DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/42

# A survey of $CO_2$ storage capacity of Danish oil and gas fields

## A GESTCO contribution

Palle Rubæk Andersen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

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# Introduction

Over the past three years the potential for underground storage of $CO_2$ in Denmark has been evaluated as part of the European Community supported research project GESTCO (Geological storage of $CO_2$ from fossil fuel combustion). The present report forms study area G in the GESTCO proposal (Christensen 2000) and describes the potential for $CO_2$ storage in the hydrocarbon fields in the Danish sector of the North Sea. The overall GESTCO results are also summarised in Schuppers (2002). The Danish part of the project also comprised evaluation of the storage potential of deep saline aquifers and a combined application in geothermal energy systems (Larsen, Bidstrup & Dalhoff 2003; Mathiesen, Larsen & Mahler 2003).

The hydrocarbon production in Denmark is related to carbonates and sandstones. The production occurs chiefly from Chalk reservoirs of Late Cretaceous–Early Paleocene age which at present constitute 14 producing fields. A single Lower Cretaceous carbonate reservoir is in production. Sandstone reservoirs in production comprise 3 minor fields of Jurassic and Paleocene age.

All fields are located offshore within the North Sea. Production were initiated in 1972 starting with the Dan chalk field, and all fields are still active. Any possible plans for enhanced oil recovery using $CO_2$ injection into the reservoirs are at present not known, but some of the fields may well constitute later likely candidates for such action.

Only fields on stream prior to January 1st 2001 are considered. Eight discoveries declared commercial and classified as "future developments" are (apart from the Boje area) not included in this outline mainly because reserves estimates etc. are not available. These "future developments" include 2 chalk reservoir fields, 2 chalk+carbonate reservoir fields, 2 sandstone reservoir fields and 2 chalk+sandstone reservoir fields.

In a previous study in part funded by the JOULE II Programme the total storage capacity in Denmark was estimated to equal 0.13 Gigatonnes of $CO_2$ in oil fields and 0.46 Gigatonnes in gas fields (Holloway et al. 1996). The present GESTCO project estimate the total storage capacity to equal 0.18 Gigatonnes of $CO_2$ in oil fields and 0.45 Gigatonnes in gas fields (Schuppers 2002).

# Methodology

For the present short outline, the potentially available storage capacity for each field is simply assumed to equal *the expected ultimate recoveries* of the contained hydrocarbons. This value is per common agreement within the project group obtained as the sum of *the volume of already produced hydrocarbons* plus *the volume of expected producible reserves* considering known technology. During production the fluids are brought from subsurface pressure conditions in the reservoir to atmospheric pressure environment at the surface. This change in pressure causes oil to shrink because of liberation of dissolved gases (=associated gas), and it causes free hydrocarbon gas to expand. The figures for produced volumes as well as for producible reserves are standardly given as volumes at surface pressure conditions (e.g. standard 1 atmosphere and 15°C). Therefore the expected ultimate recovery volumes calculated from these surface volumes must be restored to subsurface conditions in order to express *the actual storage volume present in the reservoir in the subsurface*.

The calculated storage capacities are based on figures per January 1$^{st}$ 2001 for accumulated produced volumes and remaining reserves published by the Danish Energy Agency (DEA) in the 2000 annual report *Oil and Gas Production in Denmark 2000* (published June 2001). The published figures are all volumes given at surface standard conditions. The underground volumes, which these represent, were for the present use in most cases calculated using an average free gas formation volume factor $B_g=1/275$ and an average oil formation volume factor $B_o=1.35$. However, in some cases – mostly for the deeper seated oil and gas accumulations – other formation volume factors were applied.

The reserves published by the Energy Agency are in general often a combination of *developed reserves*, which are the hydrocarbons judged producible with the existing production/injection wells, and *planned development reserves*, which are the hydrocarbons modelled to be producible with additional wells drilled into either already developed areas of a field or into hitherto undrilled areas. The consequence of this is, that the hereby available estimates for ultimate reserves depends on the maturity of the development of a given field, and can be regarded a true ultimate reserve estimate for some fields but may be conservative estimates for other fields. This will not be dealt with further since refinement in principle will require more detailed, individual field studies. However, it should be borne in mind.

It should also be pointed out, that storage volumes estimated from the method chosen here are inherently inaccurate and may be considered either minimum or maximum values for a number of individual situations. They may be considered minimum values in cases where hydrocarbon zones have high water saturations, for which reason larger volumes of water are produced along with the hydrocarbons without being accounted for as representing storage space. They will also be minimum values in cases where fields are not filled to spill-point, and water zones therefore occur which may also be available for storage. They may be considered maximum values for cases where reservoirs compact during production or where reservoirs compartmentalises accompanying the movement of hydrocarbons. The constructed storage volumes may therefore be closer to the truth for some fields than for others, but are nevertheless considered satisfactory for the present purpose, which is to produce reasonable estimates without entering into detailed studies of individual fields.

# General

The producing Danish oil and gas fields consist of 14 chalk fields and 3 sandstone fields, a grouping also used in the text below.

Figure 1 shows the field locations and the position of discovery well of the fields considered, i.e. those on stream prior to January 1st 2001. Field outlines do not perforce indi-

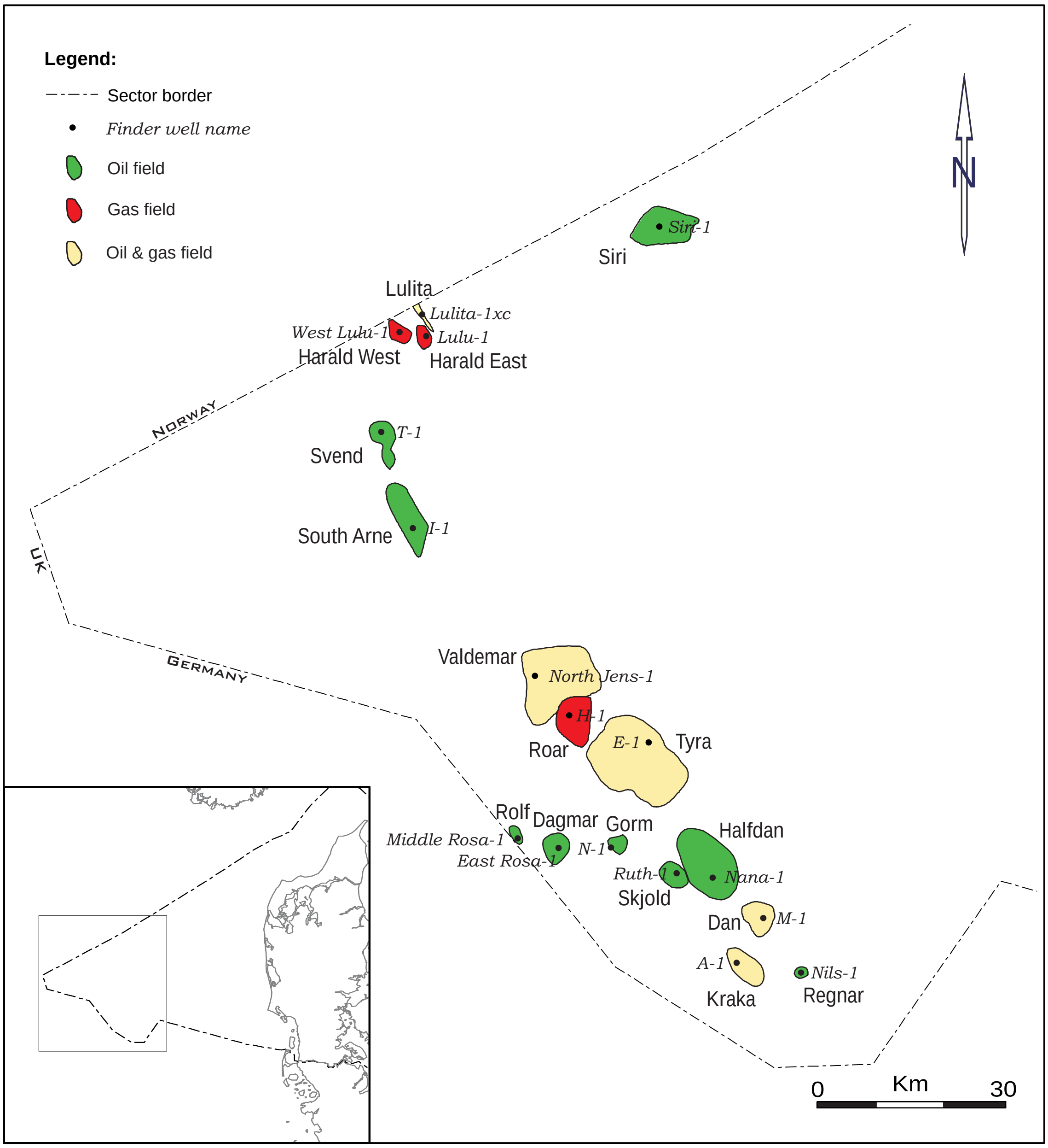


**Figure 1.** *Location map of producing Danish hydrocarbon fields and their discovery wells. All fields are located offshore within the Danish North Sea. Discoveries declared commercial but not put into production prior to January 1st 2001 are not shown. Field outlines do not perforce indicate the extent of the oil/gas pools but are in many cases guided by field structural conditions. In some cases outlines encircle several minor accumulations.*

cate the extent of the oil/gas pools but are in many cases guided by field structural conditions. In some cases outlines encircle several minor accumulations.

Table 1 lists relevant field data: For each field age and type of reservoir rock(s), the trap type, type of hydrocarbons, depth to top of reservoir, and the calculated potential $CO_2$ storage capacities expressed as ultimate oil and/or gas recoveries restored to underground reservoir conditions. Also listed in Table 1 are name of discovery well, year of production start, name of operator, and the number of production/injection wells. Finally water production and injection data are listed to allow the reader some indication of the magnitude of the possible underestimation of the storage capacity by not considering produced water.

In Figure 2 and 3 the potential underground volumes available for $CO_2$ storage are illustrated in bar chart format in two ways: For each field the expected ultimately recoverable hydrocarbon volumes restored to reservoir conditions are shown in Figure 2, and in Figure 3 these volumes are specified for oil and free gas.

One of the fields, the Valdemar field, is stacked consisting of a Danian and Upper Cretaceous chalk reservoir plus a Lower Cretaceous carbonate reservoir. These two reservoir levels are represented separately in Table 1 and in the bar charts (as Valdemar UC and Valdemar LC respectively) in order not to list unnecessary unrealistic storage potential. The reserve estimates from the two levels are of similar magnitude, but the Lower Cretaceous carbonate reservoir has so unfavourably low permeabilities that $CO_2$ storage is highly unlikely to be attempted.

The Chalk Group is by far the most important formation concerning oil and gas occurrences in Denmark. A time-thickness map in two-way-time (TWT) of the Chalk Group in the Danish area (Vejbæk et al. 2003) is reproduced in Figure 4. From a production point of view – and therefore also from a $CO_2$ injection point of view – the chalk fields can be divided into *matrix fields* (fields with relatively "high" permeabilities and producing from the chalk matrix) and *fracture fields* (fields with very low matrix permeabilities and producing mainly from fractures, locally supported by matrix flow into the fractures). Table 2 lists the fields according to this subdivision.

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| | **Field** | **Primary reservoir rock** | **Age of primary reservoir rock** | **Secondary reser-voir rock** | **Structure** | **Discovery well** |
| **1** | Dagmar | Chalk | Danian & Upper Cretaceous | Zechstein carbon-ates | Domal | East Rosa-1 |
| **2** | Dan | Chalk | Danian & Upper Cretaceous | | Domal | M-1 |
| **3** | Gorm | Chalk | Danian & Upper Cretaceous | | Domal | N-1 |
| **4** | Halfdan | Chalk | Danian & Upper Cretaceous | | Stratigraphic | Nana-1 |
| **5** | Harald East | Chalk | Danian | Maastrichtian chalk | Domal | Lulu-1 |
| **6** | Kraka | Chalk | Danian & Upper Cretaceous | | Domal | A-1 |
| **7** | Regnar | Chalk | Danian & Upper Cretaceous | Zechstein carbon-ates | Domal | Nils-1 |
| **8** | Roar | Chalk | Danian & Upper Cretaceous | | Anticlinal | H-1 |
| **9** | Rolf | Chalk | Danian & Upper Cretaceous | Zechstein carbon-ates | Domal | Middle Rosa-1 |
| **10** | Skjold | Chalk | Danian & Upper Cretaceous | | Domal | Ruth-1 |
| **11** | Svend | Chalk | Danian & Upper Cretaceous | | Domal | T-1 |
| **12** | South Arne | Chalk | Danian & Upper Cretaceous | Lower Cretaceous carbonates | Anticlinal | I-1 |
| **13** | Tyra | Chalk | Danian & Upper Cretaceous | | Anticlinal | E-1 |
| **14a** | Valdemar | Chalk | Danian & Upper Cretaceous | | Anticlinal | North Jens-1 |
| **14b** | Valdemar | Carbonate | Lower Creta-ceous | | Anticlinal | North Jens-1 |
| | | | | | | |
| **15** | Harald West | Sandstone | Middle Jurassic | Danian & Upper Cretaceous chalk | Tilted fault block | West Lulu-1 |
| **16** | Lulita | Sandstone | Middle Jurassic | | Fault block | Lulita-1xc |
| **17** | Siri | Sandstone | Palaeocene | | Domal | Siri-1 |

**Table 1a.** *Selected field data. The expected ultimate recoveries (UR) restored to underground reservoir conditions, thus expressing the volume potentially available for $CO_2$ storage, are listed in column 12. Please note that these UR volumes are given in $10^6 m^3$ for gas as well as for oil accumulations.*

*The Valdemar field Danian & Upper Cretaceous chalk (Valdemar UC) and the Lower Cretaceous carbonate (Valdemar LC) reservoir levels are listed separately as 14a and 14b.*

| | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|
| | **Field** | **Area ($km^2$)** | **Depth to reservoir (m)** | **Hydrocarbon type** | **Condensate on production** | **Expected ultimate recovery restored to reservoir conditions per 1.1.2001 ($10^6 m^3$)** |
| **1** | Dagmar | 9 | 1.400 | **Oil** | | 1.34 |
| **2** | Dan | 22 | 1.850 | **Oil** with a gas cap | | 187.65 |
| **3** | Gorm | 8 | 2.100 | **Oil** | | 70.54 |
| **4** | Halfdan | 80 | 2.100 | **Oil** with a gas cap | | 57.43 |
| **5** | Harald East | 6.5 | 2.700 | **Gas** | Condensate | 20.70 |
| **6** | Kraka | 20 | 1.800 | **Oil** with minor gas cap | | 8.98 |
| **7** | Regnar | 3 | 1.700 | **Oil** | | 1.24 |
| **8** | Roar | 20 | 2.025 | **Gas** with minor oil zone | Condensate | 51.64 |
| **9** | Rolf | 8 | 1.800 | **Oil** | | 6.09 |
| **10** | Skjold | 14 | 1.600 | **Oil** | | 58.82 |
| **11** | Svend | 19 | 2.500 | **Oil** | | 6.51 |
| **12** | South Arne | 35 | 2.800 | **Oil** | | 47.24 |
| **13** | Tyra | 100 | 2.000 | **Gas** with thin oil zone | Condensate | 214.71 |
| **14a** | Valdemar | 15 | 2.000 | **Oil** and **gas** | Condensate | 7.66 |
| **14b** | Valdemar | 65 | 2.600 | **Oil** | | 3.97 |
| | | | | | | |
| **15** | Harald West | 8.5 | 3.650 | **Gas** | Condensate | 53.38 |
| **16** | Lulita | 3 | 3.525 | **Oil** with a gas cap | | 3.25 |
| **17** | Siri | 10 | 2.060 | **Oil** | | 9.06 |

**Table 1b.** *Selected field data. The expected ultimate recoveries (UR) restored to underground reservoir conditions, thus expressing the volume potentially available for* $CO_2$ *storage, are listed in column 12. Please note that these UR volumes are given in* $10^6 m^3$ *for gas as well as for oil accumulations.*

*The Valdemar field Danian & Upper Cretaceous chalk (Valdemar UC) and the Lower Cretaceous carbonate (Valdemar LC) reservoir levels are listed separately as 14a and 14b.*

| 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|
| | **Field** | **Wells producing** | **Wells water injection** | **Wells gas injection** | **Year on stream** | **Operator** |

| | **Field** | **Wells pro-ducing** | **Wells water injection** | **Wells gas injection** | **Year on stream** | **Operator** |
|---|---|---|---|---|---|---|
| **1** | Dagmar | 2 | ÷ | ÷ | 1991 | Mærsk Oil |
| **2** | Dan | 57 | 40 | ÷ | 1997 | Mærsk Oil |
| **3** | Gorm | 31 | 14 | 2 | 1981 | Mærsk Oil |
| **4** | Halfdan | 5 | 1 | ÷ | 2000 | Mærsk Oil |
| **5** | Harald East | 2 | ÷ | ÷ | 1997 | Mærsk Oil |
| **6** | Kraka | 7 | ÷ | ÷ | 1991 | Mærsk Oil |
| **7** | Regnar | 1 | ÷ | ÷ | 1993 | Mærsk Oil |
| **8** | Roar | 3 | ÷ | ÷ | 1996 | Mærsk Oil |
| **9** | Rolf | 2 | ÷ | ÷ | 1986 | Mærsk Oil |
| **10** | Skjold | 21 | 7 | ÷ | 1982 | Mærsk Oil |
| **11** | Svend | 3 | ÷ | ÷ | 1996 | Mærsk Oil |
| **12** | South Arne | 6 | 2 | ÷ | 1999 | Amerada Hess |
| **13** | Tyra | 40 | ÷ | 20 | 1984 | Mærsk Oil |
| **14a** | Valdemar | 1 | ÷ | ÷ | 1993 | Mærsk Oil |
| **14b** | Valdemar | 4 | ÷ | ÷ | 1993 | Mærsk Oil |
| | | | | | | |
| **15** | Harald West | 2 | ÷ | ÷ | 1997 | Mærsk Oil |
| **16** | Lulita | 2 | ÷ | ÷ | 1998 | Mærsk Oil |
| **17** | Siri | 5 | 2 (combined w+g injection) | | 1999 | Statoil (per Aug. 2002 DONG) |

**Table 1c.** *Selected field data. The expected ultimate recoveries (UR) restored to underground reservoir conditions, thus expressing the volume potentially available for $CO_2$ storage, are listed in column 12. Please note that these UR volumes are given in $10^6 m^3$ for gas as well as for oil accumulations.*

*The Valdemar field Danian & Upper Cretaceous chalk (Valdemar UC) and the Lower Cretaceous carbonate (Valdemar LC) reservoir levels are listed separately as 14a and 14b.*

| | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|
| | **Field** | **Expected ultimate recovery restored to reservoir conditions per 1.1.2001 ($10^6 m^3$)** | **Produced water per 1.1.2001 ($10^6 m^3$)** | **Water injection per 1.1.2001 ($10^6 m^3$)** | **Gas injection per 1.1.2001 ($10^9 m^3$ surface $Nm^3$)** |
| **1** | Dagmar | 1.34 | 3.19 | ÷ | ÷ |
| **2** | Dan | 187.65 | 20.54 | 73.67 | ÷ |
| **3** | Gorm | 70.54 | 22.72 | 60.24 | 8.13 |
| **4** | Halfdan | 57.43 | 0.29 | 0.10 | ÷ |
| **5** | Harald East | 20.70 | c. 0.03 | ÷ | ÷ |
| **6** | Kraka | 8.98 | 2.30 | ÷ | ÷ |
| **7** | Regnar | 1.24 | 2.01 | ÷ | ÷ |
| **8** | Roar | 51.64 | 0.77 | ÷ | ÷ |
| **9** | Rolf | 6.09 | 4.09 | ÷ | ÷ |
| **10** | Skjold | 58.82 | 21.75 | 56.01 | ÷ |
| **11** | Svend | 6.51 | 2.28 | ÷ | ÷ |
| **12** | South Arne | 47.24 | 0.07 | 0.05 | ÷ |
| **13** | Tyra | 214.71 | 17.36 | ÷ | 23.39 |
| **14a** | Valdemar | 7.66 | c. 0.15 | ÷ | ÷ |
| **14b** | Valdemar | 3.97 | c. 0.15 | ÷ | ÷ |
| | | | | | |
| **15** | Harald West | 53.38 | c. 0.03 | ÷ | ÷ |
| **16** | Lulita | 3.25 | 0.02 | ÷ | ÷ |
| **17** | Siri | 9.06 | 2.19 | 5.01 | 0.23 |

**Table 1d.** *Selected field data. The expected ultimate recoveries (UR) restored to underground reservoir conditions, thus expressing the volume potentially available for $CO_2$ storage, are listed in column 12. Please note that these UR volumes are given in $10^6 m^3$ for gas as well as for oil accumulations.*

*The Valdemar field Danian & Upper Cretaceous chalk (Valdemar UC) and the Lower Cretaceous carbonate (Valdemar LC) reservoir levels are listed separately as 14a and 14b.*

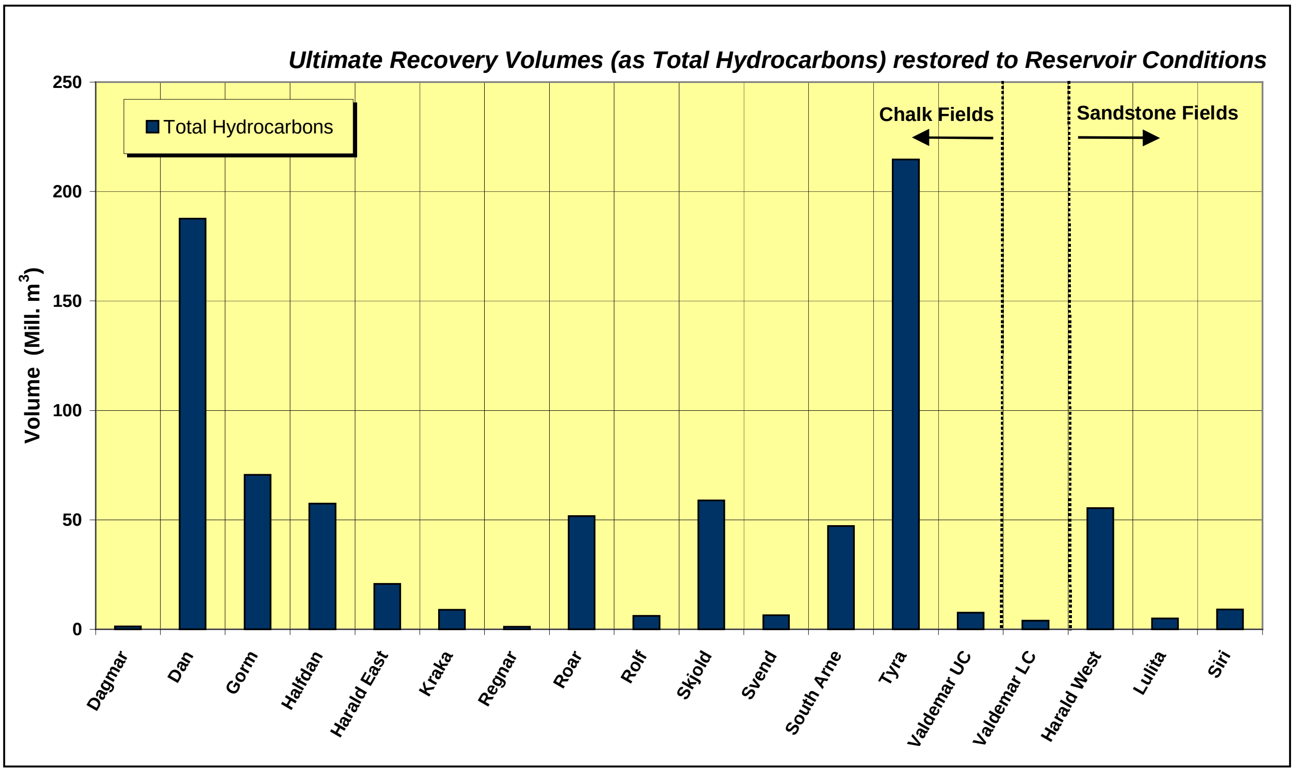


**Figure 2.** *Bar chart of Danish hydrocarbon fields $CO_2$ potential storage capacities expressed as total hydrocarbons* ***ultimate recovery volumes*** *restored to reservoir conditions.*

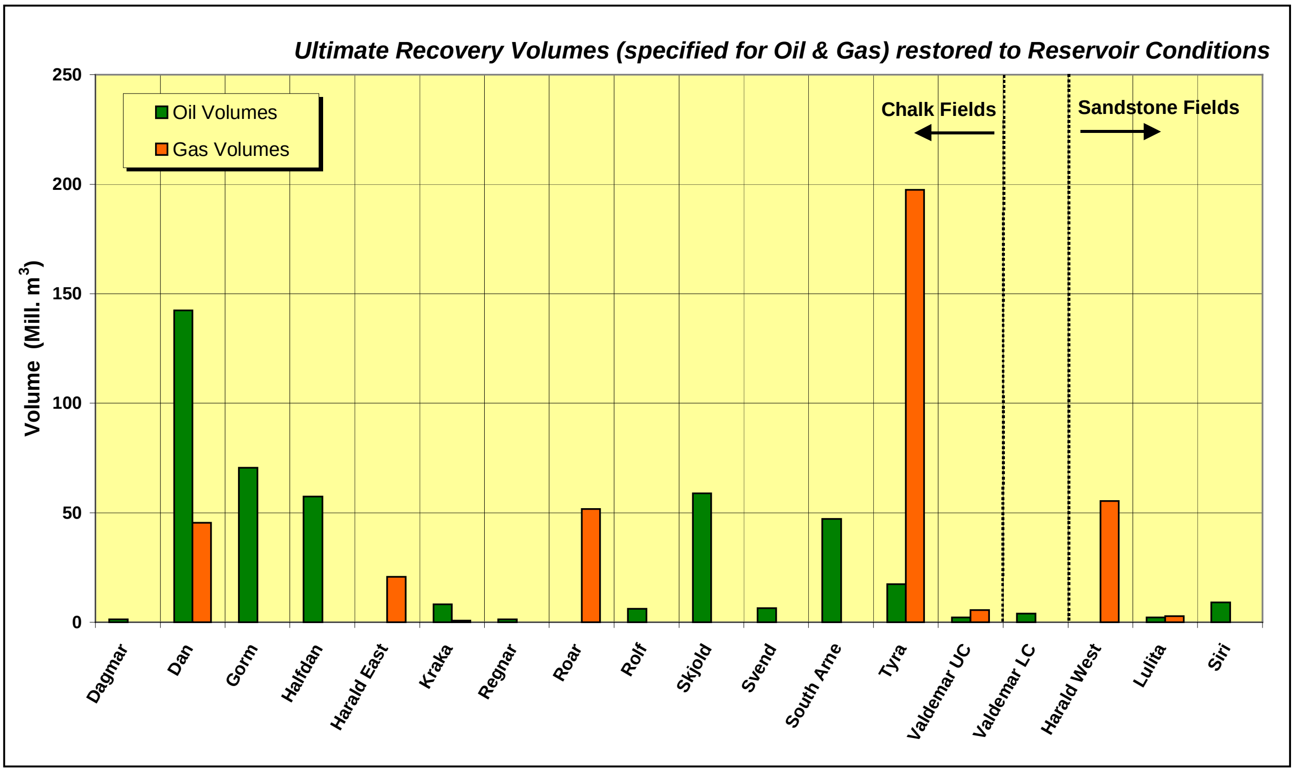


**Figure 3.** *Bar chart of Danish hydrocarbon fields $CO_2$ potential storage capacities expressed as oil and gas* ***ultimate recovery volumes*** *restored to reservoir conditions.*

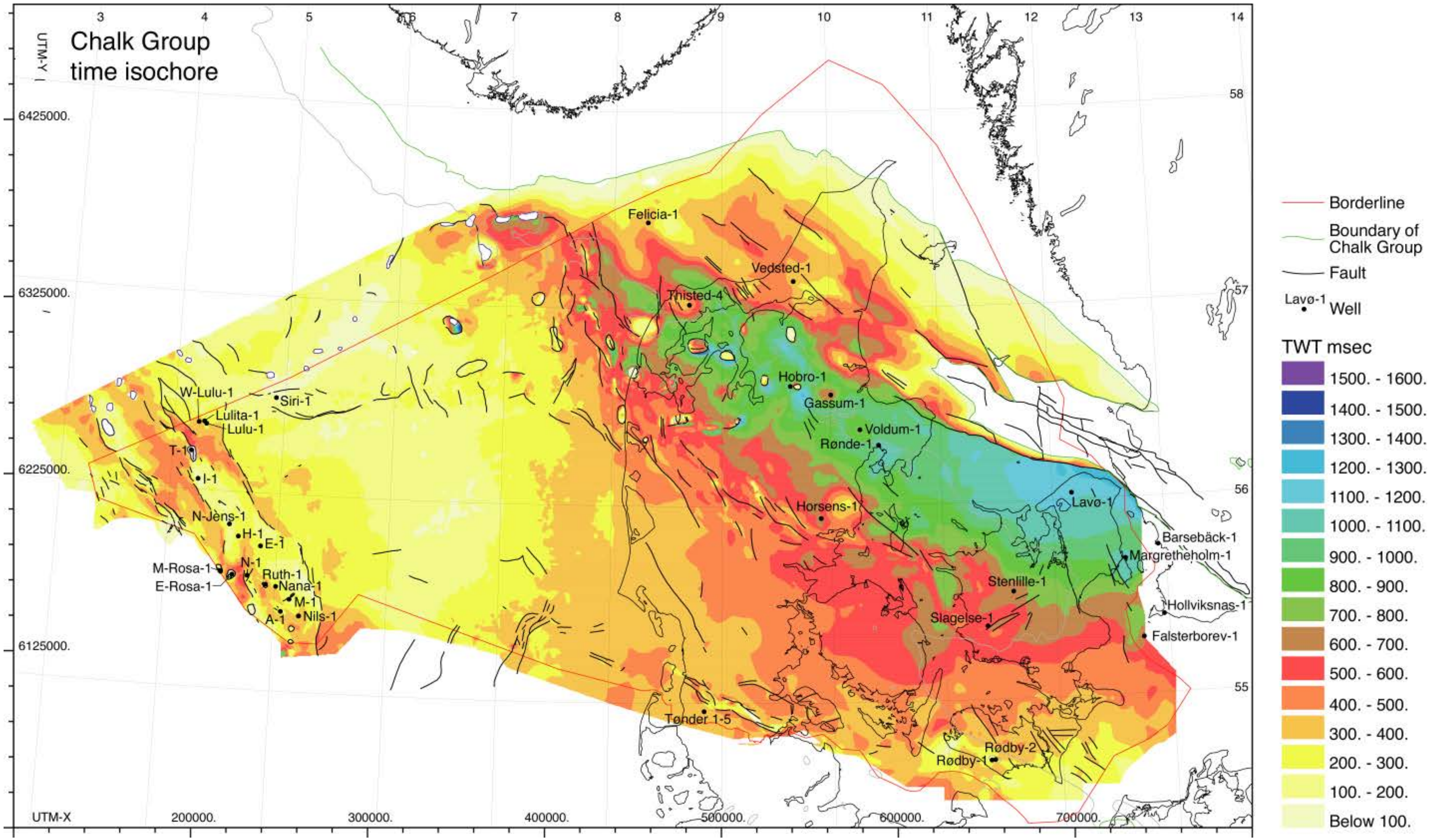


**Figure 4.** *Time-thickness map in two-way-time (TWT) of Chalk Group in Danish area (Vejbæk et al. 2003). The Chalk Group is contoured in intervals of 100 milliseconds TWT, which depending on local velocities correspond to approximately 150 to 200 metre. Wells in the North Sea Central Graben area are hydrocarbon field discovery wells. Wells in the eastern Danish area are selected exploration wells relevant to the GESTCO study.*

| MATRIX FIELDS | HYDRO-CARBONS | MATRIX PO-ROSITY (%) | MATRIX PER-MEABILITY (mD) | NATURAL FRACTURES | PRODUCTION STRATEGY |
|---|---|---|---|---|---|
| Dan | Gas cap<br>**Oil** | 22 - 34 | 0.3 - 2 | none | Fracturing<br>Water injection + natural depletion<br>Horizontal production wells |
| Gorm | **Oil** | 25 - 35 | 0.3 - 5 | few | Water injection<br>Horizontal production wells |
| Halfdan | (Gas cap)<br>**Oil** | 20 - 30 | 1 - 2 | few | Natural depletion + water injection<br>Horizontal production wells |
| Harald East | **Gas** | 15 - 40 | 0.1 - 5 | none | Natural depletion<br>Horizontal production wells |
| Roar | **Gas**<br>Minor oil | 35 - 45 | 2 - 20 | few | Natural depletion<br>Horizontal production wells |
| South Arne | **Oil** | 25 - 45 | 1 - 10 | few | Natural depletion + water injection<br>Horizontal production wells |
| Tyra | **Gas**<br>Thin oil zone | up to 50 | 1 - 25 | few | Gas injection<br>Horizontal production wells |
| Valdemar UC | **Gas**<br>**Oil** | 37 - 47 | 1 - 20 | none | Natural depletion<br>Horizontal production wells |

| FRACTURE FIELDS | HYDRO-CARBONS | MATRIX PO-ROSITY (%) | MATRIX PER-MEABILITY (mD) | NATURAL FRACTURES | PRODUCTION STRATEGY |
|---|---|---|---|---|---|
| Dagmar | **Oil** | 15 - 30 | < 1 | *Central part:*<br>Highly fractured<br><br>*Flanks:*<br>Less fractured | Natural depletion |
| Regnar | | | | | Natural depletion |
| Rolf | | | | | Natural depletion |
| Skjold | | | | | Water injection; hor. prod. wells |
| Svend | | | | | Natural depletion; hor. prod. wells |
| Kraka | Minor gas cap<br>**Oil** | 24-32 | < 1 | many | Natural depletion<br>Horizontal production wells |

**Table 2.** *Danish chalk fields divided into the major types matrix fields and fracture fields. Listed with type of hydrocarbons, reservoir rock conditions and production strategies. 'Horizontal production wells' refers primarily to 'layer boundary parallel wells' but also includes 'deviated wells'. Based on compilation by L. Kristensen (pers. com.).*

# Chalk fields

## Dagmar

The Dagmar field is a domal structure, induced through Zechstein salt tectonics. The field covers an area of c. 9 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk and locally Zechstein carbonates. The chalk has matrix permeabilities <1 mD and is naturally heavily fractured. Dagmar is an oil field with no gas cap. The field is compartmentalised to some degree.

The field is produced through primary recovery.

## Dan

The Dan field is a domal structure, induced through Zechstein salt tectonics. The field covers an area of c. 22 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. The matrix permeabilities of the chalk are generally 0.3-2 mD and the chalk has no natural fractures. Dan is an oil field with a gas cap, and the initial volume-in-place oil:gas ratio was c. 7:1. A major fault divides the field into two separate reservoir blocks.

The field is produced from 57 production wells and recovery is increased through water injection from at present 40 wells and through hydraulic fracturing.

An additional oil discovery on the west flank of the field, stretching from the Dan field towards the Halfdan field and possibly merging with this, is not included in the Energy Agency reserves estimates, and for this reason the Dan West flank occurrence is not shown on the field map.

## Gorm

The Gorm field is a domal structure partly induced by Zechstein salt tectonics. The field covers an area of c. 8 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. The chalk has matrix permeabilities of generally 0.3-5 mD and has natural fractures to a minor degree. Gorm is an oil field with no gas cap. A major fault divides the field into two separate reservoir blocks. The western of these blocks is intersected by numerous, minor faults.

The field is produced from 31 production wells supported by water injection from at present 14 wells. The Gorm Processing Centre receives associated gas produced from the Dagmar, Gorm, Skjold and Rolf oil fields. This gas is normally passed on to the Tyra Processing Centre for exportation to land through pipeline or for injection into the Tyra Field. When gas export from the Gorm Centre to Tyra for some reason is interrupted, the gas is injected into the Gorm field through two gas injection wells.

## Halfdan

The Halfdan field is an accumulation in Danian & Upper Cretaceous chalk. The present trapping type may be termed stratigraphic, since the accumulation is without structural closure. However, the field is interpreted as an initial domal structure, which because of inversion movements north-east of the accumulation were later tilted to removal of the structural closure. This caused the trapped hydrocarbons to migrate. Because of low permeabilities and local hydrodynamic conditions this occurs very slowly, and pressure data indicate that the hydrocarbons are at present migrating towards the south-east into the Dan field. The field covers an area of c. 80 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. The chalk has matrix permeabilities of generally 1-2 mD and no natural fractures. Halfdan is an oil field with a gas cap above the north-eastern part of the oil accumulation.

The field went on stream year 2000. It is produced initially through natural depletion, but water injection will be implemented stepwise to support reservoir pressure. At present 5 production wells and 1 water injection well are active.

The Halfdan storage capacity calculated for this report ought to be regarded as a minimum figure. The oil and gas reserves listed by the Energy Agency appears to be developed reserves and not total field ultimate recovery. The free gas is evidently not included in the reserves estimates which is in compliance with a status as undeveloped with no gas producers planned or drilled yet. It is possible that the free gas for practical reasons is ascribed to the related Igor/Sif discovery, which at present is classified as one of the "future developments" by the Energy Agency.

## Harald East

The Harald East field is a domal structure, induced through Zechstein salt tectonics. The field covers an area of c. 6.5 $km^2$.

The primary reservoir is Danian chalk. The chalk has matrix permeabilities of generally 0.1-4 mD and no natural fractures. The field contains gas with condensate. Stacked, secondary reservoirs occur in Maastrichtian chalk, which contains an economically marginal oil occurrence, and in Upper Jurassic sandstone, which contains very subordinate amounts of gas. These secondary oil and gas occurrences may not be produced, and their related reservoir volume is therefore not reflected in the calculation of the storage capacity.

The field is produced by natural depletion through 2 production wells.

## Kraka

The Kraka field is a domal structure, induced through Zechstein salt tectonics. The field covers an area of c. 20 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. The chalk has matrix permeabilities <1 mD and is naturally fractured. Kraka is an oil field with a minor gas cap.

The field is produced from 7 production wells through natural depletion.

## Regnar

The Regnar field is a domal structure, induced through Zechstein salt tectonics. The field covers an area of c. 3 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk and very subordinate Zechstein dolomites. The chalk has matrix permeabilities <1 mD and is naturally highly fractured. Regnar is an oil field with no gas cap.

The field is produced from 1 crestal production well through natural depletion.

## Roar

The Roar field is an anticlinal structure, induced by Tertiary inversion tectonics. The field covers an area of c. 20 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. The chalk has rather high matrix permeabilities of generally 2-20 mD and has few natural fractures. Roar is a gas-condensate field with a minor oil zone.

The field is produced from 3 production wells through natural depletion.

## Rolf

The Rolf field is a domal structure, formed through Zechstein salt tectonics. The field covers an area of c. 8 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk and subordinate Zechstein dolomite. The chalk has matrix permeabilities <1 mD and is naturally highly fractured. Rolf is an oil field with no gas cap.

The field is produced from 2 crestal production wells through natural depletion.

## Skjold

The Skjold field is a domal structure, formed through Zechstein salt tectonics. The field covers an area of c. 14 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. The chalk has matrix permeabilities <1 mD and is naturally highly fractured. Skjold is an oil field with no gas cap.

The field is produced from 21 mainly horizontal production wells and water injection from at present 7 wells to support production.

## Svend

The Svend field is a domal structure, formed through Zechstein salt tectonics. The field consists of a northern and a southern accumulation positioned closely together. The total field covers an area of c. 19 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. The chalk has matrix permeabilities <1 mD and is naturally highly fractured. Svend is an oil field with no gas cap.

The field is produced from 3 wells through natural depletion.

## South Arne

The South Arne field is an anticlinal structure, formed through compressional inversion tectonics, probably in combination with Zechstein salt movements. The field covers an area of c. 35 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. Hydrocarbons are also accumulated in Lower Cretaceous chalk which is, however, considered non-reservoir because of low permeabilities. The Danian/Upper Cretaceous chalk has matrix permeabilities in the range 1-10 mD, and has few natural fractures. South Arne is an oil field with no gas cap.

The field is produced from 6 wells, and reservoir pressure is supported by water injection from at present 2 wells.

## Tyra

The Tyra field is an anticlinal structure, formed through compressional inversion tectonics. The field covers an area of c. 100 $km^2$.

The reservoir rock is Danian & Upper Cretaceous chalk. The chalk has rather high matrix permeabilities generally in the range 1-25 mD, and has few natural fractures. Tyra is a gas-condensate field with a thin underlying oil zone.

The field is produced through 40 vertical and horizontal wells. To produce as much as possible of the oil and condensate, the reservoir pressure is maintained at high levels by gas injection from at present 20 wells. The demand for injection gas is met by increased gas production from particularly the Harald and Roar gas fields.

## Valdemar

The Valdemar field consists of three anticlinal structures – the North Jens, the Bo and the Boje structure – formed through compressional inversion tectonics. The Boje structure is at present classified as "future developments", but for consistency storage capacity has been estimated also for this structure, and the data given thus includes all three structures combined.

The reservoir is stacked consisting of Danian & Upper Cretaceous chalk and of Lower Cretaceous carbonate rock. The combined field (North Jens + Bo + Boje structure) covers an area of c. 15 $km^2$ at the Danian/Upper Cretaceous chalk level and c. 65 $km^2$ at the Lower Cretaceous carbonate rock level. The Danian/Upper Cretaceous chalk has matrix permeabilities in the range 3-21 mD, while the Lower Cretaceous carbonate has matrix permeabilities in the range 0.2-2 mD. At Danian/Upper Cretaceous chalk level the North Jens structure contains oil+gas, the Bo structure contains gas, and the Boje structure contains oil. At Lower Cretaceous carbonate level all structures contain oil.

Because of the very low matrix permeabilities (0.2-2 mD) of the Lower Cretaceous carbonate it is unlikely that this reservoir level should be suitable for storage of carbon dioxide maybe unless in combination with $CO_2$ EOR efforts.

At present only the North Jens structure has been developed. The production relies on natural depletion through horizontal wells of which two are active.

# Sandstone fields

## Harald West

The Harald West field structure is a tilted Jurassic fault block. The field covers an area of c. 8.5 $km^2$.

The reservoir rock is sandstone of Middle Jurassic age. Harald West is a gas field with condensate. Significant compartmentalising is present in consequence of layering within the sandstone sequence and juxtaposition by many intersecting faults. A stacked but very subordinate, secondary hydrocarbon reservoir occur within the Upper Cretaceous chalk.

The field is produced with 2 production wells through natural depletion.

## Lulita

The Lulita field is a fault related, structural trap influenced by Zechstein salt tectonics. The field covers an area of c. 3 $km^2$.

The reservoir rock is sandstone of Middle Jurassic age. Lulita is an oil field with a gas cap. The field is compartmentalised to some degree.

The field is produced with 2 production wells through natural depletion.

## Siri

The Siri field is a complex of several accumulations (Siri Central, Siri North, Stine) which are domal, structural traps in part combined with stratigraphic component. The field covers an area of c. 10 $km^2$.

The reservoir rock is sandstone of Palaeocene age. Siri is an oil field.

In order to support the reservoir pressure, the field is produced through injection of water and of produced, associated gas. At present 5 horizontal production wells and 2 gas/water injection wells are active.

## Storage Prospects

Drilling of in-fill and appraisal wells is still ongoing in many of the fields, and at present no expected dates for exhaustion and subsequent abandonment can be given. Several of the chalk fields have experienced upgrading of reserves during recent years because of introduction of new play concepts involving non-structurally trapped oil on the flanks, and new fields have been identified through drilling confirming such trapping mechanisms (Albrecthsen et al. 2001). Some of the fields appear close to their point of exhaustion (see Figure 5: Gorm, Kraka, Rolf, Svend), but new evaluation may change this situation. Further Mærsk Olie og Gas AS, who is the principal oil and gas producer in the Danish area, hold their fields under a separate licence agreement which is active until July 2012.

Any possible plans for enhanced oil recovery using $CO_2$ injection into the reservoirs are presently not known.

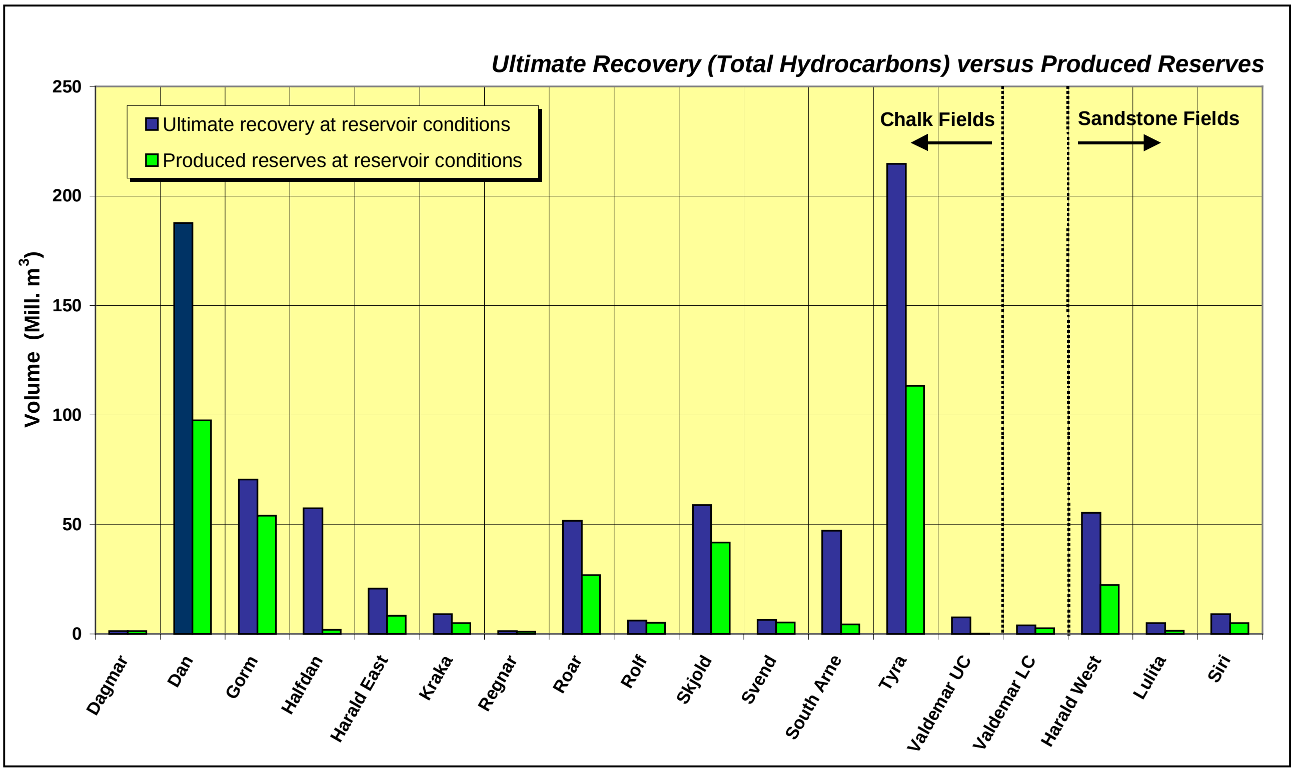


**Figure 5.** *Bar chart of Danish hydrocarbon fields total hydrocarbons* ***ultimate recovery volumes*** *and* ***produced*** *reserves per 1. January 2001, both restored to reservoir conditions.*

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