbon plays and their resources. *In* Glennie, K. & Hurst, A. (eds): *Northwest Europe's Hydrocarbon Industry*. Geological Society, London, 25-41.

Statistisk sentralbyrå 2000: Natural resources and the environment 2000. Chapter 7, Emissions to air, 93-139. *Statistisk sentralbyrå*, Oslo-Kongsvinger.

Steel, R., Siedlecka, A. & Roberts, D. 1985: Devonian basins of Norway and their deformation. *In* Gee, D.G. & Sturt, B.A. (eds.): *The Caledonian Orogen - Scandinavia and Related Areas*. John Wiley & Sons, Chichester, 293-315.

Stewart, I.J. 1993: Structural controls on the Late Jurassic age shelf system, Ula Trend, Norwegian North Sea. *In* Parker, J.R. (ed): *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 469-484.

Stewart, D.J., Schwander, M. & Bolle, L. 1995: Jurassic depositional systems of the Horda Platform, Norwegian North Sea: practical consequences of applying sequence stratigraphic models. *In* Steel, R.J., Felt, V.L., Johannessen, E.P. & Mathieu, C. (eds): *Sequence Stratigraphy on the Northwest European Margin.* Special Publication No. 5, Norwegian Petroleum Society (NPF), 291-323.

Schuppers, J.D., Holloway, S., May, F., Gerling, P., Bøe, R., Magnus, C., Riis, F., Osmundsen, P.T., Larsen, M., Andersen, P.R. & Hatzyannis, G. 2002: Storage capacity and quality of hydrocarbon structures in the North Sea and Aegean region. TNO Report NITG02-020-B.

Thorsnes, T. 1995: Structural setting of two Mesozoic half-grabens off the coast of Trøndelag, Mid-Norwegian shelf. *Norges geologiske undersøkelse Bulletin 427*, 68-71.

Torp, T. & Christensen , N.P. 1998: Capture and reinjection of CO_2 in a saline aquifer at Sleipner Field and the future potential of this technology. *Dinner-debate with the Foundation Européenne de l'Energie in Brussels on 2 June 1998.*

Tveten, E., Lutro, O. & Thorsnes, T. 1998a: Geologisk kart over Noreg, berggrunnskart ULSTEINVIK - 1:250 000. *Noregs geologiske undersøkelse*.

Tveten, E., Lutro, O. & Thorsnes, T. 1998b: Geologisk kart over Noreg, berggrunnskart ÅLESUND - 1:250 000. *Noregs geologiske undersøkelse*.

Underhill, J.R. 1998: Jurassic. *In* Glennie, K.W. (ed.): *Petroleum Geology of the North Sea. Basic concepts and recent advances. Fourth Edition.* Blackwell Science, Oxford, 245-293.

Vergara, L., Wreglesworth, I., Trayfoot, M. & Richardsen, G. 2001: The distribution of Cretaceous and Paleocene deep-water reservoirs in the Norwegian Sea basins. *Petroleum Geoscience 7*, 395-408.

Vollset, J. & Doré, A.G. 1984. A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea. *Norwegian Petroleum Directorate Bulletin No. 3,* 53 pp.

Vorren, T.O., Laberg, J.S., Blaumme, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J. & Werner, F. 1998: The Norwegian-Greenland Sea Continental Margins: Morphology and Late Quaternary Sedimentary Processes and Environment. *Quaternary Science Reviews 17,* 273-302.

Ziegler, P.A. 1990: Geological Atlas of Western and Central Europe, 2nd edn. *Shell Internationale Petroleum Maatschappij B.V., Geological Society, Bath (distributors),* 239 pp.

Zwaan, K.B., Fareth, E. & Grogan, P.W. 1998: Geologisk kart over Norge, berggrunnskart TROMSØ, M:1:250 000. *Norges geologiske undersøkelse.*

Zweigel, P. & Lindeberg, E. 2000: 4D seismikk løser gåten. *GEO 6 - 2000*, 16-18.