DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2008/12

Geologiske strukturer potentielt egnede til CO_2 lagring i Danmark

Bilag 1

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G E U S

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). This Danish part of the project comprised evaluation of the storage potential of hydrocarbon fields, deep saline aquifers and a combined application in geothermal energy systems (Andersen 2003; Mathiesen *et al.* 2003). This report describes the potential for CO_2 storage in deep saline aquifers in Denmark forming study area B in the Gestco proposal (Christensen 2000).

Large sedimentary basins of Late Palaeozoic-Cenozoic age are present in Denmark and provide a potential for CO_2 storage. Sandstones with good reservoir properties are thus known from the Lower Triassic Bunter Sandstone Formation, the Upper Triassic – Lower Jurassic Gassum Formation, the Middle Jurassic Haldager Sand Formation, and the Upper Jurassic – Lower Cretaceous Frederikshavn Formation.

The Gestco aquifer study has focused on sandstone formations within a depth range of 900–2500 m, i.e. between the depth required for CO_2 to become a dense fluid and the depth below which reservoir quality typically deteriorates. General studies suggest that diagenetic effects below approximately 2500 m depth have reduced porosity and permeability to a degree that in most cases make CO_2 injection practically impossible.

In a previous study the total storage capacity of unconfined aquifers in Denmark was estimated to be 47 Giga ton of CO_2, however, only a small part of the volume was related to structural closures (Holloway *et al.* 1996). In order to gain public and political acceptance, structural traps are considered essential, at least initially, when considering storage onshore Denmark, and consequently the Gestco study was focused on eleven large structures (Fig. 1). These structures were mapped from seismic surveys and evaluated using data from existing deep wells to assess the storage potential. The present study suggests that the eleven structures alone may provide storage for at least 16 Giga ton CO_2.

General geology

The geology of Denmark is characterised by a thick cover of sedimentary rocks of Late Palaeozoic – Cenozoic age. In the Danish Basin the sedimentary succession are up to 9 km thick (Fig. 1). The basin is bounded to the north by the Fennoscandian Border Zone characterised by a relatively thin succession of Triassic, Jurassic and Early Cretaceous age. To the south the Danish Basin is bounded by the northwest–southeast striking basement high, the Ringkøbing-Fyn-Møn High. The sedimentary cover on this structural high is relatively thin, 1–2 km and characterised by absence Upper Permian sediments, thin Triassic and thin or absence of Jurassic sediments. The North German Basin is situated south of the basement high with sediment thickness comparable to the Danish Basin.

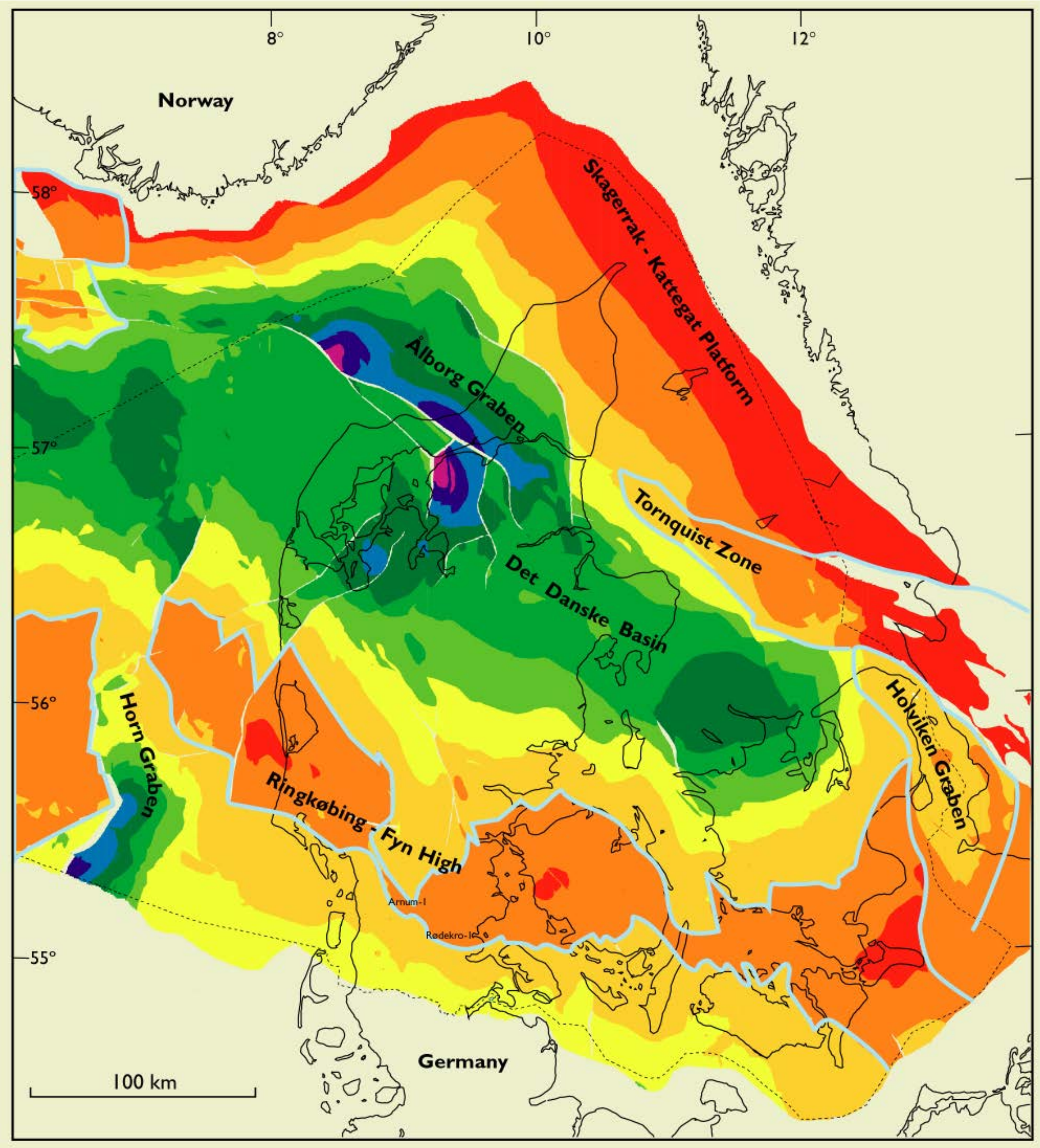

Figure 1. *Map showing major structural elements and depth (twt) to top Pre-Zechstein in Denmark. Modified from Vejbæk & Britze (1984).*

The sediments are affected by mainly northwest–southeast striking normal faults. In the Danish and North German Basin post depositional flow of Permian salt formed large domal structures, which strongly influenced later deposition. Locally the overlying sedimentary succession is deeply truncated over the top of rising saltdomes. Minor faults often accompany the salt structures.

The Central Graben area is present in the westernmost part of the Danish offshore area. Large hydrocarbon reserves are present in chalk of Late Cretaceous and Danian age in this region and active exploration and production are taking place (see related report by Andersen 2003). The Chalk Group continues and thicken eastwards into the onshore area of Denmark where it reaches between 1 and 2 km in thickness in the Danish Basin (Fig. 2). The presence of carbonates of the Chalk Group in the onshore and Kattegat areas may be of great importance providing a secondary chemical seal for CO_2 reservoirs situated in deep saline aquifers (Olsen & Stentoft 2003).

During the Cenozoic the North Sea constituted a large epicontinental sea with a north-south axis. The sediments are dominated by offshore mudstones reaching a total thickness of more than 3000 m in the western part of the Danish area (Michelsen 1994). Locally sandstones are present in the succession representing a target for hydrocarbon exploration and CO_2 storage, e.g. the Siri Canyon system.

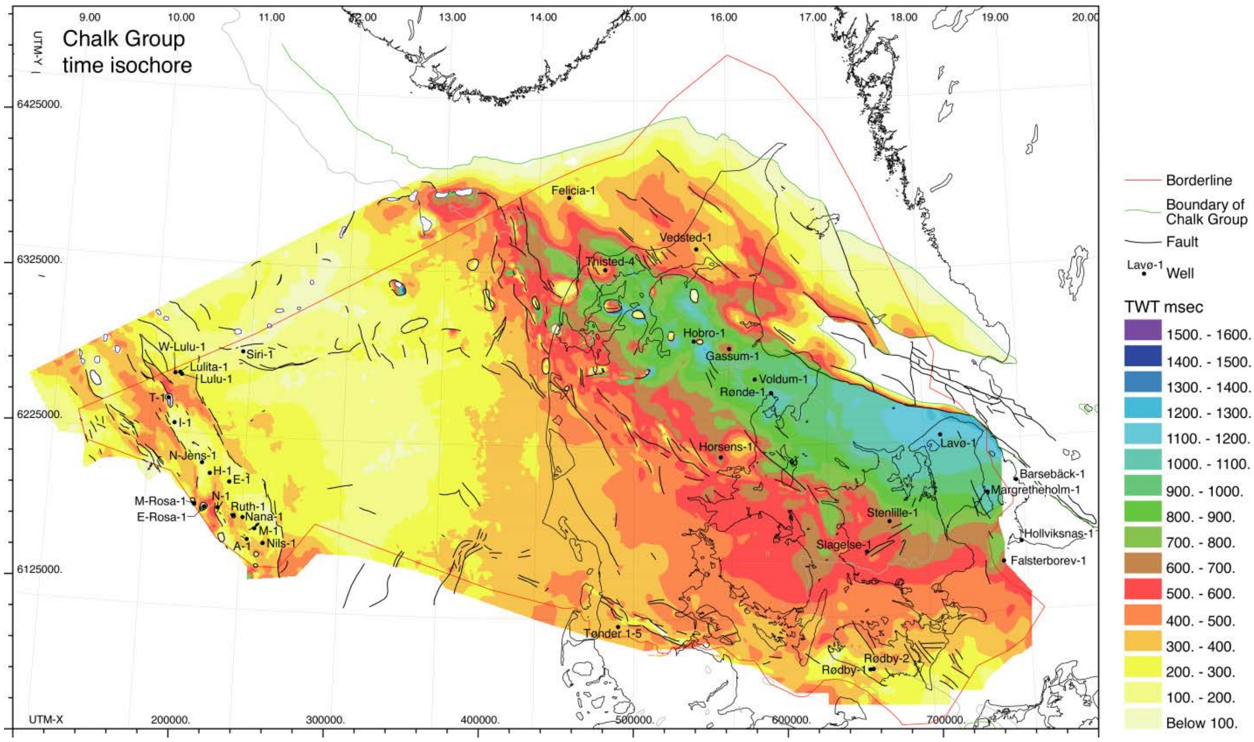

Figure 2. *Time-thickness map in two-way-time (TWT) of Chalk Group in Danish area contoured in intervals of 100 milliseconds (Vejbæk et al. 2003). The TWTmay be translated to thickness (100 msec ~ 150 to 200 m) depending on the density of the chalk. The thick carbonate rocks present above the Mesozoic aquifers may act as a secondary (chemical) seal to any CO_2 that may leak from the storage sites. Wells in the North Sea Central Graben area are hydrocarbon field finder wells. Wells onshore are selected exploration wells relevant to the GESTCO study.*

Deep saline aquifers

In the onshore or nearshore Danish area the potential reservoirs are of Mesozoic and Late Palaeozoic age. Mapping of these units has been performed in search for hydrocarbons and geothermal reservoirs (Michelsen 1981; Sørensen *et al*. 1998). Sørensen *et al*. (1998) summarises the reservoir parameters (porosity and permeability) whereas seal properties and presence of structural closures (trap) were not considered.

To supplement earlier studies this study was focused on four stratigraphic intervals (Fig. 3)

- Bunter Sandstone and Skagerrak Formations (Triassic)
- Gassum Formation (Upper Triassic–Lower Jurassic)
- Haldager Sand Formation (Middle Jurassic)
- Frederikshavn Formation (Upper Jurassic–Lower Cretaceous)

The burial depth versus reservoir properties makes the Gassum Formation the most attractive storage option and the formation is currently used as reservoir for liquid natural gas (LNG) by DONG in the Stenlille area. The large net sand thicknesses of the Bunter Sandstone/Skagerrak Formations, however, provides huge storage volumes although probably with low injectivity. Locally the Triassic formations may form excellent reservoirs as shown by the Lower Triassic Ljunghusen Formation in the Copenhagen-Malmö area.

With the exploration for hydrocarbons in Lower Paleogene sandstones on the platform area situated of the eastern margin of the Central Graben Offshore (Siri, Nini, Cecilie), new information have been gained from the Paleogene succession, although detailed well-data are still confidential (Energistyrelsen 2002). In this area saline aquifers which are not targets for hydrocarbon exploration may form possible reservoirs for future CO_2 storage in an analogue situation to the Utsira Formation of the Sleipner Field (Gale 2001). In a short-term view Paleogene sandstones form a possible secondary reservoir for CO_2 recovered during hydrocarbon production in the Danish Sector. The main geological problem for CO_2 storage will be updip closure of the aquifers. In the onshore and nearshore areas of the Danish Basin the Paleogene reservoirs are situated at shallow depths and have no storage potential.

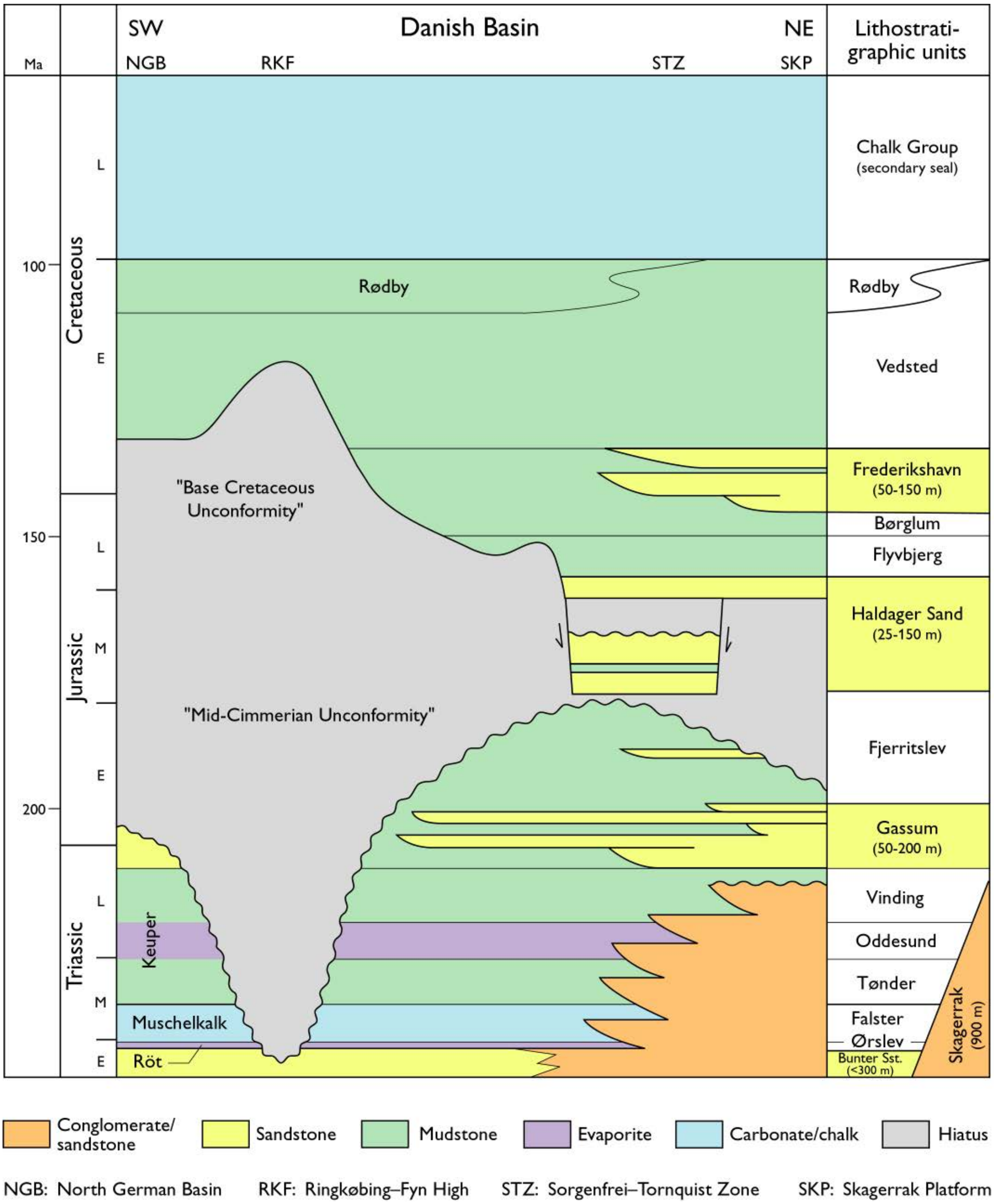

Figure 3. *Simplified stratigraphy and lithostratigraphy of the sedimentary succession in the Danish Basin. (Based on Bertelsen 1980, Michelsen & Clausen 2002; Michelsen et al. 2003).*

Bunter Sandstone/Skagerrak Formations (Triassic)

The Bunter Sandstone/Skagerrak Formations are present throughout the Danish area (Fig. 4A). Sandstones of the Bunter Sandstone Formation are dominant in the southernwestern and central part of the Danish area and are gradually replaced by the Skagerrak Formation towards the northeastern basin margin.

The Bunter Sandstone Formation represents deposition in an arid continental environment dominated by fluvial channels, aeolian dunes and marginal marine facies (Bertelsen 1980). The Skagerrak Formation is poorly known but the coarse-grained often poorly sorted lithology and the marginal extend along the northern and northeastern basin margin suggest deposition in alluvial fans (Bertelsen 1978, 1980).

The Lower Triassic sandstone dominated succession (Bunter Sandstone and Skagerrak) form a widespread unit with thickness around 300 m although it may reach 900 m in the central part of the Danish Basin. The succession is thin and locally absent across the Ringkøbing-Fyn-Møn High. It is anticipated that no strong primary hydraulic barriers exist within the sheet sandstone (Sørensen *et al*. 1998). The storage potential of the Bunter Sandstone Formation in the southern North Sea is evaluated in Brook *et al*. (2002).

Reservoir properties are poorly known and often based on estimates from petrophysic logs (Michelsen *et al*. 1981). The porosity estimates range between 0–24% (maximum 38%) whereas the permeability is generally low (10–100 mD) due to the relatively deep burial depth causing diagenetic changes and cement formation. Unexpected good reservoir properties have recently been found in the time equivalent Ljunghusen Formation in the Copenhagen area.

Three structurel traps are defined at Bunter Sandstone/Skagerrak stratigraphic level: Thisted/Legind, Tønder and Rødby. The formations may form an additional storage potential in the Vedsted, Gassum, Voldum, Pårup, Horsens, Havnsø and Stenlille structures, where the Triassic formations are present below the main reservoir unit.

Gassum Formation (Upper Triassic–Lower Jurassic)

The Gassum Formation consists of fine- to medium-grained, locally coarse-grained sandstones interbedded with heteroliths, claystones and locally thin coal beds (Michelsen *et al*. 2003; Nielsen *et al.* 2003). The sandstones were deposited by repeated progradation of shoreface and deltaic units forming laterally continuous sheet sandstones separated by offshore marine claystones. Fluvial sandstones dominate in the lower part of the formation in the Fennoscandian Border Zone.

The porosity and permeability of the Gassum sandstones are known from a number of wells and illustrate the relation between reservoir properties and depth in the Danish Basin (Fig. 5). Generally the reservoir properties are excellent with porosity 18–27% (maximum 36%) and permeabilities up to 2000 mD.

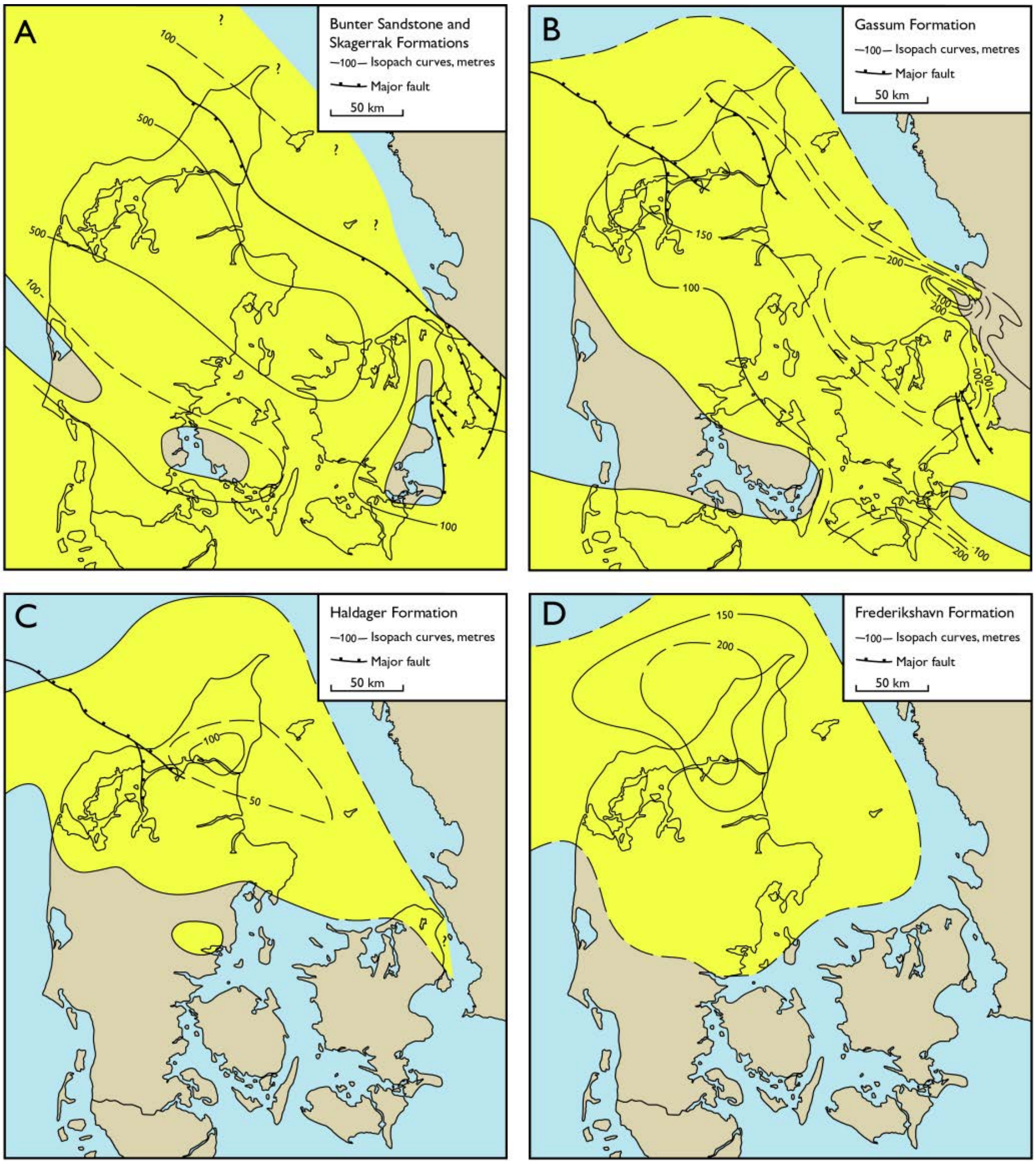

Figure 4. *Isopach maps showing the distribution and formation thickness of the four major sandstone units with potential for storage of CO2 in the Danish area. Modified from Michelsen et al. (1981) and Haenel & Staroste (1988).*

The Gassum Formation forms the reservoir in the Stenlille natural gas storage and has been studied in great detail (Nielsen *et al*. 1989; Hamberg 1994; Hamberg & Nielsen 2000; Nielsen 2003). The studies illustrate the facies complexity and the lateral variability present within the reservoir units. In the Stenlille area the formation is thus shown to consist of stacked shoreface units with excellent reservoir properties separated with thin claystone or heterolithic units. Each of these units may act as discrete reservoir units and is characterised by a set of porosity/permeability parameters. Based on palaeogeographic reconstructions it is anticipated that the net/gross sand contents will decrease towards the northwest. In order to properly evaluate the storage potential within the formation, it may thus be necessary to address the individual sandstone units.

The formation is present in the Danish Basin, the North German Basin and on the Ringkøbing-Fyn High in the Lolland Falster area (Fig. 4B). It shows a remarkable continuity with thickness between 100 and 150 m throughout most of Denmark, reaching a maximum thickness of 300 m in the Sorgenfrei-Tornquist Zone. The Gassum Formation is truncated by the base Cretaceous unconformity on the Ringkøbing–Fyn High.

Seven structural traps are defined at Gassum stratigraphic level: The Hanstholm, Vedsted, Gassum, Voldum, Pårup, Horsens, Havnsø and Stenlille structures. The formation acts as reservoir for storage of natural gas in Stenlille and as geothermal reservoir in the geothermal plant at Thisted.

Haldager Sand Formation (Middle Jurassic)

The Middle Jurassic Haldager Sand Formation consists of thick beds of fine- to coarse-grained, locally pebbly sandstones intercalated with thin siltstone, claystone and coal beds. Sandstones were deposited in a range of depositional environments covering shallow marine, estuarine, fluvial and lacustrine facies (Michelsen *et al*. 2003, Nielsen *et al.* 2003). Deposition was locally affected by synsedimentary movements of underlying salt structures. The formation is present in the central and northern part of the Danish Basin, in the Sorgenfrei-Tornquist Zone and on the Skagerrak-Kattegat Platform reaching a maximum thickness of 150 m (Fig. 4C). A marked thinning is seen southwest and northeast of the Sorgenfrei-Tornquist Zone. The porosity varies between 12 and 33% (maximum 42%) whereas permeabilities have only been estimated in two wells having 600 and 2000 mD respectively.

None of the studied storage structures have the Haldager Sand Formation as main reservoir unit, but the formation forms an upside storage potential in four structures: Vedsted, Voldum, Pårup and Horsens structures.

Frederikshavn Formation (Upper Jurassic–Lower Cretaceous)

The formation consists of siltstones and fine-grained sandstones forming 2–3 coarsening-upwards units separated by claystones (Michelsen *et al.* 2003). The formation is present in the northern part of the Danish Basin and reaches a maximum thickness of more than 230 m in the Sorgenfrei-Tornquist fault zone (Fig. 4D). Local faults and salt tectonics mainly control thickness variations. The most coarse-grained parts of the formation are present in the northeast towards the Skagerrak-Kattegat Platform whereas the formation interfingers with the fine-grained Børglum Formation towards the west (Michelsen *et al.* 2003) .

None of the described storage structures have the Frederikshavn Formation as main reservoir unit, but the formation forms an upside storage potential in Vedsted, Horsens and Gassum and Voldum structures.

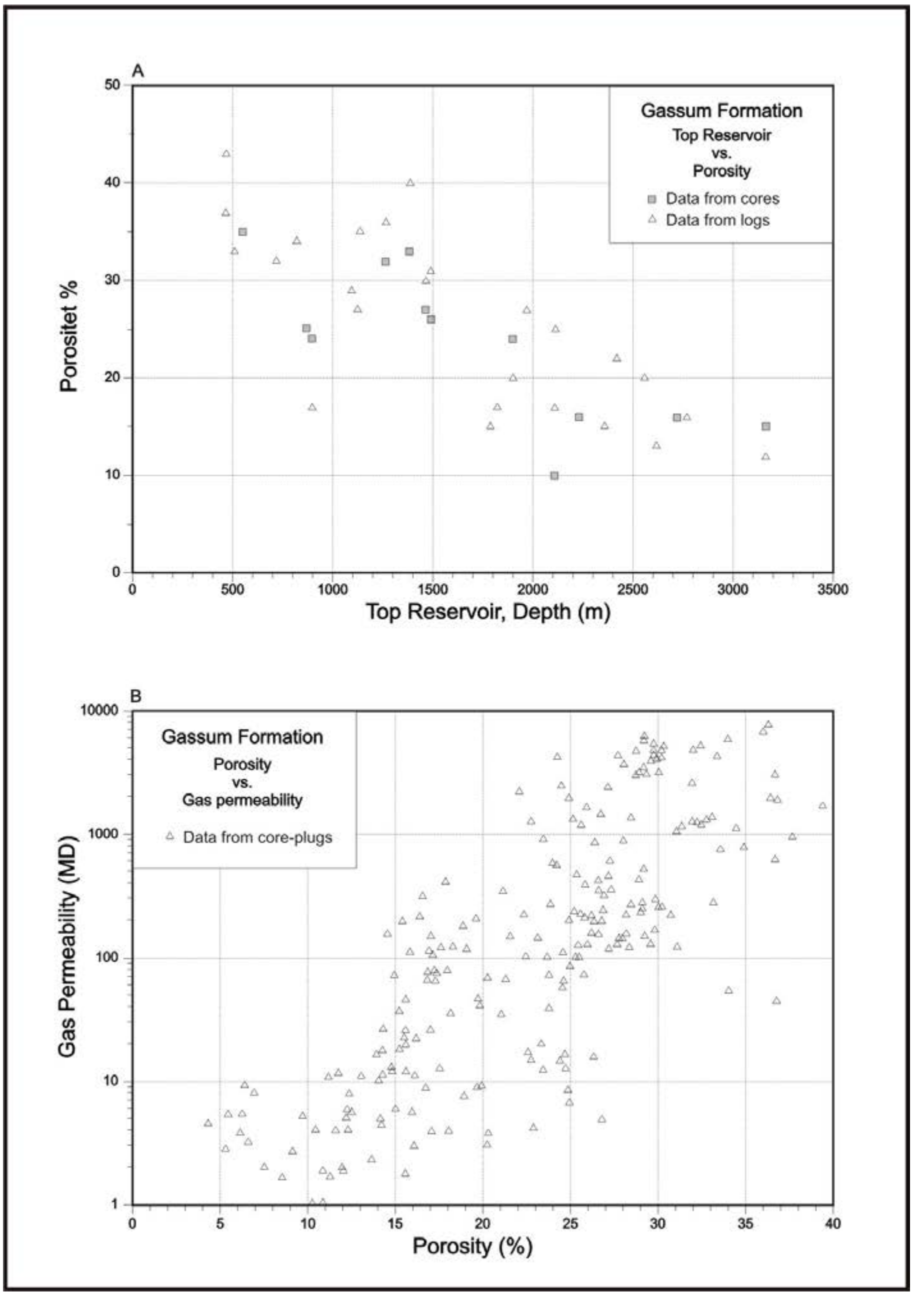

Figure 5. *Porosity and permeability versus depth for the Upper Triassic–Lower Jurassic Gassum Formation. From Sørensen et al. (1998).*

Geothermal reservoirs

The sandstone reservoirs forming a potential for recovery of geothermal energy are identical to the deep saline aquifers discussed in this study, however the combination of CO_2 storage with geothermal return water may result in conflicts of interest in relation to geothermal production and safety. The aquifers used for geothermal reservoirs form study area E of the original Gestco proposal (Christensen 2000) and are discussed in a separate report (Mathiesen *et al.* 2003).

Seal

The aquifer storage of CO_2 is dependent not only on the properties of the reservoir but also on the integrity of the sealing formation. Geological formations in Denmark with sealing properties are lacustrine and marine mudrocks, evaporites and carbonates. The most important sealing rock type in the Danish area is marine mudstone, which is present at several stratigraphic levels. Leakage may take place through the cap rock due to slow capillary migration, through micro-fractures or along faults. Detailed site surveys will be needed in order to test the integrity of the seal at future storage sites.

At Stenlille natural gas storage site marine mudstones of the Lower Jurassic Fjerritslev Formation form the sealing formation. The mudrock was tested before the beginning of the gas injection. The seal has proven tight to natural gas stored in the Gassum reservoir below.

Ørslev Formation (Röt)

The Lower Triassic Ørslev Formation was defined by Bertelsen (1980) to include a lower evaporitic unit overlain by calcareous claystones. The evaporites were deposited in a playa or salt lake, whereas the claystones represents low energy continental plain deposits (Bertelsen 1980). A revised stratigraphy for the Triassic was suggested by Michelsen & Clausen (2002). They suggest that the name Ørslev Formation should be replaced by the Röt Formation currently used for a similar stratigraphic unit in the North German Basin.

The formation is transitional to the coarse-grained deposits of the Skagerrak Formation forming the northern edge of the depositional system. The fine-grained Ørslev Formation reaches 100–400 m in thickness south of the Ringkøbing-Fyn High. It forms the primary seal for the Bunter Sandstone Formation in the Rødby and Tønder structures.

Falster Formation (Muschelkalk)

The Middle Triassic Falster Formation was defined by Bertelsen (1980) for a unit characterised by intercalated limestones, claystones and halites. Fine-grained sandstones are locally present in the upper part of the formation. The fine-grained sediments were deposited in a sabkha environment interchanging with a shallow marine environment open to the south. Michelsen & Clausen (2002) suggested that the name Falster Formation should be replaced by the Muschelkalk Formation currently used for a similar stratigraphic unit in the North German Basin. The formation reaches 100–200 m in thickness and forms a secondary seal for the Bunter Sandstone Formation in the Rødby and Tønder structures.

Oddesund Formation (Keuper)

The Upper Triassic Oddesund Formation was defined by Bertelsen (1980) for a unit characterised by calcareous, anhydritic claystones and siltstones intercalated with thin beds of dolomitic limestone. In the central part of the Danish Basin two prominent units of halite is present dividing the formation into three informal members. The formation varies in thickness due to syndepositional halokinesis of the underlying Zechstein salt and reaches a maximum thickness of 1500 m.

The claystones and evaporites were deposited in a brackish to hypersaline environment in periodically flooded sabkhas and ephemeral lakes (Bertelsen 1980). Michelsen & Clausen (2002) suggested that the name Oddesund Formation should be replaced by the Keuper Formation currently used for a similar stratigraphic unit in the North German Basin. The fine-grained formation forms the primary seal for the Skagerrak Formation in the Thisted/Legind structure.

Fjerritslev Formation

Marine mudstones of the Lower Jurassic Fjerritslev Formation form the primary sealing unit for the Gassum Formation. The formation overlies and locally interfingers with the sandstones of the Gassum Formation.

The formation is characterised by a relatively uniform succession of marine, slightly calcareous claystones, with varying content of silt and siltstone laminae. Siltstones and fine-grained sandstones are locally present being most common in the northeastern, marginal areas of the Danish Basin. Deposition took place in a deep offshore to lower shoreface environment (Michelsen 1975, 1978, Michelsen *et al*. 2003). The formation is present over most of the Danish Basin with a thickness of up to 1000 m although this varies significantly due to mid-Jurassic erosion. Detailed studies of the integrity against natural gas have been made by DONG at the Stenlille natural gas storage.

Flyvbjerg and Børglum Formations

The Flyvbjerg Formation consists primarily of siltstones and fine-grained sandstones with poor reservoir quality and is thus not regarded a primary seal. However, it directly overlies the Haldager Sand Formation and thus may act as a transitional formation into the sealing claystones of the overlying Børglum Formation.

The Upper Jurassic Børglum Formation consists of a uniform succession of slightly calcareous claystones. The sediments were deposited in an offshore marine environment (Michelsen *et al*. 2003). The Børglum Formation is present in most of the Danish Basin and reaches a maximum thickness of 300 m towards the Fjerritlev Fault. It rapidly thins towards the northeast, south and southwest. The marine mudstones of the Børglum Formation form the primary sealing formation for the Haldager Sand Formation

Vedsted and Rødby Formations

Marine mudstones of the Vedsted and Rødby Formations form the primary sealing formation for the Frederikshavn Formation.

Chalk Group

In most of the Danish area a several kilometres thick succession of carbonate rocks of Late Cretaceous – Danian age forms a possible secondary seal (Fig. 2). The sealing effect is dependent on chemical reactions between dissolved CO_2 and the carbonate rock. These reactions are described in detail in the Gestco report on the CO_2 – Carbonate system by Olsen & Stentoft (2003).

Definition of potential storage sites

In order to gain public and political acceptance, structural traps are considered essential, at least initially, when considering saline aquifer storage onshore Denmark. Storing CO_2 in defined traps in the subsurface allow continuous monitoring of the fate of the injected CO_2 and eventually meets the demand for future recovery of all or parts of the injected gas.

In the Gestco project eleven structures are included in the calculations of the total storage potential (Fig. 6 and Table 1) and are described in detail in Appendix 1. These structures were defined from existing seismic surveys. The reservoir and seal properties of the formations were evaluated using data from exploration wells drilled at the site or at nearby structures.

The structures were selected on the basis ofa number of criteria:

1. The top of the reservoir should be situated deeper than 900 m below the surface (the CO_2 gas changes into a supercritical fluid around 800 m).
2. The reservoir should be situated at depths less than 2500 m in order to ensure that enough porosity/permeability is preserved (unless well data were present to validate porosity and permeability values)
3. The structure should be of significant size (storage capacity approximately 100 Mtonnes)
4. A proper seal (cap rock) should be present
5. The structure and seal should be unfaulted
6. The structure should be within reasonable distance from a CO_2 source

A number of structures were described, but excluded from the final list due to problems of satisfying one or more of the above criteria. These structures may form additional storage sites, but detailed site-specific studies are needed in order to prove their ability to store CO_2. The most common problem was the presence of faults either at the top of domal structures or forming the updip closure of traps. The fault bounded traps, however form an interesting storage type along the Ringkøbing-Fyn-Møn High were domal storage structures are lacking.

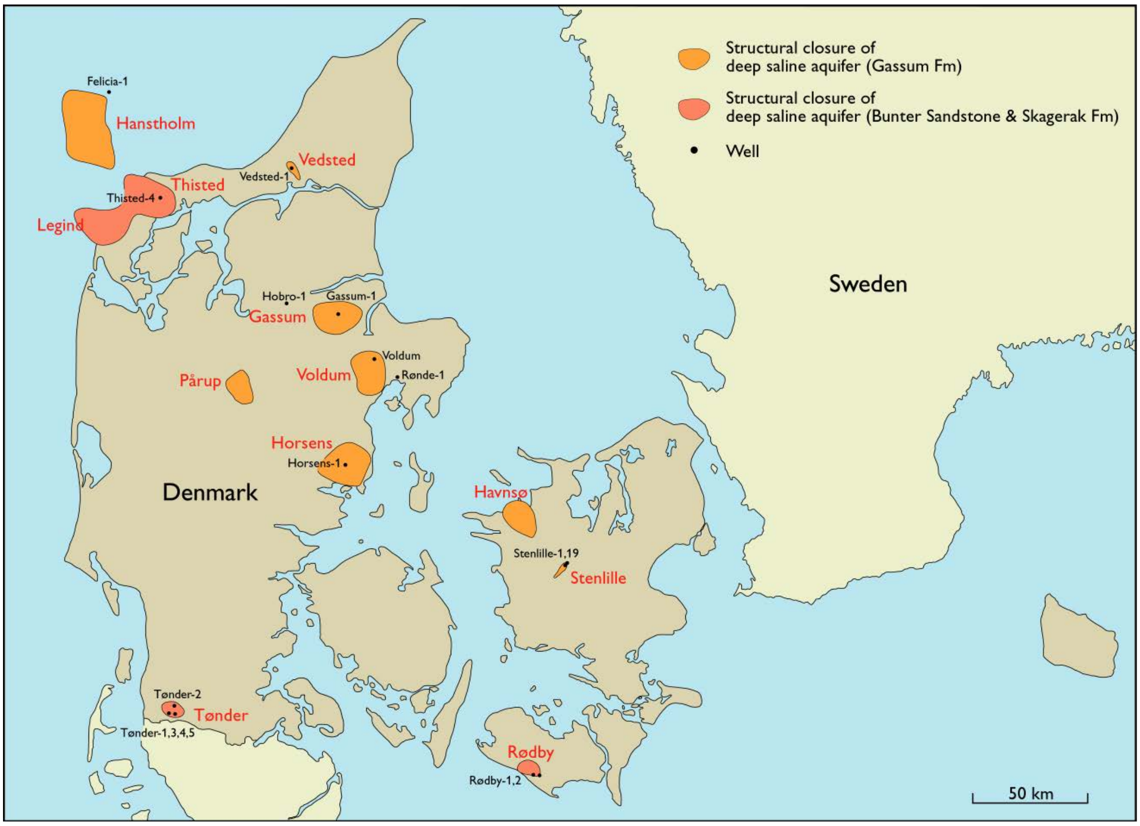

Figure 6. *Map showing the position and outline of the eleven structural closures mapped in this study. Black dots indicate the position of deep exploration wells used in the evaluation of the reservoir formation.*

Name	Reservoir	Seal	Well at structure
Hanstholm	Gassum Fm.	Fjerritslev Fm.	-
Gassum	Gassum Fm.	Fjerritslev Fm.	Gassum-1
Havnsø	Gassum Fm.	Fjerritslev Fm.	-
Horsens	Gassum Fm.	Fjerritslev Fm.	Horsens-1
Pårup	Gassum Fm.	Fjerritslev Fm.	-
Rødby	Bunter Sandstone Fm.	Ørslev/Falster Fm.	Rødby-1, -2
Stenlille	Gassum Fm.	Fjerritslev Fm.	Stenlille1–19
Thisted/Legind	Skagerrak (Bunter) Fm.	Oddesund/Vinding Fm.	Thisted-2, -4
Tønder	Bunter Sandstone Fm.	Ørslev/Falster Fm.	Tønder1–5
Vedsted	Gassum Fm.	Fjerritslev Fm.	Vedsted-1
Voldum	Gassum Fm.	Fjerritslev Fm.	Voldum-1

Table 1. *Table giving the name, reservoir and sealing formation for the eleven mapped structures.*

Storage capacity in open and closed aquifer

In the Joule II project (Holloway *et al*. 1996) the saline aquifers were divided into open and closed systems, the latter representing storage potential within traps. The two types were assigned different reservoir properties. In the open aquifers the CO_2 phase is allowed to displaced the pore fluids within the entire extent of the aquifer.

In the case of closed systems the pore fluid is not allowed to migrate outside the closure of the trap. This results in instantaneous pressure increase at the beginning of CO_2 injection and a storage volume that is restricted by the compressibility of the pore fluid and the rock phase.

In this study the aquifers of the eleven structural closures are considered unconfined meaning that the saline formation water may be displaced to the aquifer outside the closure by the injected CO_2. It is however assumed that the injected CO_2 will stay within the closure defined by the structural trap.

Dissolution of CO_2 into the formation water

CO_2 is dissolvable into water as demonstrated by sparkling water. The dissolution process is controlled mainly by temperature, pressure and salinity. Under normal geological conditions between 5 and 8% CO_2 may be dissolved. The rate of dissolution is dependent on the efficiency of mixing at the CO_2/water interface.

CO_2 is more buoyant and much less viscous than the saline formation water. Depending on the injection point the CO_2 will migrate from the head of the injection well towards the top of the aquifer trap. During this process a small proportion of the CO_2 will dissolve in the formation water. By choosing an injection point at the flank of the structures instead of the top the amount of CO_2 dissolved into the formation water may be increased due to the longer migration path of the CO_2.

Simulation of the reactions between the formation water and the injected CO_2 show that there is a slow but continuous diffusion of CO_2 also after the CO_2 has reached the top of the structure. This process may in a long time perspective (thousands of years) remove all of the free injected CO_2 phase from the trap (Ennis-King & Paterson 2003).

Storage capacity

Evaluation of the storage capacity for CO_2 in Denmark was presented in the Joule II report (Holloway *et al.* 1996). The report concluded that 47 Giga ton CO_2 could be stored in the unconfined onshore aquifers of Triassic and Jurassic age based on the assumption that 2% of the entire pore volume of the mapped formations were filled. Restricting the storage to confined traps reduced the estimated total storage capacity to 5.6 Giga ton CO_2 due to the momentaneous pressure increase.

The low storage efficiency (2%) was based on reservoir simulations indicating that the CO_2 would spill from the traps before a significant amount of the formation pore space was filled. In this study we limit the calculations to structural traps with well-defined spill points. Based on experience from LNG storage facilities in Denmark, Germany and France we assume that 40% of the total pore volume within a trap may be filled with CO_2. The effective storage capacity will depend on a number of parameters including the geometry of the trap e.g. difference in height between top point and spill point, number of injection wells and injection rates, migration barriers within the reservoir unit and reservoir characteristics.

Several reservoir units are present in a number of the described structures. These stacked reservoir units provide an upside potential for storage increasing the total storage capacity. The secondary reservoir units are, however, often poorly known and storage volumes have not been calculated for these units. The storage capacity presented in Table 2 is thus calculated on the primary reservoir unit alone.

Conclusions

The Gestco study of the storage capacity of deep saline aquifers in Denmark was focused on eleven structural traps with main reservoirs in the Triassic Bunter Sandstone and Skagerrak Formations and the Upper Triassic – Lower Jurassic Gassum Formation. The structures were mapped from existing seismic lines and evaluated using exploration wells to assess the storage potential. A simple reservoir simulation was performed on the Havnsø Structure in order to validate calculated storage capacities. The present data suggest that the eleven structural traps alone may provide storage for at least 16 Giga ton CO_2 assuming that the effective storage capacity is 40% of the total pore volume within the trap (Table 2). Unfaulted, thick units of claystones or evaporites seal the traps. The integrity of the cap rock to CO_2 has not been questioned and no risk analysis were made in this study.

Structure	Stratigraphy	Formation	Available from	Area	Top depth msl	Gross thick	Net / gross	Net sand	Porosity	Pore volume	Effective storage volume	Reservoir density of CO_2	Storage capacity
				km^2	m	m		m	%	km^3	%	kg/m^3	Mt CO_2
Gassum	U. Trias - L. Jurassic	Gassum	2002	242	1460	130	0.32	53	25	2,517	40	627	631
Hanstholm[a]	U. Trias - L. Jurassic	Gassum	2002	603	1000	230	0,40	92	20	11,095	40	620	2752
Havnsø[a]	U. Trias - L. Jurassic	Gassum	2002	166	1500	150	0.67	100	22	3,670	40	629	923
Horsens	U. Trias - L. Jurassic	Gassum	2002	318	1506	94	0.26	24	25	1,943	40	630	490
Pårup[a]	U. Trias - L. Jurassic	Gassum	2002	121	1550	130	0.23	30	10	0,362	40	625	90
Rødby	E. Triassic	Bunter Sst.	2002	55	1125	256	0.18	45	24	0,608	40	620	151
Stenlille[b]	U. Trias - L. Jurassic	Gassum	Not available	10	1507	130	0.76	100	25	0,247	40	631	62
Thisted	E. Triassic	Skagerrak	2002	649	1166	747	0,6	449	15	43,632	40	641	11187
Tønder[c]	E. Triassic	Bunter Sst.	2002	53	1615	203	0.17	35	20	0,366	40	634	93
Vedsted	U. Trias - L. Jurassic	Gassum	2002	31	1898	139	0,74	103	20	0,638	40	633	161
Voldum	U. Trias - L. Jurassic	Gassum	2002	235	1757	128	0.38	30	10	1,143	40	630	288
Total storage capacity													**16867**

[a] Extrapolated values, [b] Presently a natural gas storage operated by DONG, [c] Reserved for Natural Gas Storage

Table 2. *Table listing the key data for the eleven aquifer structures evaluated for future CO_2 storage in Denmark*

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Appendix

This appendix contains background information for the eleven aquifer traps mapped in this study. The structures are listed in alphabetical order. The estimate of the CO_2 storage capacity given for each structure is based on a number of generalisations and assumptions described below.

Area: The outline of the closures were digitised and plotted using ArcView 8.0 (Lambert Conformal Conical Projection of the WGS84 ellipsoid). The area is automatically given by the GIS system.

Temperature: The reservoir temperature of undrilled structures and wells without temperature data is calculated from the regional geothermal gradient 50°C+(30°C /1000m)(depth msl – 1500m) (Niels Beck, GEUS pers.com 2003).

Pressure: The aquifers are considered to react as open reservoirs meaning that the reservoir pressure is assumed to equal the hydrostatic pressure, P_{hyd} = g x row x depth (g=9.81 m/sec^2 and row = density of water ~1000 kg/m^2)

The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).

Porosity and permeability data are sparse for the Danish onshore area. Measured values are referred to in the text. In structures without well data values are extrapolated from nearby wells or calculated using a regional porosity/permeability plot (Sørensen et al. 1998). Difference in vertical versus horizontal permeability values is not taken into account.

The net/gross values are estimated by the use of a well specific cut off value for the gamma (GR) or spontaneous potential (SP) log. This method only allows separation of sand (reservoir) and shale (nonreservoir) units and does not account for poor reservoir sand quality etc.

The storage volumes are based on the physical pore volume present in the trap. It is assumed that reaction between reservoir rock and CO_2 is negligible.

Reservoir density of CO_2 is calculated by the use of PVTsim (Calsep 2000) as a function of pressure and temperature.

The diffusion of CO_2 into the formation water has not been taken in to account when calculating the maximum storage volume. Diffusion would increase the volume of CO_2 that can be stored in a given structure.

Unfaulted, thick units of claystones or evaporites seal the traps. The integrity of the cap rock to CO_2 has not been questioned.

Gassum structure

The structure is situated in the eastern part of Jutland and has been defined at the level of the Upper Triassic – Lower Jurassic Gassum Formation (Fig. 7).

General geological setting

The structure is situated in the central part of the Danish Basin. The structure is caused by uplift due to post depositional salt tectonics.

Well database

The seal and reservoir is penetrated by the Gassum-1 well situated close to the top point of the structure. The data for the Gassum aquifer is extrapolated from the deep wells Gassum-1, Hobro-1 and Voldum-1 (Fig. 8 and Table 3).

Seismic coverage

The structure is interpreted from the depth structure map of the “Top Triassic” as defined by Japsen and Langtofte (1991) (Fig. 7).

Storage quality

Sandstones of the Gassum Formation form the primary reservoir in the Gassum structure with an expected porosity up to 25 % and a permeability around 300–2000 mD (Table 3). The permeability figures, however are based on petrophysical log interpretations that are very doubtful due to old and poor logs (Michelsen 1981).

Depth to top reservoir in the Gassum-1 well is 1460 m below msl. In the Gassum-1 well the Gassum Formation is 130 m thick. With a net/gross value of 0.32 this leads to a net sand thickness of 53 m. It is expected that the reservoir will be compartmentalised by layers of heteroliths and claystones (Fig. 9).

Subsurface storage capacity

The closure is defined by an almost circular domal structure approximately 800 m high with very steep flanks. The last closing contour is at 2300 m depth and defines an area of approximately 242 km^2. The spill point is situated towards the south. The pressure and temperature are expected to follow the normal Danish gradients and lead to an estimated maximum storage capacity of 705 Mt CO_2 for the Gassum aquifer.

Seal

The marine mudstones of the Fjerritslev Formation are 320 m thick in the Gassum-1 well and form the primary seal of the aquifer (Fig. 8).

Major CO_2 emission points

Randers power plant is situated within a distance of 10 km from the Gassum structure. The annual emission, however is rather limited (0.28 Mtonnes/year) compared to the size of the structure. The Gassum structure is situated within a distance of 50 km from the city of Århus with several major point sources (total emission 3.63 Mtonnes/year).

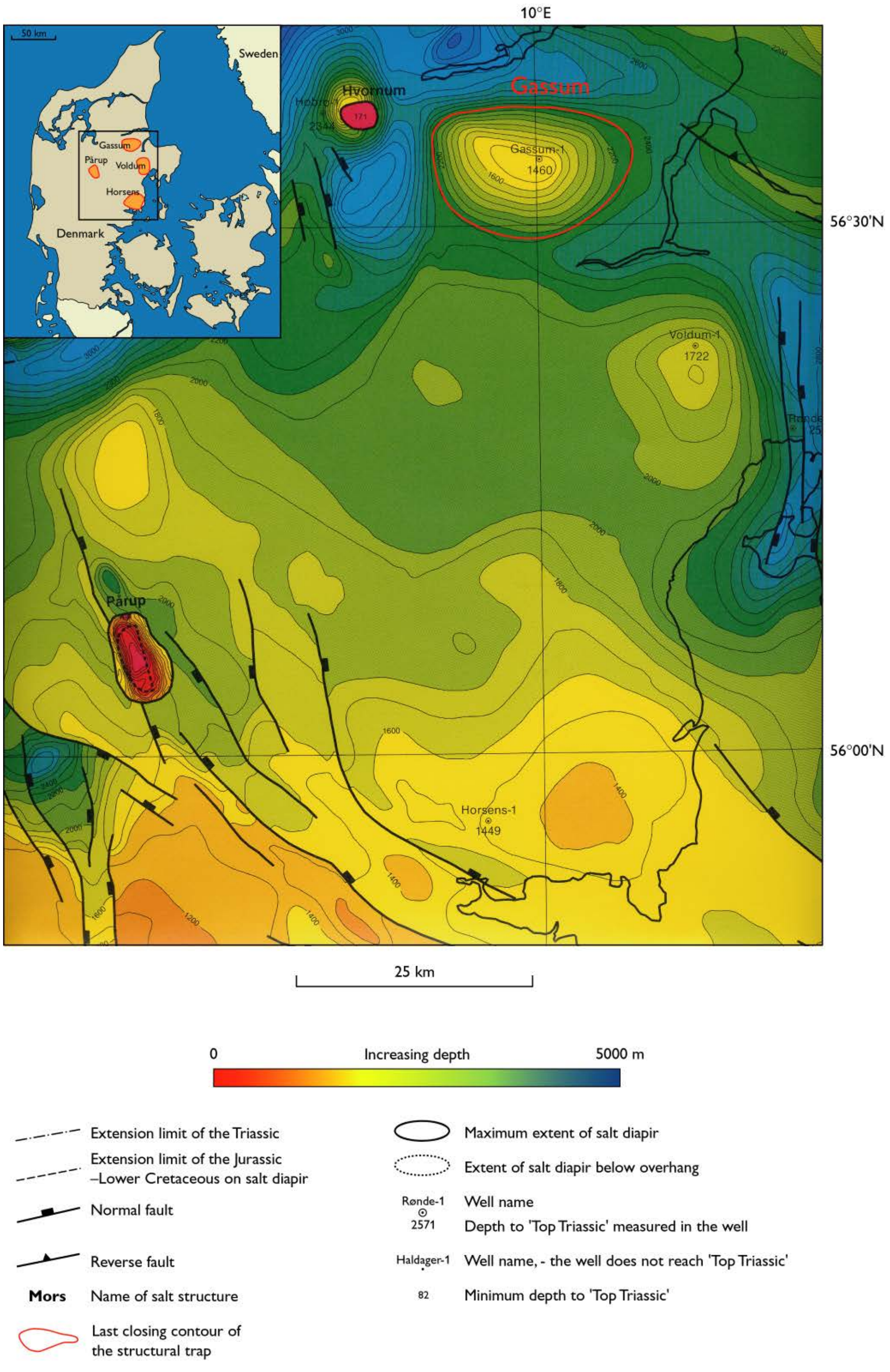

Figure 7. *Outline of the structural trap defining the potential storage site at Gassum . The structure is interpreted from the depth structure map of the "Top Triassic" as defined by Japsen and Langtofte (1991).*

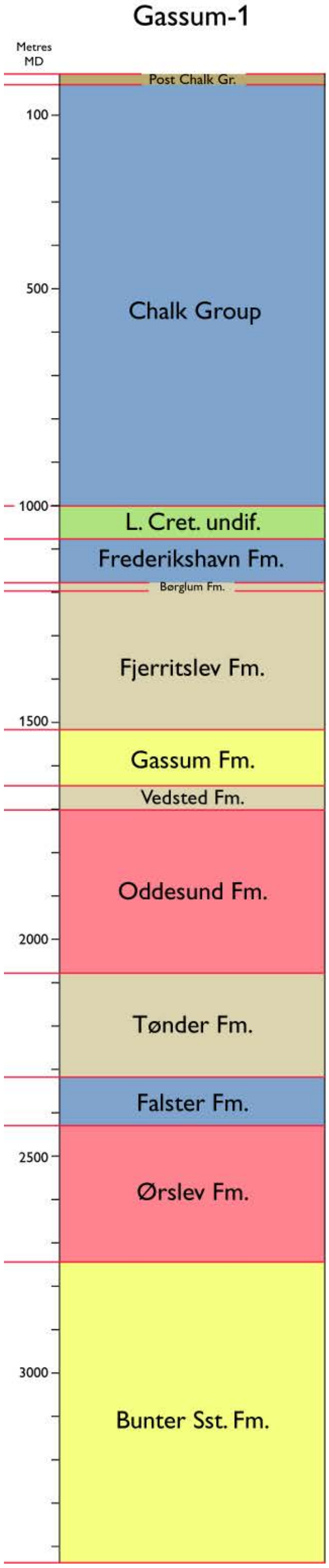

Figure 8. *Stratigraphic depth section of the Gassum-1 well showing the lithostratigraphic units and their thickness. The main reservoir in sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

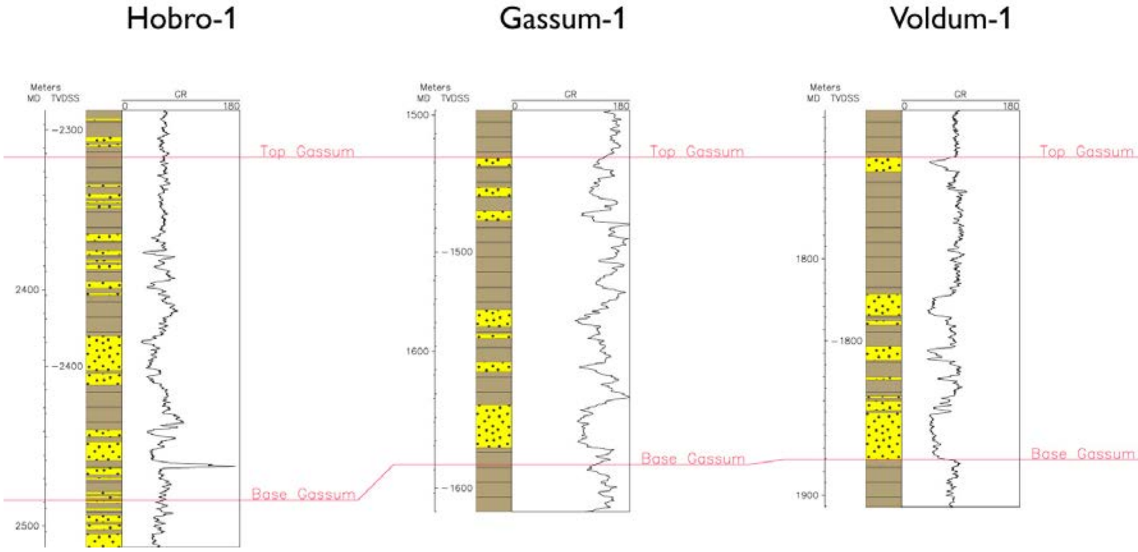

Figure 9. *Petrophysical well logs of the Hobro-1, Gassum-1 and Voldum-1 wells showing the interpreted sand/shale ratios and lateral variability of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991).*

Gassum	Stratigraphic units with possible reservoirs			Reservoirs					
Wells	Name	Depth Interval MD m	Gross Reservoir Thick. m	SAND Cut-off Value	Net Reser-voir Thick. m	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Voldum-1	Lower Cretaceous undiff.	1212-1278	66						
	Gassum Fm.:	1722-1850	128	71.5 API GR	30	0.23	F-15 (avg. 8%)		
Gassum-1	Lower Cretaceous undiff.	944-1020	76						
	Gassum Fm.:	1460-1590	130	133.5 API GR	53	0.41	C-26	G-2000, L-300	
	Bunter Sandstone Fm.	2689-3383	694		690	0.99	C-15	G-100	

Table 3. *Table listing the wells drilled at the Gassum structure and nearby and reservoir characteristics of stratigraphic units with potential for storage of CO_2 . The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981).*

Hanstholm structure

The informal name Hanstholm structure is used for an offshore domal closure at Gassum Formation level situated approximately 40 km northwest of the city of Hanstholm (Fig. 10). The water depth at the site of the structure is approximately 30 m.

General geological setting

The structure is situated close to the edge of the Fjerritslev Fault of the Sorgenfrei-Tornquist zone. The main sediment input during the Triassic–Jurassic was from the north-east. The structure is caused by uplift due to post depositional salt tectonics.

Well database

The structure has not been drilled. Well information is extrapolated from the nearby Felicia-1 well (Figur 10 and Table 4). It should be noted however, that Felicia-1 is drilled at the crest of a rotated fault block, whereas the Hanstholm structure is situated further downdip of the footwall block. This may result in marked differences in reservoir properties between the well and the undrilled structure.

Seismic coverage

The structure is interpreted from the depth structure map of the “Top Triassic” as defined by Japsen and Langtofte (1991) (Fig. 10).

Storage quality

Sandstones of the Upper Triassic – Lower Jurassic Gassum Formation form the main reservoir unit of the structure. As the structure is undrilled no direct information on reservoir quality is available. Based on log interpretation in the Felicial-1 well the aquifer is assigned a porosity of 20 % whereas no values are given for the permeability (Table 4).

Subsurface storage capacity

The structure is a huge domal closure covering 603 km^2. The depth to top reservoir is approximately 850 m below msl. and the last closing contour is at approximately 1350 m. The spill point is situated at the southeastern flank of the structure leading into the Thisted domal structure (Fig. 10). Using the existing seismic survey and well information from Felicia-1 the reservoir unit is expected to have a thickness of approximately 230 m with a net/gross of 0.40 (Fig. 12). This results in an estimated maximum storage capacity of 3107 Mt CO_2. The estimate however, is based on a number of assumptions and thereby holds a large uncertainty. For tabulated figures of the Hanstholm aquifer see Table 4.

Seal

The claystones of the Fjerritslev Formation form the top seal of the aquifer. The Fjerritslev Formation is expected to be approximately 500 m thick above the Hanstholm aquifer (Fig. 11).

Major CO_2 emission points

The Hanstholm structure is situated approximately 100 km from the major emission sources in the city Ålborg (5.06 Mtonnes/year) including two public power stations and a cement plant. However, the size of the structure makes it attractive for CO_2 sources covering most of Jylland.

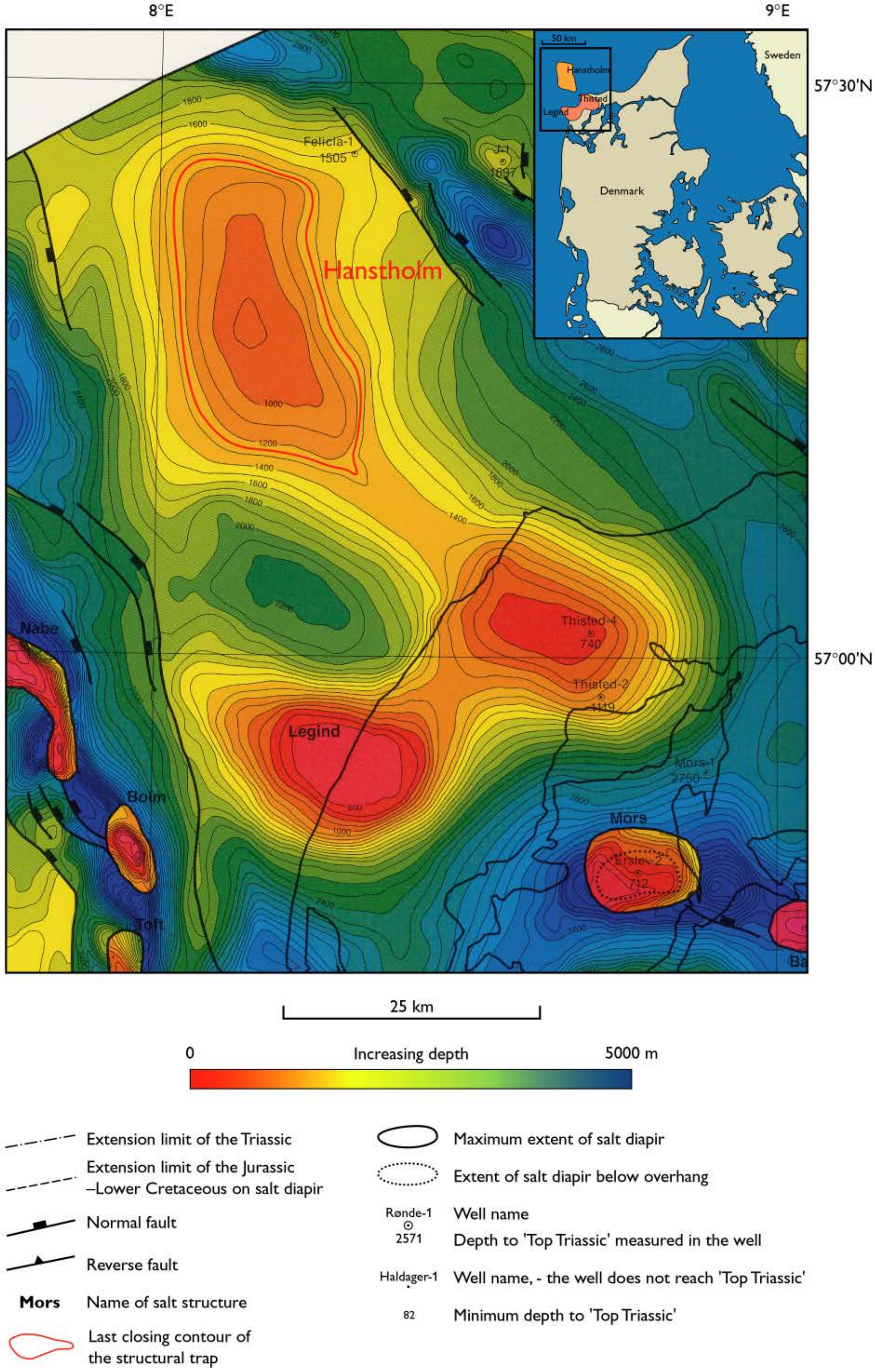

Figure 10. *Outline of the structural trap defining the potential storage site at Hanstholm. The structure is interpreted from the depth structure map of the "Top Triassic" as defined by Japsen and Langtofte (1991).*

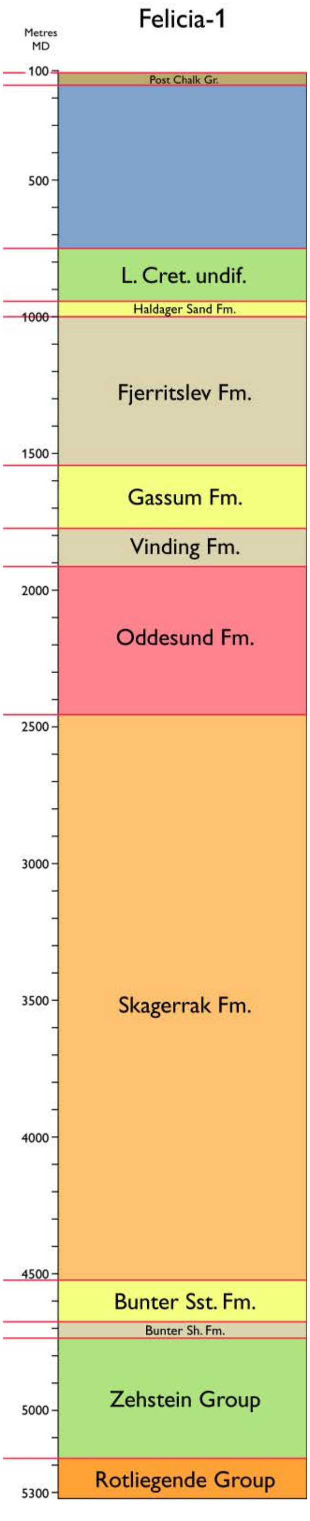

Figure 11. *Stratigraphic-depth section of the Felicia-1A well showing the lithostratigraphic units and their thickness. The main reservoir is sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

Felicia-1

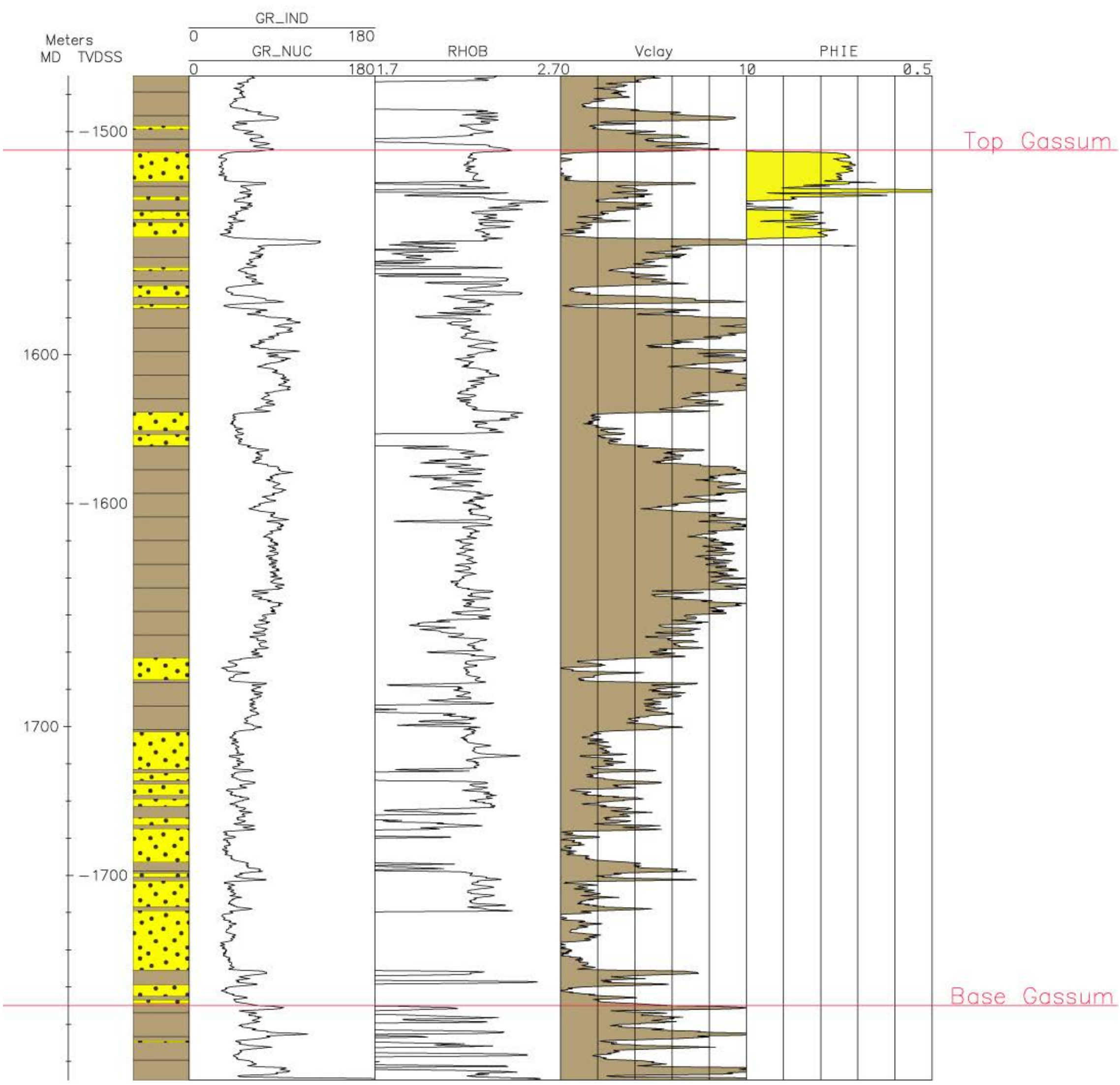

Figure 12. *Petrophysical well logs of the Felicia-1A well showing the interpreted sand/shale ratios of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991).*

Hanstholm	Stratigraphic units with possible reservoirs			Reservoirs					
Wells	Name	Depth b. msl m	Gross Reservoir Thick m	SAND Cut-off Value	Net Reservoir Thick m	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Felicia-1	Gassum Fm.:	1505	230	50 API GR	92	0.67	20		
	Bunter Sandstone Fm.:	4483							

Table 4. *Table listing the reservoir characteristics of stratigraphic units with potential for storage of CO_2 in the nearest well Felicia-1. The porosity value is interpreted from the geophysical log using the Petroworks interpretation tool .*

Havnsø structure

The informal name Havnsø structure is used for a domal closure at Gassum Formation level situated at the small harbour Havnsø approximately 15 km northeast of Kalundborg (Figs 13 and 14). Approximately 1/3 of the structure is situated offshore, with the top point situated onshore. The structure was evaluated as a possible natural gas storage in the eighties, but was excluded for the Stenlille structure.

General geological setting

The structure is situated in the Danish Basin. The shoreface sandstones of the Gassum Formation were sourced from the elevated areas towards the northeast. Palaeogeographic models suggest that the reservoir quality of the sandstones will decrease in an offshore direction towards the northwest relative to the Stenlille structure where the formation is well-known. The Gassum Formation has been described in detail by (Nielsen et al. 1989; Hamberg 1994; Hamberg & Nielsen 2000; Nielsen 2003).

Well database

The Havnsø structure has not yet been drilled and the aquifer data are extrapolated from the Stenlille-1, Stenlille-19 and Horsens-1 wells (Fig. 15 and Table 5).

Seismic coverage

The structure is identified on seismic SSL Survey line 73/038 and 73/039. At present no structural map has been published and the interpretation is based on GEUS internal work (Fig. 13).

Storage quality

Lithological the aquifer is expected to be relatively similar to that described for the Gassum Formation at the Stenlille gas storage facility were the basal part records a thick, relatively coarse-grained sandstone unit (Fig. 15 and Table 5). This unit is followed upwards by four sequences containing fine-grained sandstones and mudstones (Nielsen *et al.* 1989). The porosity varies between the different reservoir unit but an average of 22% has been applied for the storage calculations. The permeability of the Havnsø structure is unknown, but is estimated to be comparable to the values seen in Stenlille where the Gassum Formation occurs at similar depth, having average permeability around 500 mD. The high permeability is crucial for obtaining high injection rates of CO_2.

Subsurface storage capacity

The depth to the top point of the reservoir is 1500 m and the closure is estimated to cover an area of 166 km^2. The spill point is situated in the southeastern part of the structure at approximately 1850 m depth (Fig. 13).

Based on the reservoir information from the Stenlille natural gas storage and the north-westwards facies changes of the Gassum Formation, the gross thickness is estimated to be 150 m with a net/gross of 0.67 leading to approximately 100 m of net sand. No information exists on the actual reservoir pressure and temperature and hydrostatic pressure and regional temperature gradients have been applied in the storage calculations. The structure is calculated to hold a maximum of 1028 Mt CO_2. A more detailed model for the reservoir is presented by Bech (2003).

Seal

The structure is sealed by a thick package of marine mudstones of the Fjerritslev Formation (Fig. 14). Laboratory experiments and full-scale test at the Stenlille natural gas storage facility suggests that the claystones form a tight seal. The integrity of the claystones towards CO_2, however, has not been tested.

Major CO_2 emission points

The Havnsø structure is situated within a distance of 15 km from two major industrial point sources at Kalundborg Harbour. The power plant Asnæsværket is the largest single source of CO_2 emission in Denmark. CO_2 emission reached a low in 2000 of 3.8 Mtonnes whereas average through the years 1994–1999 was 5.6 Mtonnes. The Statoil refinery is situated as neighbour to the power plant and produces close to 0.4 Mtonnes CO_2/year.

The size of the structure furthermore makes it attractive for storage of CO_2 from the point sources in the Copenhagen rural area. The distance to Copenhagen is approximately 85 km.

Reservoir modelling

A preliminary simulation model using Eclipse 100 has been made for the Havnsø structure. The calculations are reported in Bech (2003) and show that the rock properties in the reservoir would allow injection of 200 kg CO_2/sec equal to the average daily emission rates of Asnæsværket. The CO_2 may be injected through a single injection well perforated over a length of 500 m. The simulation was run for a period of 30 years.

Injection wells

The structure may be filled by one deviated injection well drilled from the Asnæs power plant in Kalundborg to the southwest flank of the structure. A maximum length of 8–10 km is estimated for the well.

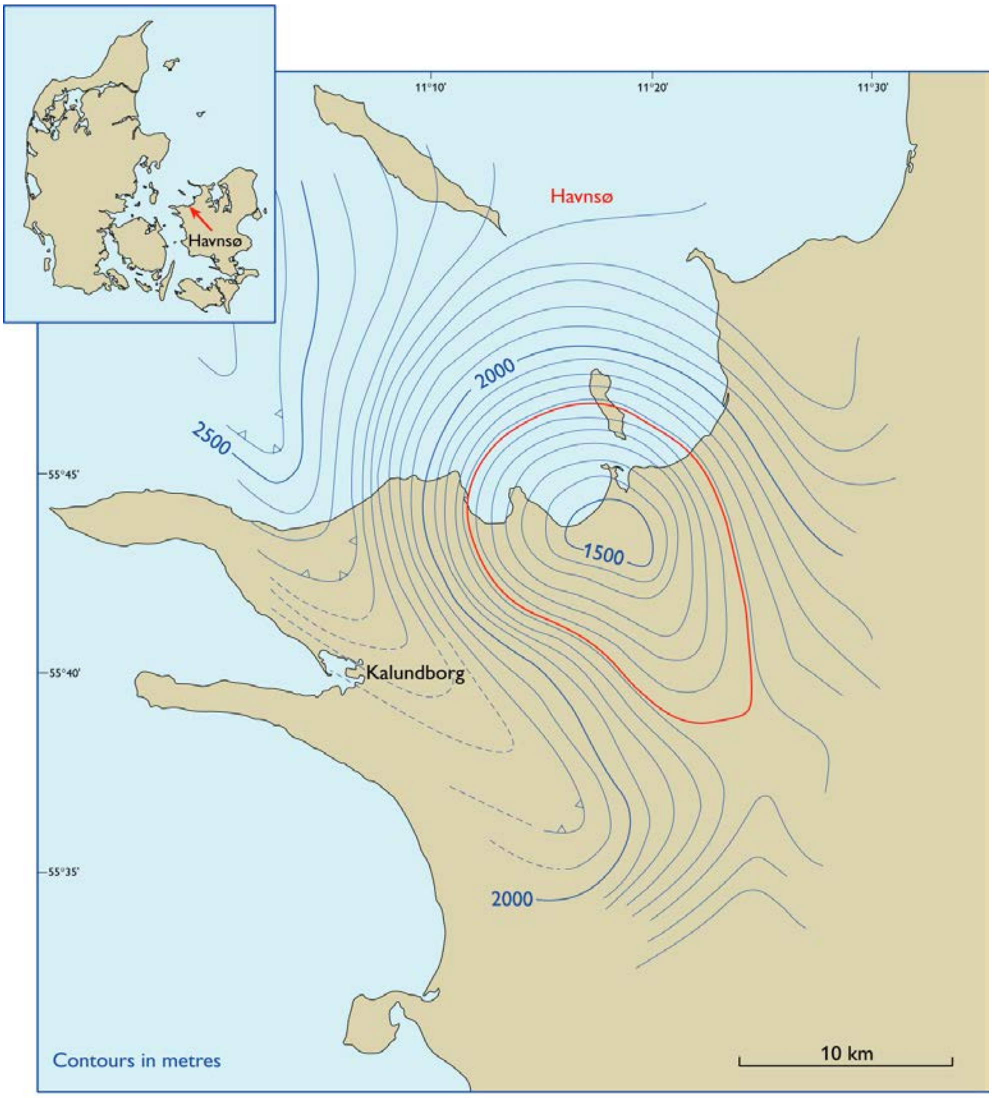

Figure 13. *Outline of the structural trap defining the potential storage site at Havnsø. The structure is interpreted from unpublished seismic maps.*

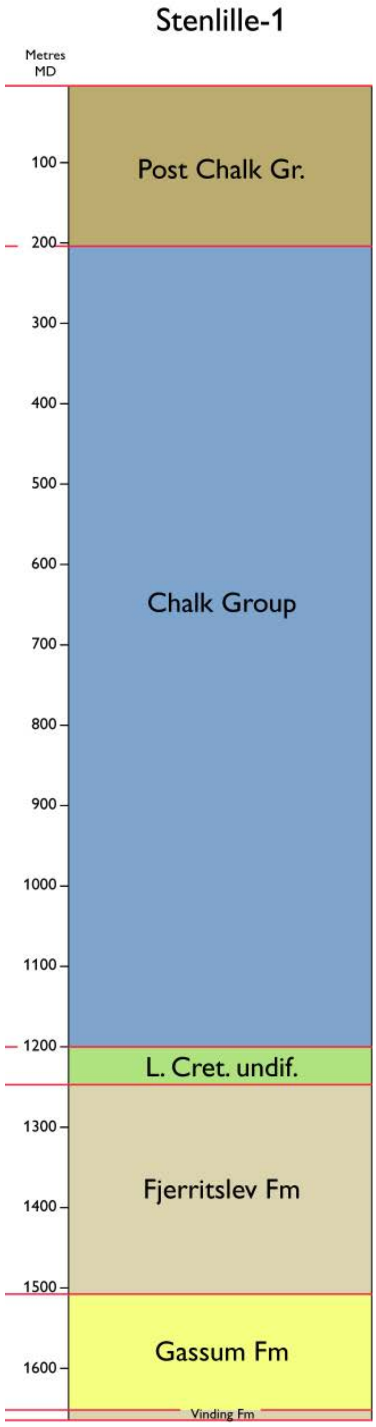

Figure 14. *Stratigraphic depth section of the Stenlille-1 well showing the lithostratigraphic units and their thickness. The main reservoir in sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

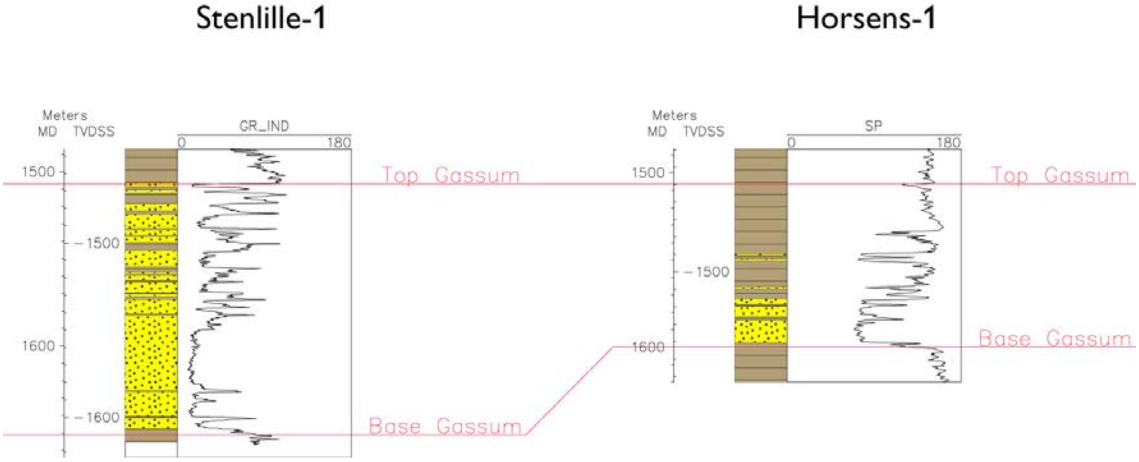

Figure 15. *Petrophysical well logs of the Stenlille-1 and Horsens-1 wells showing the interpreted sand/shale ratios and lateral variability of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991).*

Havnsø	Stratigraphic units with possible reservoirs				Reservoirs					
Wells	Name		Depth Interval MD m	Gross Reservoir Thick. M	SAND Cut-off Value	Net Reservoir Thick. M	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Horsens-1		Lower Cretaceous undiff.	1111-1168	57						
	Gassum Fm	Gassum Fm.:	1449-1543	94	90 API SP	25	0.26	S-31, C-25	G-500	
Stenlille-1		Lower Cretaceous undiff.	1158-1205	47	GR=56	1	0.02			
	Gassum Fm.	Lower Jurassic 2; TS 10 - TS 11	1326-1398	72	GR=56	9	0.13			
		Lower Jurassic 1; TS 7 - TS 10	1398-1465	67	GR=56	6	0.09			
		Gassum Fm.; Base Gassum - TS 7	1465-1609	144	GR=56	110	0.76	20-25		60-70

Table 5. *Table listing the closest wells and reservoir characteristics of stratigraphic units with potential for storage of CO_2 . The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981).*

Horsens structure

The Horsens structure is situated in eastern Jylland. The closure is mapped at the top Gassum Formation level (Fig. 16).

General geological setting

The structure is situated in the central part of the Danish Basin. The structure is a result of uplift caused by post depositional salt tectonics.

Well database

The seal and reservoir is penetrated by the Horsens-1 well situated at the western edge of the closure (Fig. 17). The reservoir is evaluated using well information from Horsens-1, Rønde-1, Stenlille-1 and Stenlille-19 (Fig. 18 and Table 6).

Seismic coverage

The structure is interpreted from the depth structure map of the “Top Triassic” as defined by Japsen and Langtofte (1991).

Storage quality

Sandstones of the Upper Triassic – Lower Jurassic Gassum Formation form the primary reservoir unit. The shaling out of the Gassum Formation from east towards west in the Danish Basin results in a relatively thin formation of only 94 m in thickness and a low net/gross of 0.26 (Fig. 18 and Table 6). The porosity was measured to 25 % in core and the gas permeability to 500 mD (Michelsen, 1981).

Subsurface storage capacity

The closure is defined by a flat circular approximately 100 m high domal structure covering 318 km^2. The depth to top aquifer is estimated to be 1500 m below msl, with spill point situated towards the southeast. The aquifer is expected to hold a normal temperature and pressure gradient. The maximum storage capacity is calculated to be 490 Mtonnes CO_2.

Seal

The Gassum Formation is overlain by marine mudstones of the Fjerritslev Formation forming the seal of the structure. In Horsens-1 the Fjerritslev Formation reaches 210 m in thickness (Fig. 17).

Major CO_2 emission points

The Horsens structure is situated close to a number of major point sources. The Skærbæk power plant and the Shell refinery with a total emission of 1.81 Mtonnes CO_2/year are situated at Fredericia within a distance of 50 km from the Horsens structure. The structure is approximately 25 from the city of Århus with several major point sources (total emission 3.63 Mtonnes/year). Due to the coastal position the structure may also form an attractive storage option for the powerplant Fynsværket (2.89 Mtonnes CO_2/year)in Odense 60 km to the southeast.

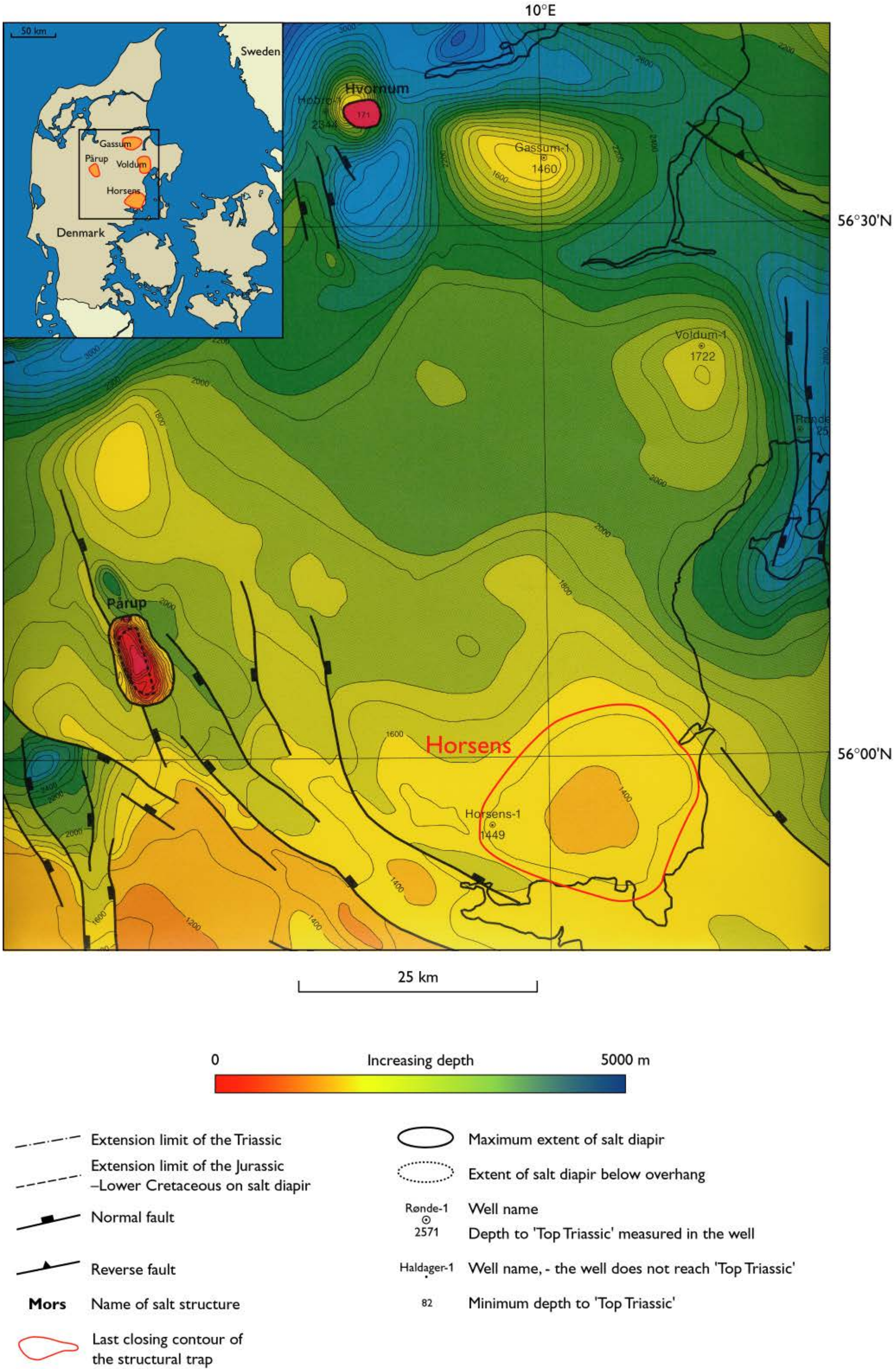

Figure 16. *Outline of the structural trap defining the potential storage site at Horsens . The structure is interpreted from the depth structure map of the "Top Triassic" as defined by Japsen and Langtofte (1991).*

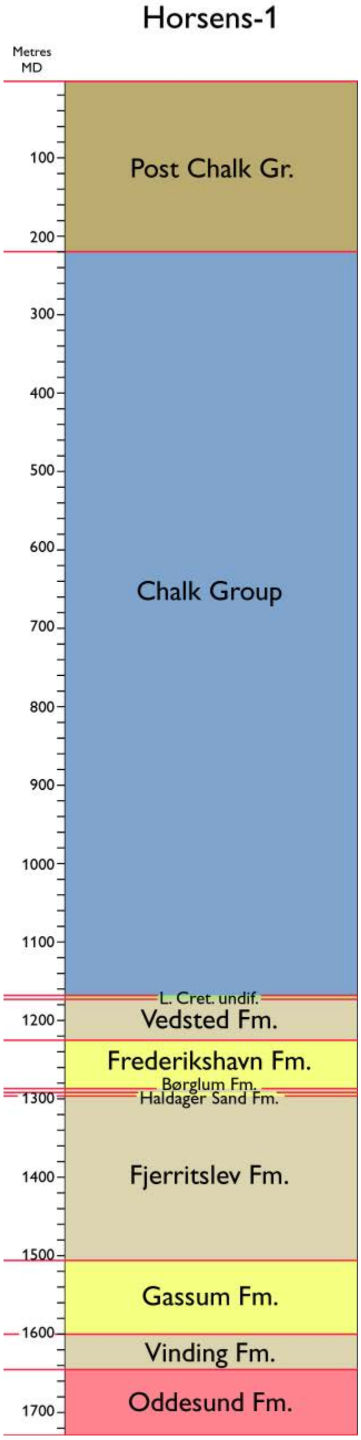

Figure 17. *Stratigraphic depth section of the Horsens-1 well showing the lithostratigraphic units and their thickness. The main reservoir in sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

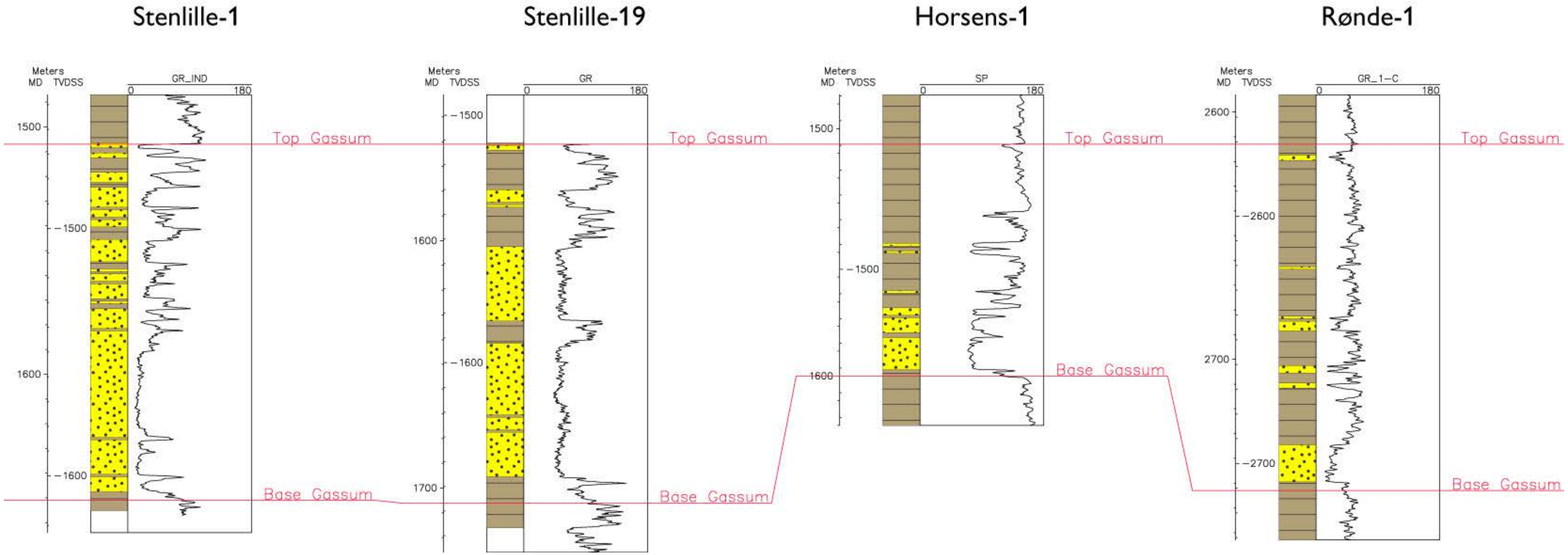

Figure 18. Petrophysical well logs of the Stenlille-1, Stenlille-19, Horsens-1 and Rønde-1 wells showing the interpreted sand/shale units and lateral variability of the primary reservoir unit. The top and base of the Gassum Formation is based on interpretations given in Nielsen & Japsen (1991).

Horsens	**Stratigraphic units with possible reservoirs**				**Reservoirs**					
Wells	Name		Depth below. msl m	Gross Reservoir Thick. M	SAND Cut-off Value	Net Reservoir Thick. M	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Horsens-1		Lower Cretaceous undiff.	1111-1168	57						
	Gassum Fm	Gassum Fm.:	1449-1543	94	90 API SP	25	0.26	S-31, C-25	G-500	
Stenlille-1		Lower Cretaceous undiff.	1158-1205	47	GR=56	1	0.02			
	Gassum Fm.	Lower Jurassic 2; TS 10 - TS 11	1326-1398	72	GR=56	9	0.13			
		Lower Jurassic 1; TS 7 - TS 10	1398-1465	67	GR=56	6	0.09			
		Gassum Fm.; Base Gassum - TS 7	1465-1609	144	GR=56	110	0.76	20-25		60-70
Rønde-1		Lower Cretaceous undiff.	1941-2008	67						
		Gassum Fm.;	2571-2711	140	GR=35.5	28	0.20	F-13		60-70
Stenlille-19		Gassum Fm.:	1512	145	66 API GR	90	0.62			
		Bunter Sandstone Fm.:	2272							

Table 6. *Table listing the wells used in this study and reservoir characteristics of stratigraphic units with potential for storage of CO_2 . The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on data from Michelsen (1981).*

Pårup structure

The Pårup structure is an informal name used for a large domal closure situated north of the Pårup Saltdome in eastern Jylland. The closure is mappedat the top of the Upper Triassic – Lower Jurassic Gassum Formation (Fig. 19).

General geological setting

The structure is situated in the central part of the Danish Basin. The structure is caused by uplift due to post depositional salt tectonics.

Well database

The Pårup structure has not been drilled and the reservoir data for the aquifer are extrapolation of data from Voldum-1 and Gassum-1 wells (Fig. 20 and Table 7).

Seismic coverage

The structure is interpreted from the depth structure map of the “Top Triassic” as defined by Japsen and Langtofte (1991) (Fig. 19).

Storage quality

The main reservoir is defined in sandstones of the Upper Triassic – Lower Jurassic Gassum Formation estimated to be 130 m thick. The formation is not drilled on the structure and values from Voldum-1 and Gassum-1 have been used to evaluate the reservoir. It is assumed that the formation has a relatively low net sand thickness of 30 m with an estimated porosity of 10 % and permeability of 300–2000 mD (Table 7). These values are however subject to uncertainty.

Subsurface storage capacity

The closure is defined by a flat circular 250 m high domal structure with a steep northern flank and a flat southern flank. The spill point is situated towards to southeast. Depth to top reservoir in the Pårup aquifer is estimated to be 1550 m below msl. and pore volume of 0.4 km^3 leading to a maximum storage capacity of 101 Mtonnes CO_2. The pressure and temperature gradients are expected to follow the regional gradients.

Seal

The seal of the Pårup aquifer is the Fjerritslev Formation, which is approximately 300 m thick in the area of the Pårup structure. The seal is cut by a nortwest–southeast trending normal fault immediately to the west of the structure.

Major CO_2 emission points

The Pårup structure is situated close to a number of major point sources. The Skærbæk power plant and the Shell refinery with a total emission of 1.81 Mtonnes CO_2/year are situated at Fredericia within a distance of 50 km from the structure. The structure is approximately 40 from the city of Århus with several major point sources (total emission 3.63 Mtonnes/year).

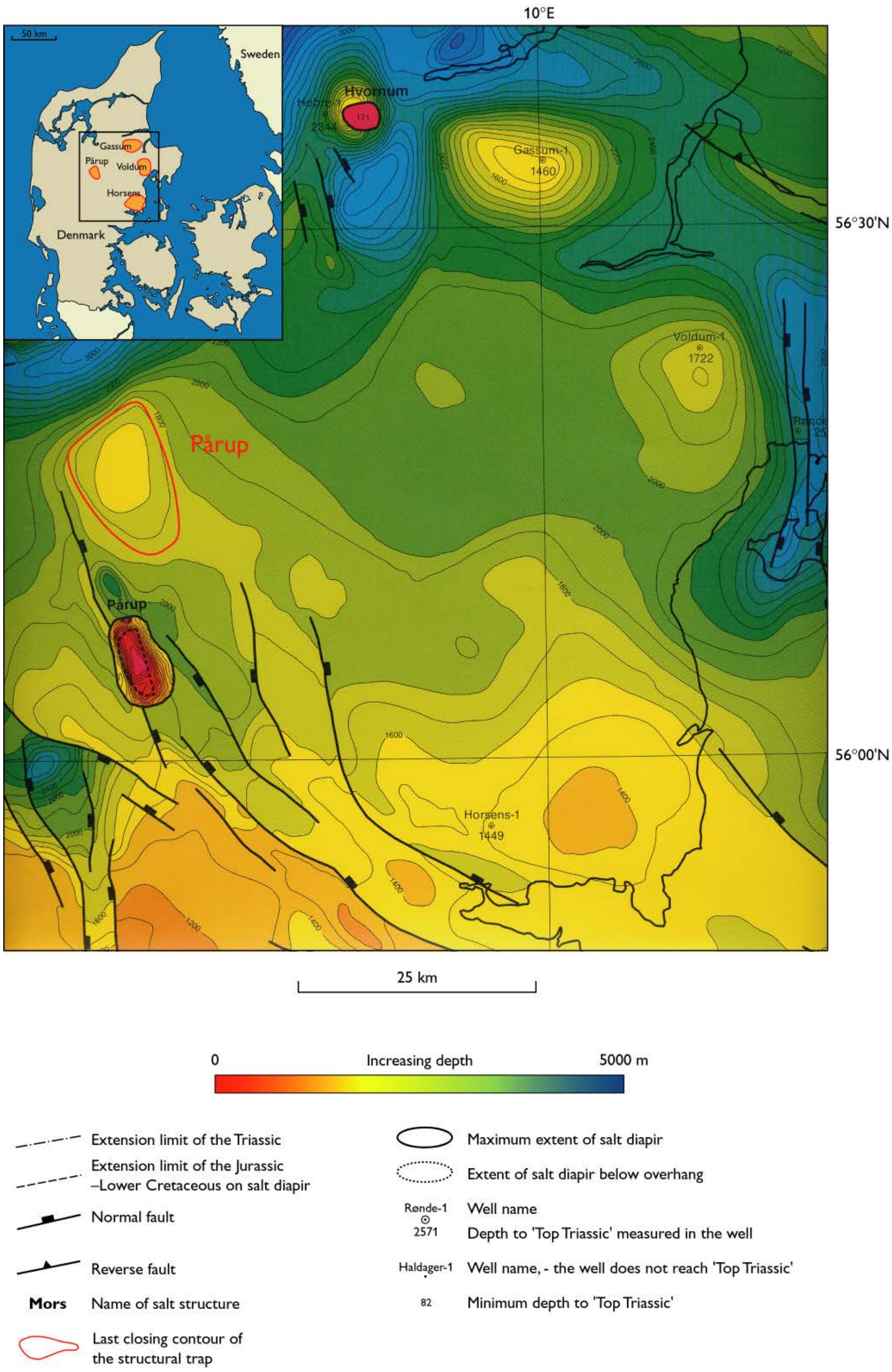

Figure 19. *Outline of the structural trap defining the potential storage site north of the Pårup saltdome. The structure is interpreted from the depth structure map of the "Top Triassic" as defined by Japsen and Langtofte (1991).*

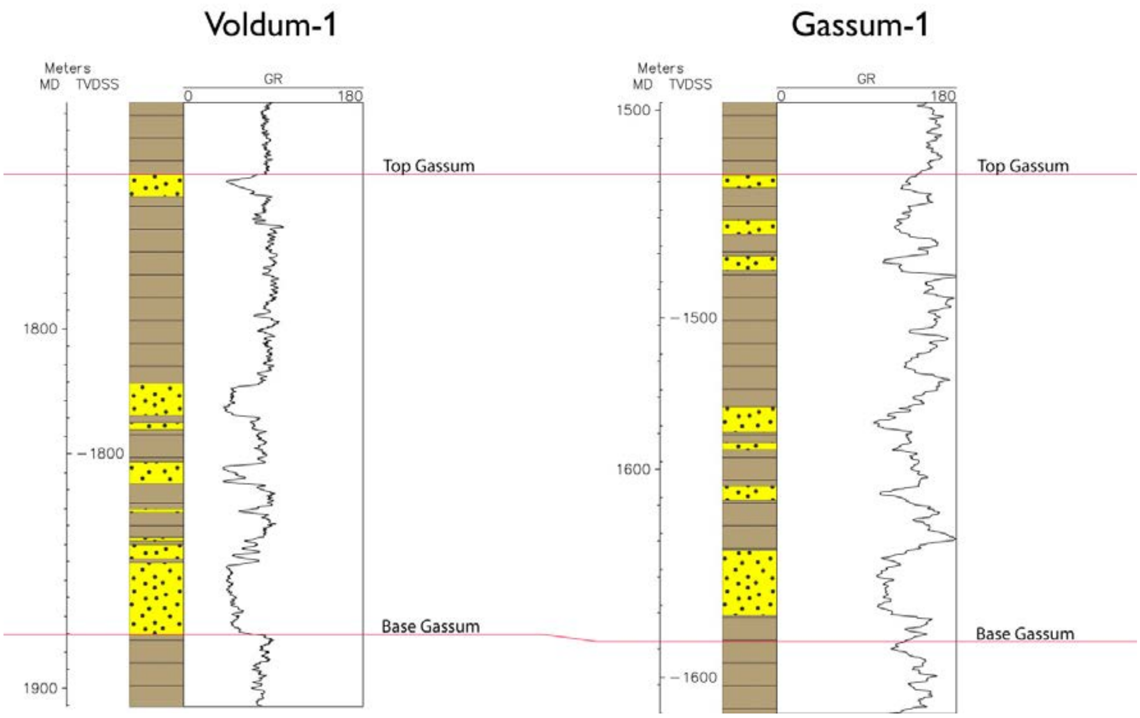

Figure 20. *Petrophysical well logs of the Voldum-1 and Gassum-1 wells showing the interpreted sand/shale ratios and lateral variability of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991).*

Paarup	Stratigraphic units with possible reservoirs			Reservoirs					
Wells	Name	Depth below msl m	Gross Reservoir Thick m	SAND Cut-off Value	Net Reservoir Thick m	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Voldum-1	Lower Cretaceous undiff.	1212-1278	66						
	Gassum Fm.:	1722-1850	128	71.5 API GR	30	0.23	F-15 (avg. 8%)		
Gassum-1	Lower Cretaceous undiff.	944-1020	76						
	Gassum Fm.:	1460-1590	130	133.5 API GR	53	0.41	C-26	G-2000, L-300	
	Bunter Sandstone Fm.	2689-3383	694		690	0.99	C-15	G-100	

Table 7. *Table listing the wells drilled at the structure and nearby and reservoir characteristics of stratigraphic units with potential for storage of CO_2 . The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981)***.**

Rødby structure

The Rødby structure is a domal closure situated at Rødby on the island Lolland . The closure is mapped at the top Lower Triassic marker which roughly corresponds to the to Bundter Sandstone Formation (Fig. 21).

General geological setting

The Rødby structure is situated south of the Ringkøbing-Fyn High in the northern part of the North German Basin.

Well database

The reservoir and seal is penetrated by the wells Rødby-1 and Rødby-2 situated near the top point of the closure (Fig. 22 and Table 8).

Seismic coverage

The structure is identified on seismic Survey lines: LFD, LFE 8021, -24, -38, 7922, -24, -25, -26, 8107, -08, -09, -10, -11, -18. At present no structural map has been published and the interpretation is based on GEUS internal work (Fig. 21).

Storage quality

Sandstones of the Lower Triassic Bunter Sandstone Formation represent the main reservoir unit (Fig. 23). The upper part of the reservoir was cored in the Rødby-1 well and show very fine to fine-grained sandstones with a porosity measured on core to 24% and permeability of 75 mD (Michelsen, 1981). The sandstones are classified as arkosic (Fine 1986).

Subsurface storage capacity

The closure is defined by an almost circular domal structure approximately 200 m high. The structure is bounded to the north by a northwest–southeast trending fault. The position of the fault defines the last closing contour of the structure. The spill point is poorly defined on the present structural map.

Pressure and temperature are expected to follow normal gradients for the Danish Basin. Depth to top aquifer is 1125 m and the total thickness of the formation is 256 m with a net sand thickness of 45 m. The maximum storage capacity of the Rødby aquifer is estimated to be 213 Mt CO_2. It is anticipated that the relatively low permeability will be a significant problem for any future CO_2 injection.

Seal

A mixed package of evaporites and claystones of the Ørslev Formation overlie the Bunter Sandstone Formation (Fig 21). The fine-grained sediments are 160 m thick in the Rødby area and form the top seal of the aquifer. The seal is cut by a major fault situated at the northern flank of the structure.

Major CO_2 emission points

The structure is situated in southernmost Denmark outside the major industrial areas. The nearest point source is the power plant Stigsnæsværket (1.34 Mtonnes CO_2/year) situated in Skælskør approximately 60 km to the north.

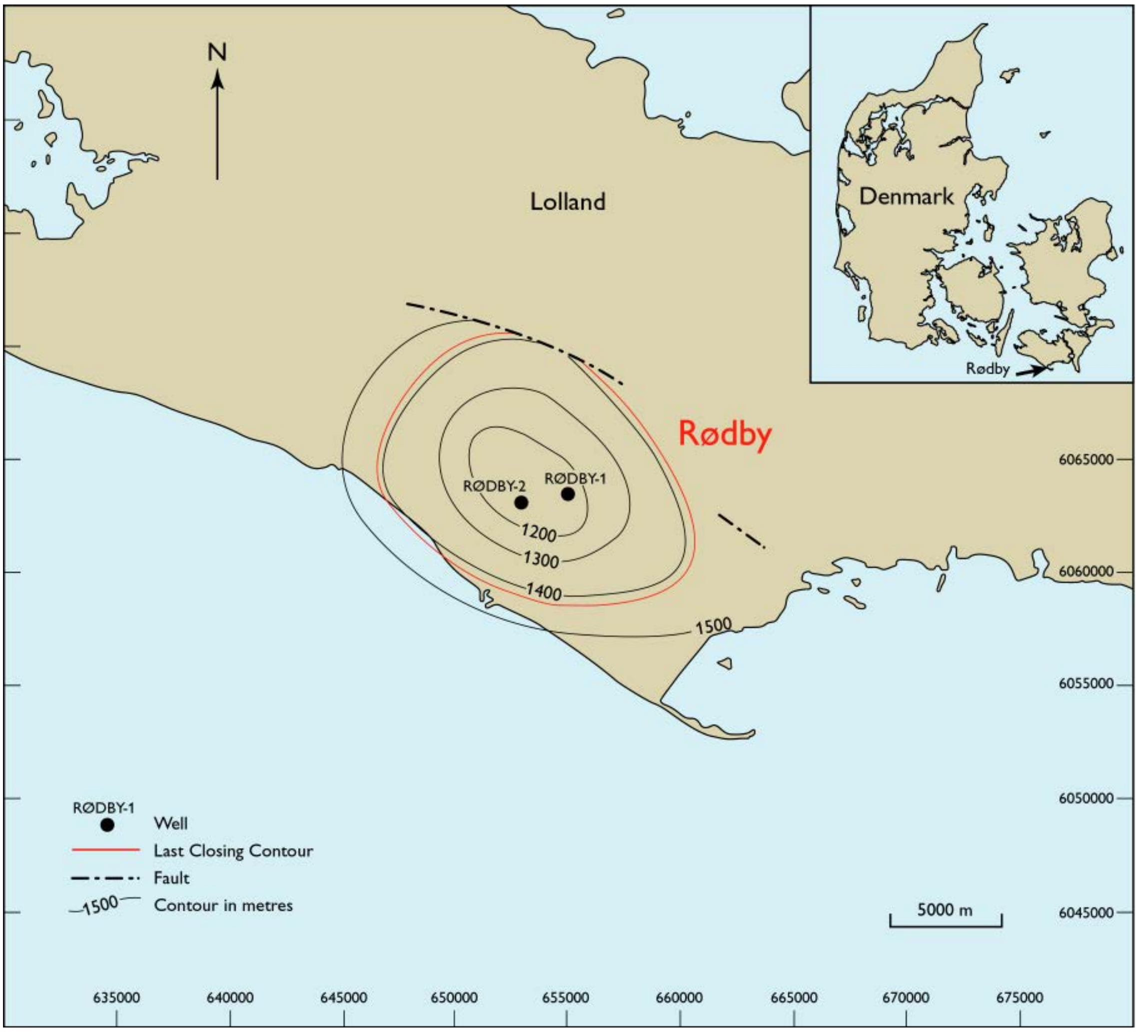

Figure 21. *Outline of the structural trap defining the potential storage site at Rødby. The structure is interpreted from unpublished seicmic maps.*

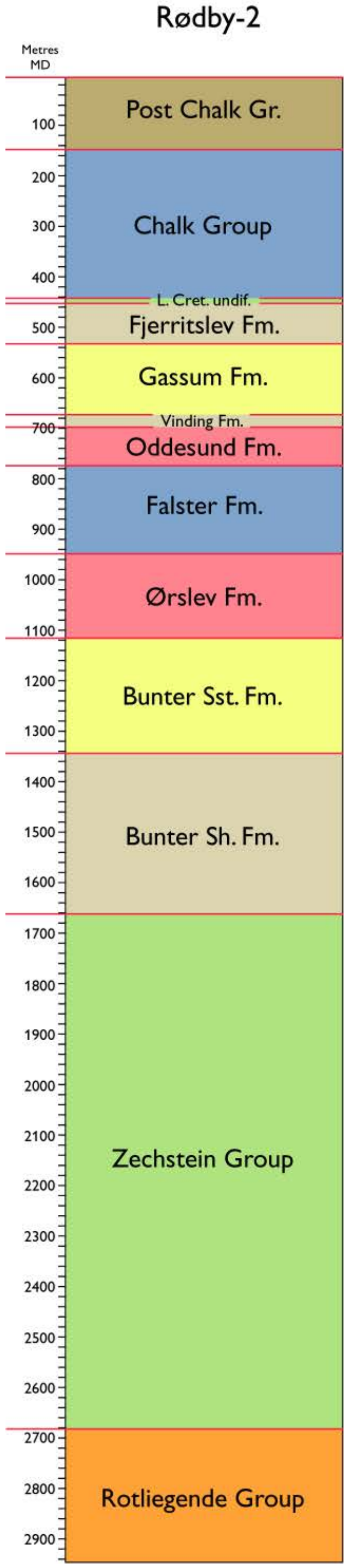

Figure 22. *Stratigraphic depth section of the Rødby-2 well showing the lithostratigraphic units and their thickness. The main reservoir in sandstones of the Bunter Sandstone Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

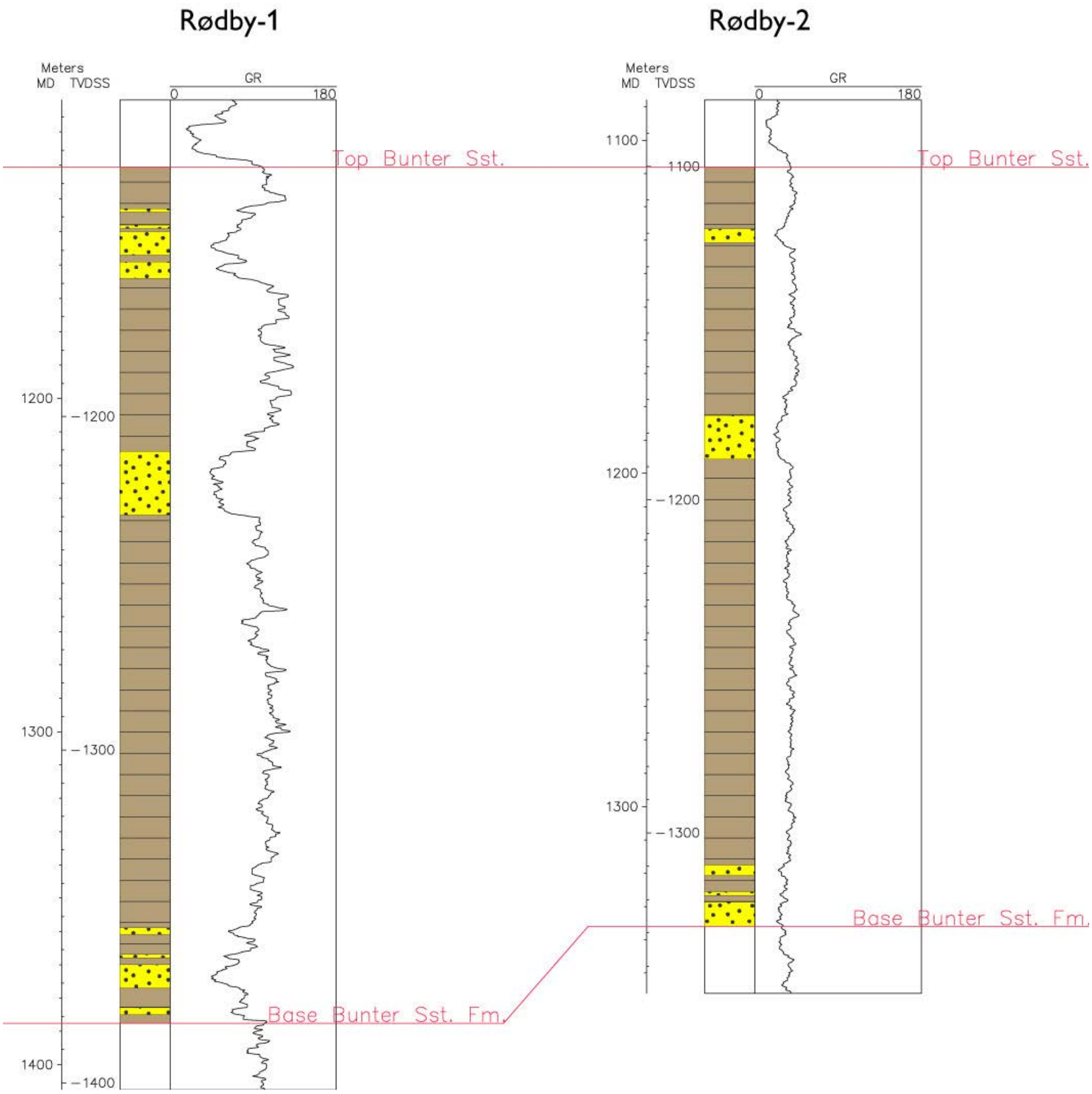

Figure 23. *Petrophysical well logs of the Rødby-1 and Rødby-2 wells showing the interpreted sand/shale units and lateral variability of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991).*

Rødby	Stratigraphic units with possible reservoirs			Reservoirs					
Wells	Name	Depth below msl m	Gross Reservoir Thick m	SAND Cut-off Value	Net Reservoir Thick m	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Rødby-1	Gassum Fm.:	555	128	55 API GR	59	0.46	S-43		
	Bunter Sandstone Fm.:	1125	257	73 API GR	45	0.18	S-38, C-24	G-75	
Rødby-2	Gassum Fm.:	525	140	20 API GR	44	0.31	S-37		
	Bunter Sandstone Fm.:	1108	228	30 API GR	28	0.12			

Table 8. *Table listing the wells drilled at the structure and reservoir characteristics of stratigraphic units with potential for storage of CO_2 . The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981).*

Stenlille structure

The Stenlille structure is situated in western Zealand and is currently in use for storage of natural gas (Fig. 24). The reservoir is in sandstones of the Upper Triassic – Lower Jurassic Gassum Formation.

General geological setting

The closure is situated in the Danish Basin relatively close to the Upper Triassic basin margin. The domal structure is governed by salt induced uplift from the underlying Zechstein salt.

Well database

The structure has been intensively drilled as part of the planning and operation of the natural gas storage. At the moment 19 wells exists at the storage site. Of these are 4 operated as injection wells, 5 as production wells and 10 as observation wells. Five of the wells are drilled trhough the seal and reservoir units. Well information from the wells Stenlille-1 and Stenlille-19 have been used to evaluate the reservoir in this study (Fig. 24 and Table 9).

Seismic coverage

The structural closure is defined by DONG in the technical report (DONG 19xx)

Storage quality

The reservoir in the Stenlille structure consist of stacked shoreface units of the Upper Triassic – Lower Jurassic Gassum Formation (Fig. 25). The sandstones show excellent reservoir parameters with an average porosity of approximately 25 % and permeability of up to 1300 mD. The reservoir is compartmentalised by units of heteroliths and claystones (Fig. 26).

Subsurface storage capacity

The Stenlille structure is rather small and defined by a flat domal structure with spill point towards the southwest. The depth to the top aquifer is approximately 1500 m and the gross thickness of the Gassum Fm is 130 m with approximately 100 m net sand. Based on simple volume calculations and assuming normal pressure and thermal gradients the maximum storage volume is 62 Mtonnes CO_2.

Seal

The seal of the Stenlille aquifer is approximately 300 claystones of the Fjerritslev Formation (Fig. 25). The formation has proven tight as seal for the gas storage since 1991, but the integrity towards CO_2 has not been tested.

Reservoir modelling

The operating company DONG A/S has performed detailed reservoir modelling but the results are not available to the Gestco project. The operation of the gas storage however has shown that the aquifer may be regarded as an open system with limited pressure increase during injection. It is anticipated that sweep efficiency in the best reservoir units reach 80% and that the structure as a whole may have an effective storage volume of 40–50% (H. Øbro, Dong, Pers. com. 2002).

Major CO_2 emission points

The Stenlille structure is situated 45 km south of the industrial point sources in Kalundborg Harbour. The power plant Asnæsværket is the largest single source of CO_2 emission in Denmark. CO_2 emission reached a low in 2000 of 3.8 Mtonnes whereas average through the years 1994–1999 was 5.6 Mtonnes. The Statoil refinery is situated as neighbour to the power plant and produces close to 0.4 Mtonnes CO_2/year.

The structure may form an storage option for point sources in the Copenhagen rural area. The distance to Copenhagen is approximately 65 km.

Injection wells

The gas storage is currently operated with 4 vertical injection wells. Due to the compartmentalisation of the reservoir the injection wells is completed at several reservoir levels.

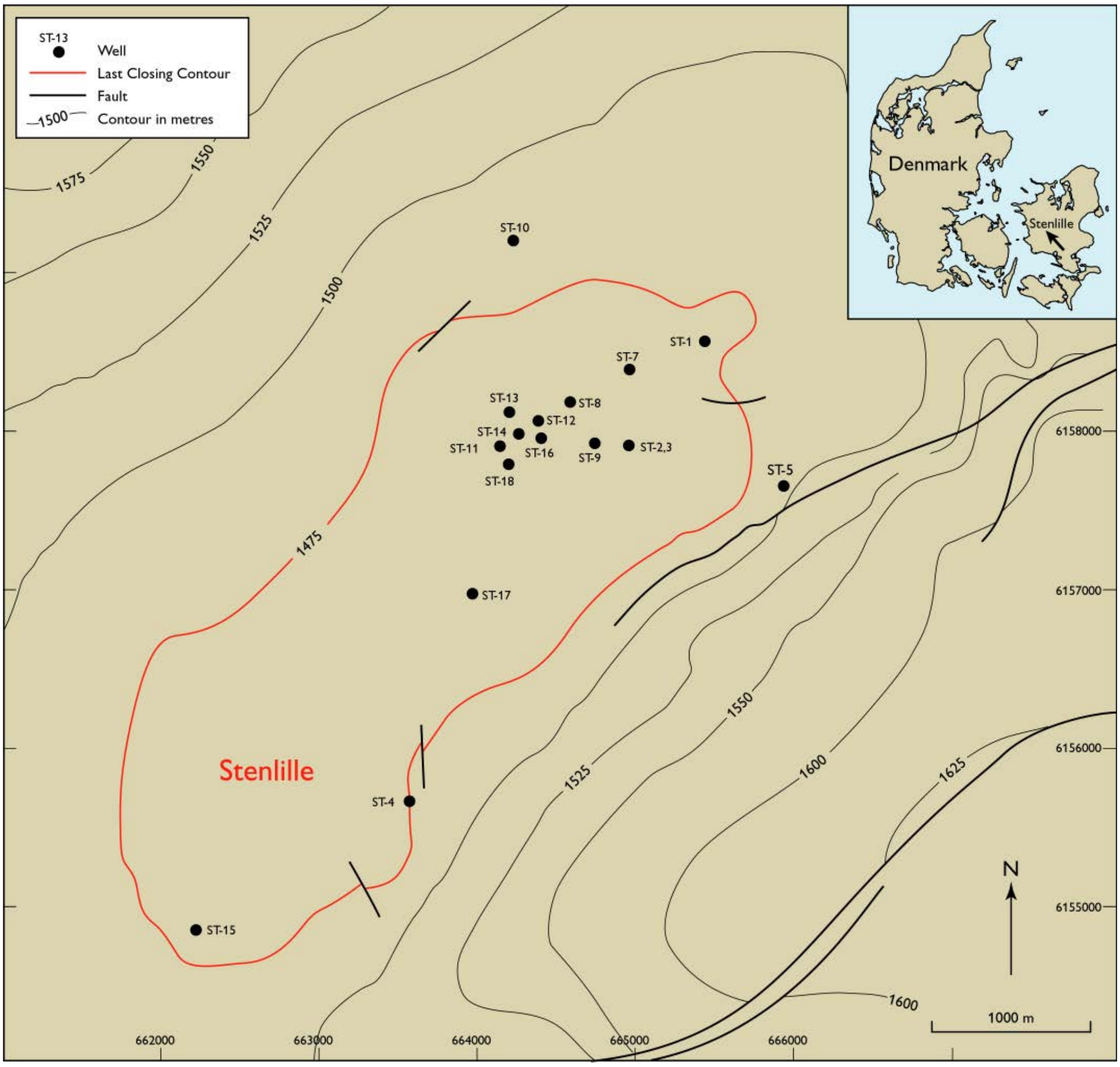

Figure 24. *Outline of the structural trap defining the natural gas storage at Stenlille. Modified from DONG.*

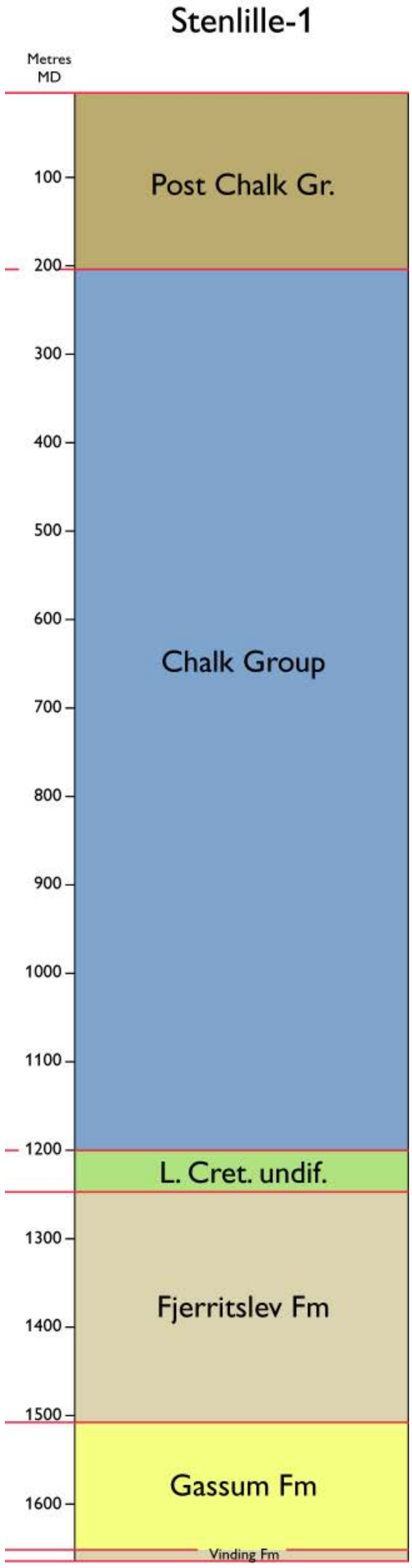

Figure 25. *Stratigraphic depth section of the Stenlille-1 well showing the lithostratigraphic units and their thickness. The main reservoir in sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

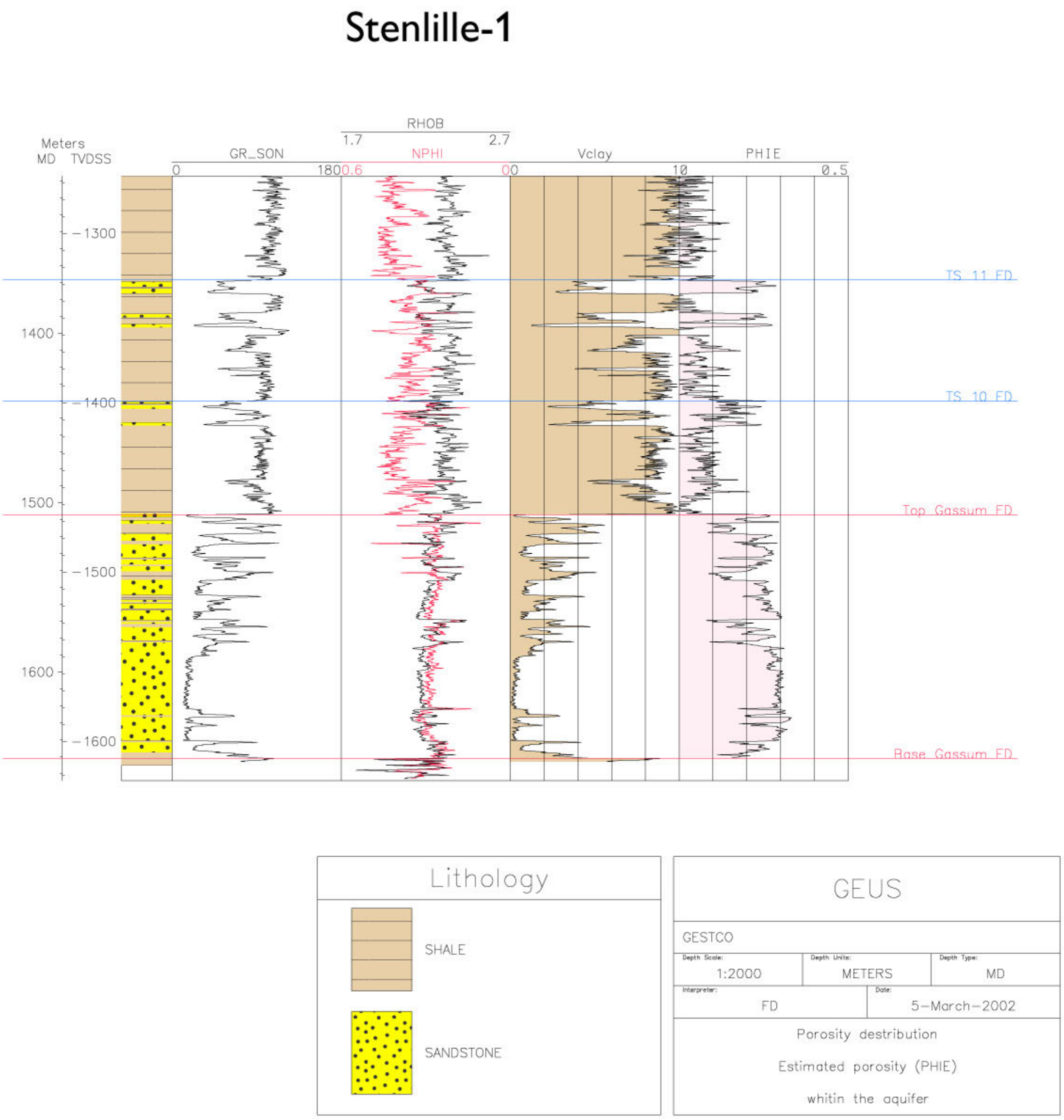

Figure 26. *Petrophysical well logs of the Stenlille-1 wells showing the interpreted sand/shale ratios of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991). TS 10 and TS 11 marks major flooding surfaces defining tops of shoreface sandstones occurring in the marine mudstones of the Fjerritslev Formation.*

Stenlille	**Stratigraphic units with possible reservoirs**				**Reservoirs**					
Wells	Name		Depth b. msl m	Gross Reservoir Thick m	SAND Cut-off Value	Net Reservoir Thick m	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Stenlille-1		Lower Cretaceous undiff.	1158-1205	47	GR=56	1	0.02			
	Gassum Fm.	Lower Jurassic 2; TS 10 - TS 11	1326-1398	72	GR=56	9	0.13			
		Lower Jurassic 1; TS 7 - TS 10	1398-1465	67	GR=56	6	0.09			
		Gassum Fm.; Base Gassum - TS 7	1465-1609	144	GR=56	110	0.76	20-25		60-70
Stenlille-19		Gassum Fm.:	1512	145	66 API GR	90	0.62			
		Bunter Sandstone Fm.:	2272							

Table 9. *Table listing the some of the wells drilled at the structure and reservoir characteristics of stratigraphic units with potential for storage of* CO_2 *. The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981).*

Thisted/Legind structure

The potential storage site is formed by a combination of two domal structures situated in northern Jylland (Fig. 27). The main reservoir is interpreted to be the Triassic Skagerrak Formation. The Thisted geothermal plant produces hot formation water from the overlying Gassum Formation. This reservoir, however is situated at a depth which is to shallow for CO_2 storage.

General geological setting

The structures are situated close to the northern margin of the Danish Basin. The two domal structures are governed by salt induced uplift from the underlying Zechstein salt.

Well database

Four wells have been drilled in connection with the geothermal energy system. Two of the wells Thisted-2 and Thisted-4 are drilled into the Skagerrak Formation (Fig. 28 and Table 10). Thisted-4 is situated close to the top of the eastern closure whereas Thisted-2 is situated at the southern flank. The western domal closure of the twin structure has not been drilled.

Seismic coverage

Although the main reservoir is suggested to be in the Triassic Skagerrak Formation we have interpreted the aerial extend from the depth structure map of the “Top Triassic” as defined by Japsen and Langtofte (1991) (Fig. 27). This may cause minor uncertainties concerning estimate of area and depth to spill point at the deeper stratigraphic level.

Storage quality

The Triassic sandstones of the Skagerrak Formation in the Thisted-4 well is expected to constitute a possible aquifer for CO_2 storage. The uppermost part of the sandstone is very fine to medium-grained, subangular, moderately sorted and argillaceous (Fig. 29).

In this study the reservoir interval is defined at 1203–1959 m depth although the formation is much thicker. The sandstones of the Skagerrak Formation are expected to have an average porosity of ca 15 % ranging from 25–30 % at the top of the formation to 10–20 % at the bottom (Table 11). The permeability is expected to be very low due to a large quantity of interstitial clay. The reservoir was tested as geothermal aquifer by DONG for the Thisted Geothermal Plant, but was abandoned due to clocking of the geothermal system. Measurements averaged 10–100 mD with a maximum of 230 mD in the middle of a sandstone interval because of fractures. The actual permeability of the formation is assumed to be less than 2 mD.

Subsurface storage capacity

The storage capacity of the Skagerrak Formation might increase considerable if an interval below 2500 m msl is considered. The petrophysical logs thus suggest a sandstone unit situated at 2880 m depth, which may have higher porosity than the unit selected for this study (Fig. 29).

Seal

The claystones and anhydrites of the Oddesund Formation forms the cap rock. The fine-grained seal is approximately 240 m thick in the Thisted area (Fig. 28).

Major CO_2 emission points

The Thisted/Legind structure is situated approximately 80 km from the major emission sources in the city Ålborg (5.06 Mtonnes/year) including two public power stations and a cement plant. The volume of the Thisted/Legind structure is huge and contributes with more than 50% of the total calculated aquifer storage volume in Denmark.

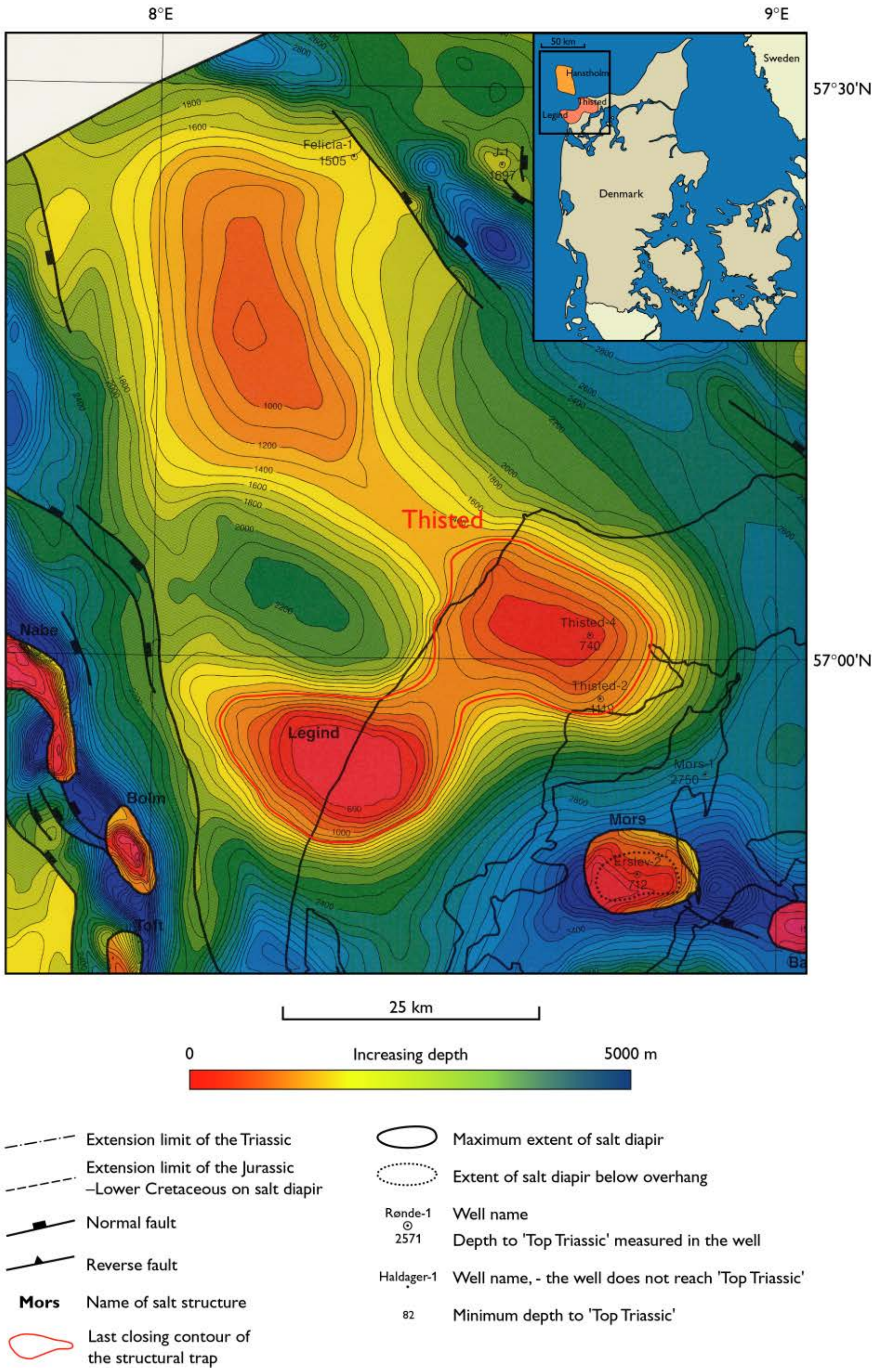

Figure 27. *Outline of the structural trap defining the potential storage site at Thisted. Note that the outline of the structure is shown on the depth structure map of the "Top Triassic" as defined by Japsen and Langtofte (1991) although the main reservoir unit is interpreted to be the Triassic Skagerrak Formation sitauted approximately 300 m deeper.*

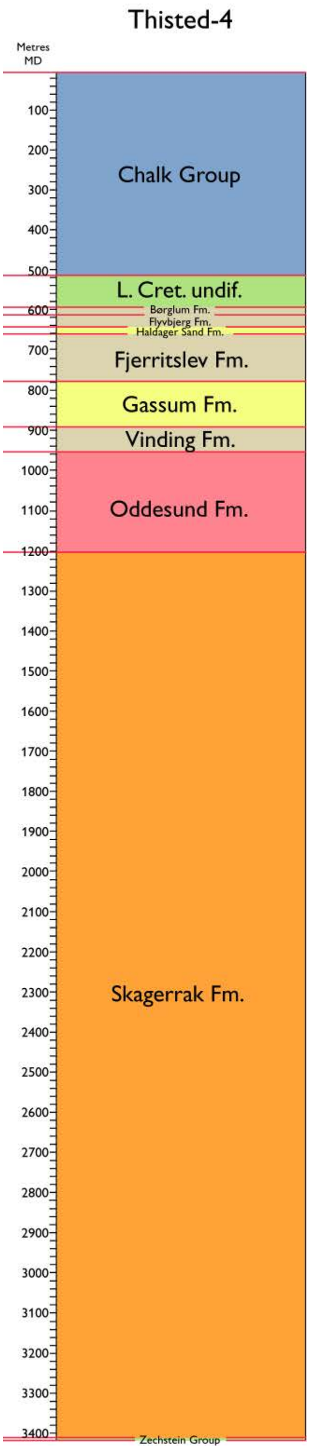

Figure 28. *Stratigraphic depth section of the Thisted-4 well showing the lithostratigraphic units and their thickness. The main reservoir is sandstones in the upper part of the Skagerrak Formation (1203–1959 m). The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

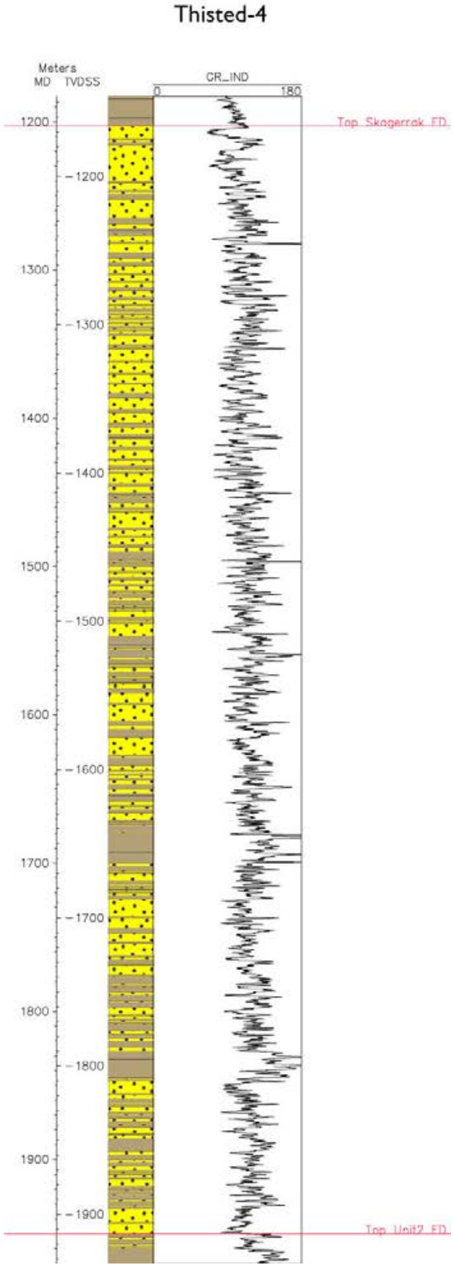

Figure 29. *Petrophysical well logs of the Thisted-4 well showing the interpreted sand/shale ratios of the primary reservoir unit present in the upper part of the Skagerrak Formartion (1203 m – 1959 m). The top of the formation is according to Nielsen & Japsen (1991).*

Thisted	Stratigraphic units with possible reservoirs				Reservoirs					
Wells	Name		Depth Interval MD m	Gross Reservoir Thick. M	SAND Cut-off Value	Net Reservoir Thick. M	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Thisted-1		Lower Cretaceous undiff.	457-539	82						
		Gassum Fm.:	710-835	125		39	0.31	F-32		
Thisted-2		Lower Cretaceous undiff.	806-937	131						
		Gassum Fm.:	1119-1254	135						
Thisted-3		Lower Cretaceous undiff.	802-898	96						
		Gassum Fm.:	1093-1208	115						
Thisted-4		Lower Cretaceous undiff.	476-555	79						
	Triassic units	Gassum Fm.:	740-854	114						
		Skagerrak Fm.:	1166-3377	747	120	449	0.60	15	2	
Mors-1		Lower Cretaceous undiff.	1482-1731	249						
		Gassum Fm.:	2750-2917	167	40 API GR	30	0.18	F-16		
		Bunter Sandstone Fm.	4367-5205	936	0	750	0.80	F-0, I-6, C-7	G-10	

Table 10. *Table listing the wells drilled at the structure and nearby and reservoir characteristics of stratigraphic units with potential for storage of CO_2. The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981).*

Tønder structure

The closure is situated in southern Jylland close to the German border (Fig. 30). The Tønder structure was mapped and evaluated for natural gas storage in the 70'es. It is still reserved for natural gas storage purpose.

General geological setting

The Tønder structure is situated south of the Ringkøbing-Fyn High in the northern part of the North German Basin. The domal structure is governed by salt induced uplift from the underlying Zechstein salt.

Well database

The reservoir and seal of the structure is penetrated by five wells. Of these are four situated close to the top of the structure (Tønder-1, -3, -4, -5) and one situated at the northern flank (Tønder-2) (Fig. 30 and Table 11).

Seismic coverage

The structure is identified on seismic Survey lines: GC85T-002, GC85T-006 and 7801, 8008, 8009, 8117, 8118. At present no structural map has been published and the interpretation is based on GEUS internal work (Fig. 30).

Storage quality

The closure is interpreted to have main reservoir in the Lower Triassic Bunter Sandstone Formation (Fig. 31). The sandstone reservoir has a thickness of 203 m showing a low net/gross value of only 17%. The reservoir is divided into two units separated with a thick mudstone succession (Fig. 32). The total net sandstone thickness of the two reservoir units is 35 m. The petrography and diagenesis of the sandstones were studied in detail by Fine (1986). Based on 29 thin section analysis from the wells Tønder-3, -4, and –5, he found that the average porosity was 18% but also that the porosity is largely controlled by facies showing marked variations between adjacent beds. The maximum porosity was estimated to 30%, whereas one sample showed only 2% porosity. The permeability is uncertain as the two nearest wells Arnum-1 and Hønning-1 shows 100 mD and 1500 mD, respectively.

Subsurface storage capacity

The closure is defined by an almost circular domal structure covering 53 km^2 and with a height of approximately 350 m. The spill point is poorly defined on the present structural map, but is probably situated at the eastern edge of the closure (Fig. 30).

Pressure end temperature are expected to follow normal gradients for the Danish Basin. Depth to top aquifer is 1615 m in the Tønder-1 well and the total thickness of the formation is 203 m with a net sand thickness of only 35 m. The maximum storage capacity of the Bunter Sandstone Formation in the Tønder closure is estimated to be 93 Mtonnes CO_2.

The Tønder structure has an upside potential for CO_2 storage in the Tønder Formation which in Tønder-1 shows a net sandstone thickness of 21 m with a porosity around 30% (Fig. 32). The possible secondary reservoir in the Tønder Formation would almost double the storage capacity of the Tønder structure.

Seal

The Bunter Sandstone Formation is sealed by approximately 180 m of evaporites and mudstones of the Ørslev Formation (Fig. 32).

Major CO_2 emission points

The Tønder structure is situated approximately 40 km from the Ensted power plant in Åbenrå with a total emission of 3.4 Mtonnes CO_2/year. Another nearby CO_2 source is the powerplant Vestkraft (2.5 Mtonnes CO_2/year) situated in Esbjerg approximately 70 north-west of Tønder.

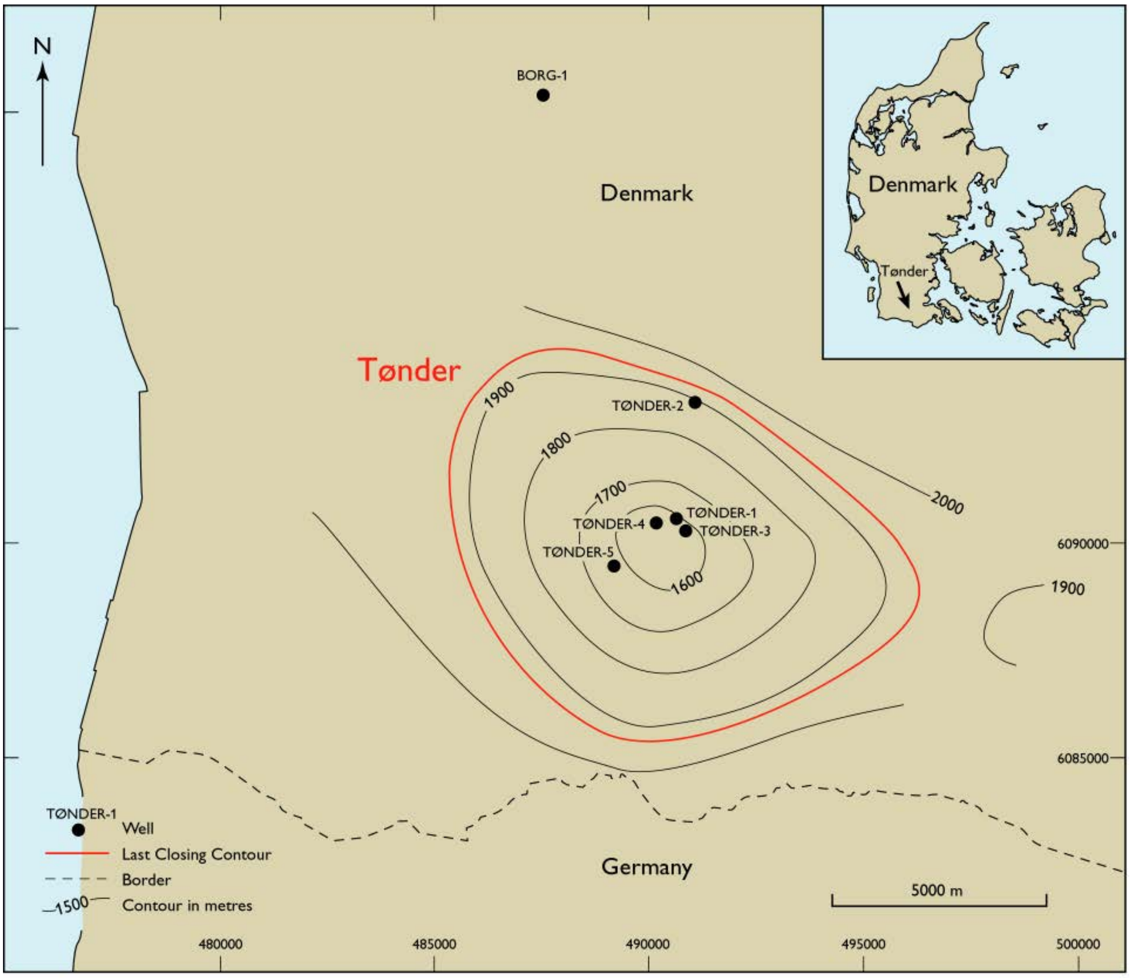

Figure 30. *Outline of the structural trap defining the potential storage site at Tønder. The structure is interpreted from unpublished depth-structure maps.*

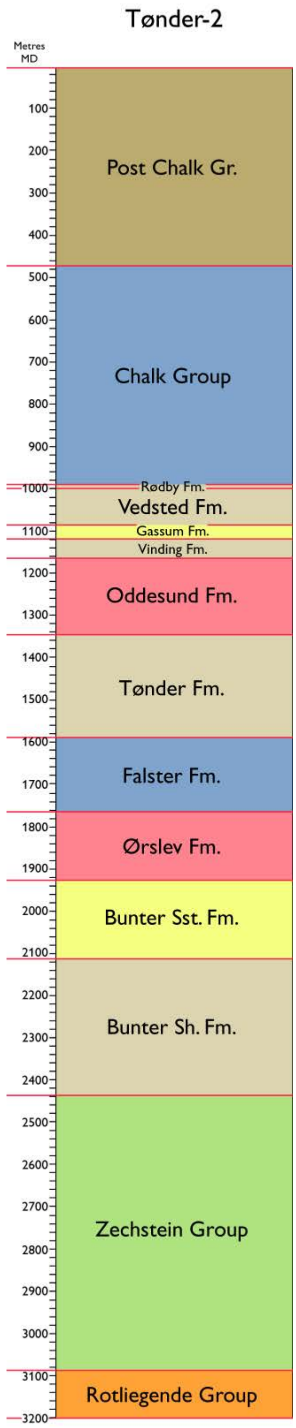

Figure 31. *Stratigraphic depth section of the Tønder-2 well showing the lithostratigraphic units and their thickness. The main reservoir is sandstones of the Bunter Sandstone Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

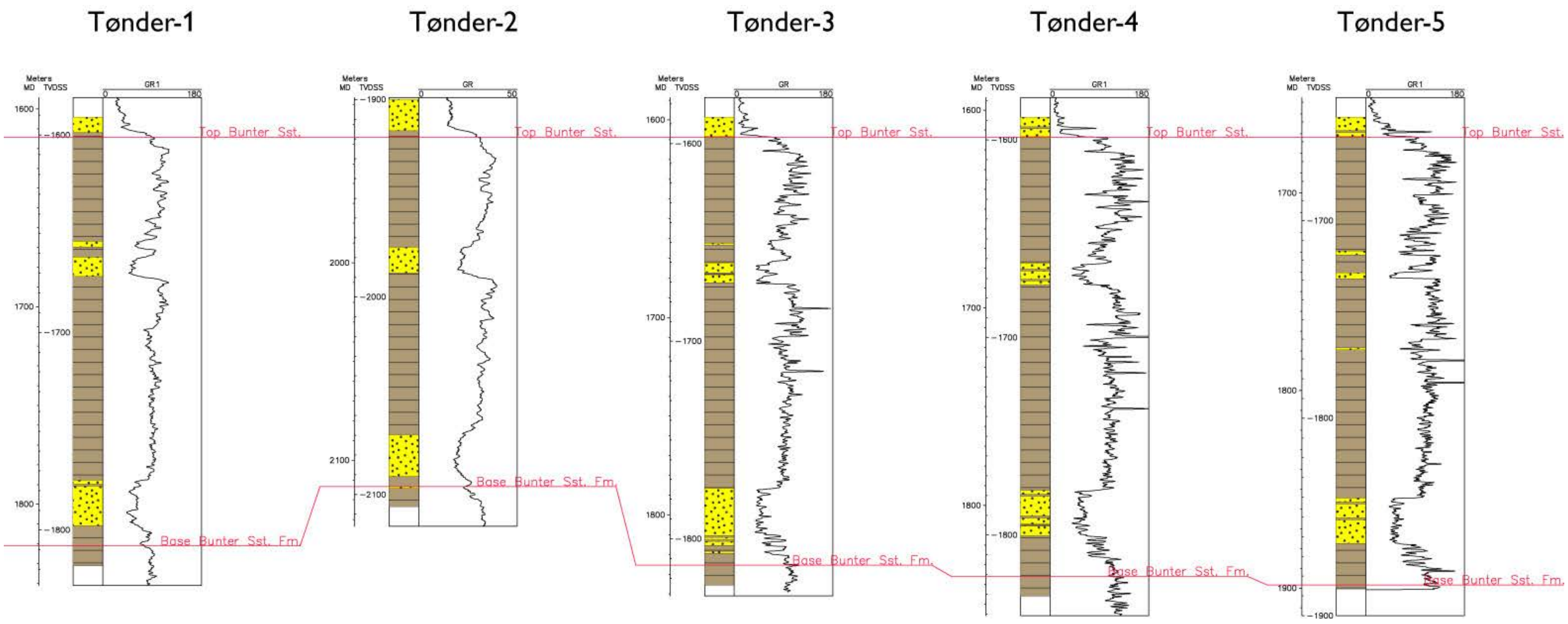

Figure 32. *Petrophysical well logs of the Tønder1–5 wells showing the interpreted sand/shale ratios and lateral variability of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991).*

Tønder	Stratigraphic units with possible reservoirs			Reservoirs					
Wells	Name	Depth below msl m	Gross Reservoir Thick m	Sand Cut-off Value	Net Reservoir Thick m	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Tønder-1	Bunter Sandstone Fm.	1601-1808	207	67 API GR	35	0.17			
Tønder-2	Lower Cretaceous undiff.	973-1069	96						
	Gassum Fm.:	1069-1102	33		12		S-29		
	Bunter Sandstone Fm.	1919-2096	177	23 API GR	34	0.19			
Tønder-3	Gassum Fm.:								
	Bunter Sandstone Fm.	1597-1813	216	67 API GR	38	0.18			
Tønder-4	Gassum Fm.:								
	Bunter Sandstone Fm.	1599-1821	222	67 API GR	29	0.13			
Tønder-5	Gassum Fm.:								
	Bunter Sandstone Fm.	1658-1884	226	67 API GR	27	0.12			

Table 11. *Table listing the wells drilled at the structure and nearby and reservoir characteristics of stratigraphic units with potential for storage of CO_2. The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Reservoir data from Tønder-1 and -2 based on Michelsen (1981). Reservoir data for Tønder-3, -4 and -5 are evaluated in this study using information from the other wells.*

Vedsted structure

The structure is situated in northern Jylland close to the city of Ålborg. It is interpreted to have main reservoir in the Upper Triassic–Lower Jurassic Gassum Formation (Fig. 33).

General geological setting

The Vedsted structure is situated in a small graben structure bounded by northwest-southeast trending faults. The graben structure is part of a Triassic rift system forming the deep Fjerritslev Trough. Both the Gassum and the Haldager Sand Formations show increased thicknesses in the graben (Bertelsen 1978). The Vedsted structure is governed by movements of an underlying salt pillow.

Well database

The seal and reservoir is penetrated by the Vedsted-1 well situated at the top point of the closure (Fig. 34 and Table 12). The well Haldager-1 is situated nearby to the east, but is outside of the small graben structure (Fig. 33).

Seismic coverage

The structure is interpreted from the depth structure map of the “Top Triassic” as defined by Japsen and Langtofte (1991) (Fig. 33).

Storage quality

Sandstones of the Upper Triassic – Lower Jurassic Gassum Formation form the primary reservoir unit. The sandstone deposition was in part controlled by the Triassic rift system and the reservoir unit reaches a thickness of 139 m with net/gross as high as 0.74 (Fig. 35). The porosity was measured to be between 20 and 24 % and the gas permeability to 1000 mD (Michelsen, 1981) (Table 12). The Middle Jurassic Haldager Sand Formation form an upside potential with excellent reservoir properties. This formation thus has a net sandstone thickness of 55 m with porosity above 30% and gas permeability measured to 2000 mD (Michelsen et al. 1981).

Subsurface storage capacity

The structure is mapped as a small ellipsoid closure approximately 250 m high covering 31 km^2. The depth to top aquifer is 1898 m below msl. The spill point is situated towards the southeast (Fig. 33). The aquifer is expected to hold a normal temperature and pressure gradient. The maximum storage capacity of the Gassum reservoir is calculated to be 161 Mtonnes CO_2. Including the upside potential of the Haldager Sand Formation would almost double the storage potential of the structure (Fig. 34).

Seal
The reservoir is sealed by a very thick (525 m) package of marine claystones of the Jurassic Fjerritslev Formation. The seal is penetrated by the well Vedsted-1 situated at the top point of the closure (Fig. 34). The fault situated immediately to the southwest of the structure may form a potential risk for a migration pathway through the seal.

Major CO_2 emission points
The Vedsted structure is situated approximately 20 km from the major emission sources in the city Ålborg (5.06 Mtonnes/year) including two public power stations and a cement plant.

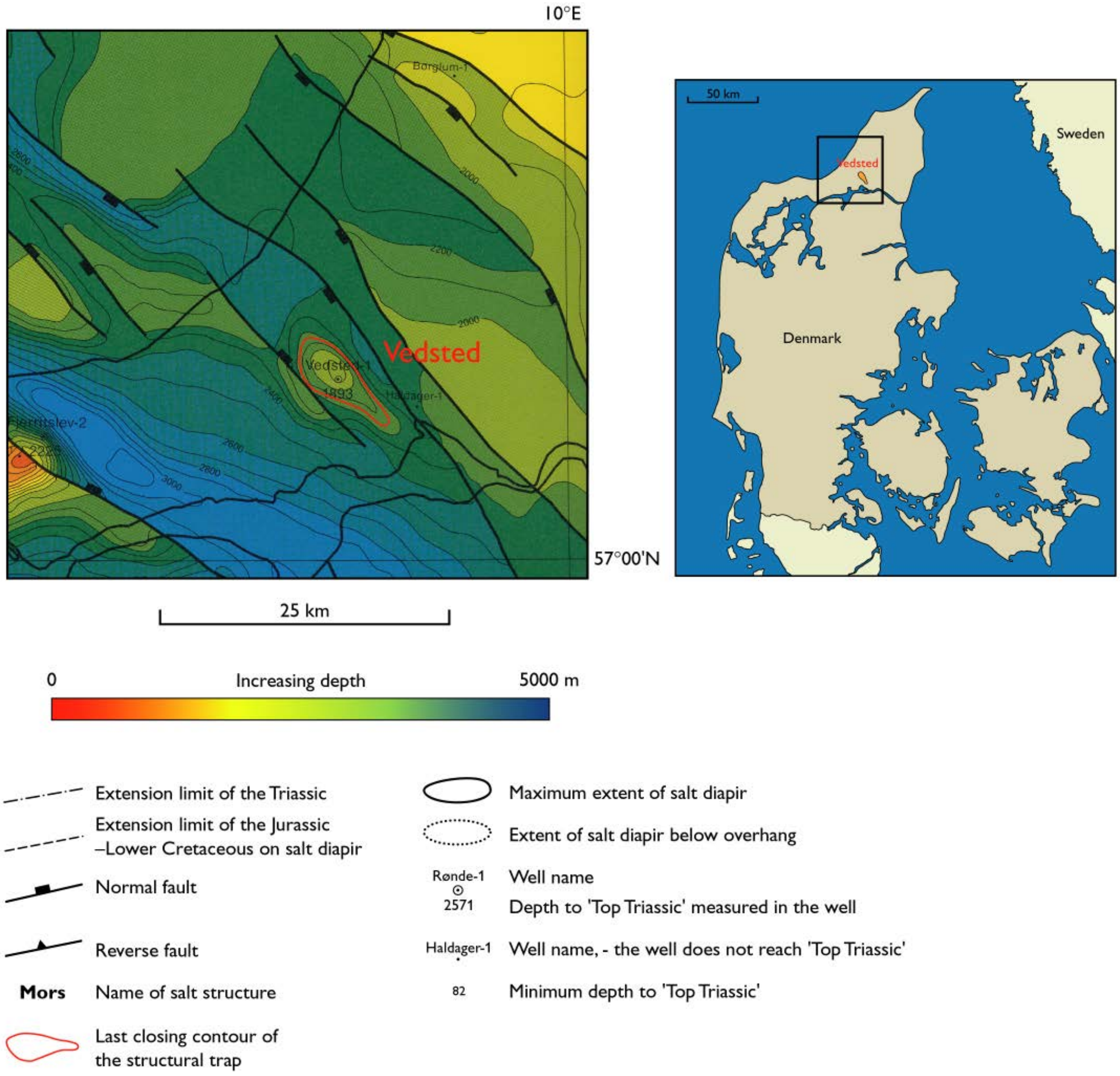

Figure 33. *Outline of the structural trap defining the potential storage site at Vedsted. The structure is interpreted from the depth structure map of the "Top Triassic" as defined by Japsen and Langtofte (1991).*

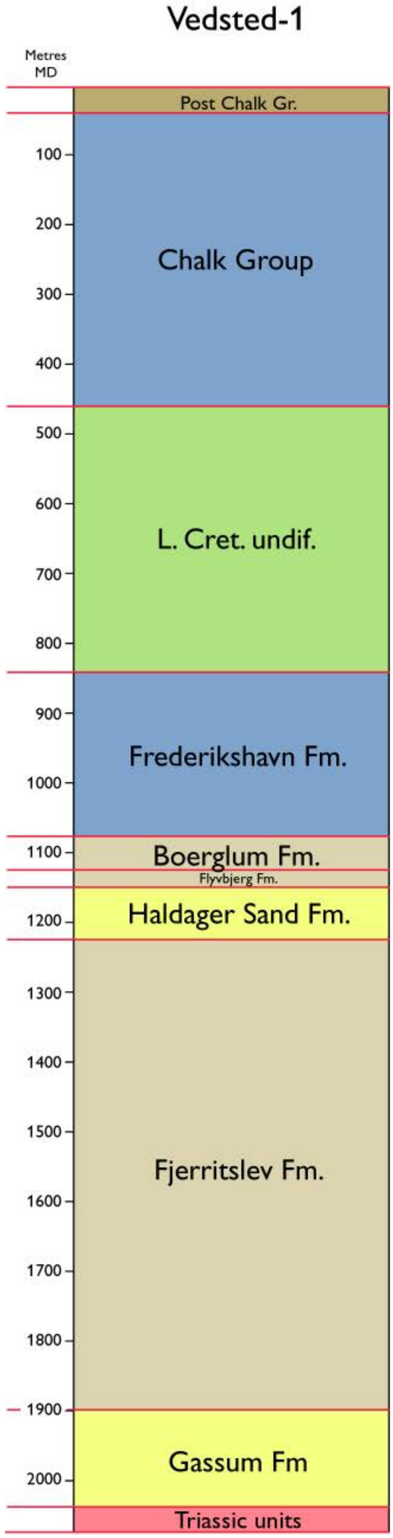

Figure 34. *Stratigraphic depth section of the Vedsted-1 well showing the lithostratigraphic units and their thickness. The main reservoir is sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

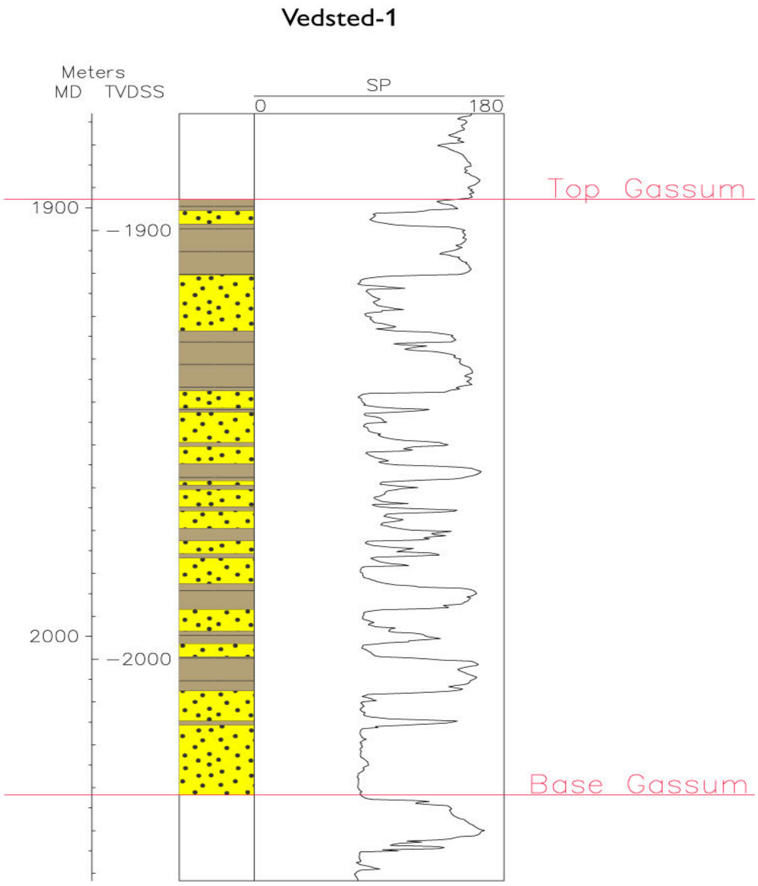

Figure 35. *Petrophysical well logs of the Vedsted-1 well showing the interpreted sand/shale units of the primary reservoirt. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991). Note that only the lower sandstone dominated part of the Gassum Formation is shown in this figure.*

Vedsted	Stratigraphic units with possible reservoirs				Reservoirs					
Wells	Name		Depth below msl m	Gross Reservoir Thick m	SAND Cut-off Value	Net Reservoir Thick m	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Vedsted-1		Lower Cretaceous undiff.	455-836	381						
	Gassum Fm.	Lower Jurassic 1; TS 10 - TS 11	1744-1766	22						
		Lower Jurassic 1; TS 7 - TS 10	1766-1893	127						
		Gassum Fm.: Base Gassum - TS 7	1893-2032	139	SP=141	103	0.74	S-20, C-24	G-1000, L-200	

Table 12. *Table listing the wells drilled at the structure and reservoir characteristics of stratigraphic units with potential for storage of CO_2. The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981).*

Voldum structure

The structure is situated in central east Jylland close to Århus, the second largest city in Denmark. The structure is defined in the Upper Triassic – Lower Jurassic Gassum Formation (Fig. 36).

General geological setting

The structure is situated in the central part of the Danish Basin. The structure is caused by uplift due to post depositional salt tectonics.

Well database

The seal and reservoir is penetrated by the Voldum-1 well situated north of the top point of the structure (Fig. 37). The reservoir is evaluated using well information from Voldum-1, Horsens-1, Rønde-1, and Gassum-1 (Table 13).

Seismic coverage

The structure is interpreted from the depth structure map of the “Top Triassic” as defined by Japsen and Langtofte (1991).

Storage quality

Sandstones of the Upper Triassic – Lower Jurassic Gassum Formation form the primary reservoir unit. The shaling out of the Gassum Formation from east towards west in the Danish Basin is reflected in a thin aquifer of only 128 m in thickness and a low net/gross of 0.38 (Fig. 38). The porosity was estimated to be 10 % whereas no estimates have been made of the permeability.

Subsurface storage capacity

The closure is defined by an almost circular, approximately 300 m high domal structure with a steep eastern flank and a flat western flank (Fig. 36). The depth to the top of the reservoir is 1757 m in the Voldum-1 well, whereas the top of the structure is situated approximately 100 m shallower. The spill point is poorly defined, but is probably situated in the southwestern part of the structure. The aquifer is expected to hold a normal temperature and pressure gradient. The interpreted closure covers an area of 235 km^2 with a maximum storage capacity of the Gassum reservoir calculated to be 288 Mtonnes CO_2.

Seal

The Voldum closure is sealed by a thick package of marine claystones of the Fjerritslev Formation. The Formation reaches 334 m in the Voldum-1 well (Fig. 37).

Major CO_2 emission points

The southern flank of the Voldum structure is situated immediately north of the city of Århus with several major point sources (total emission 3.63 Mtonnes/year). Randers power plant is situated approximately 20 km north of the Voldum structure. The annual emission, however is rather limited (0.28 Mtonnes/year) compared to the size of the structure.

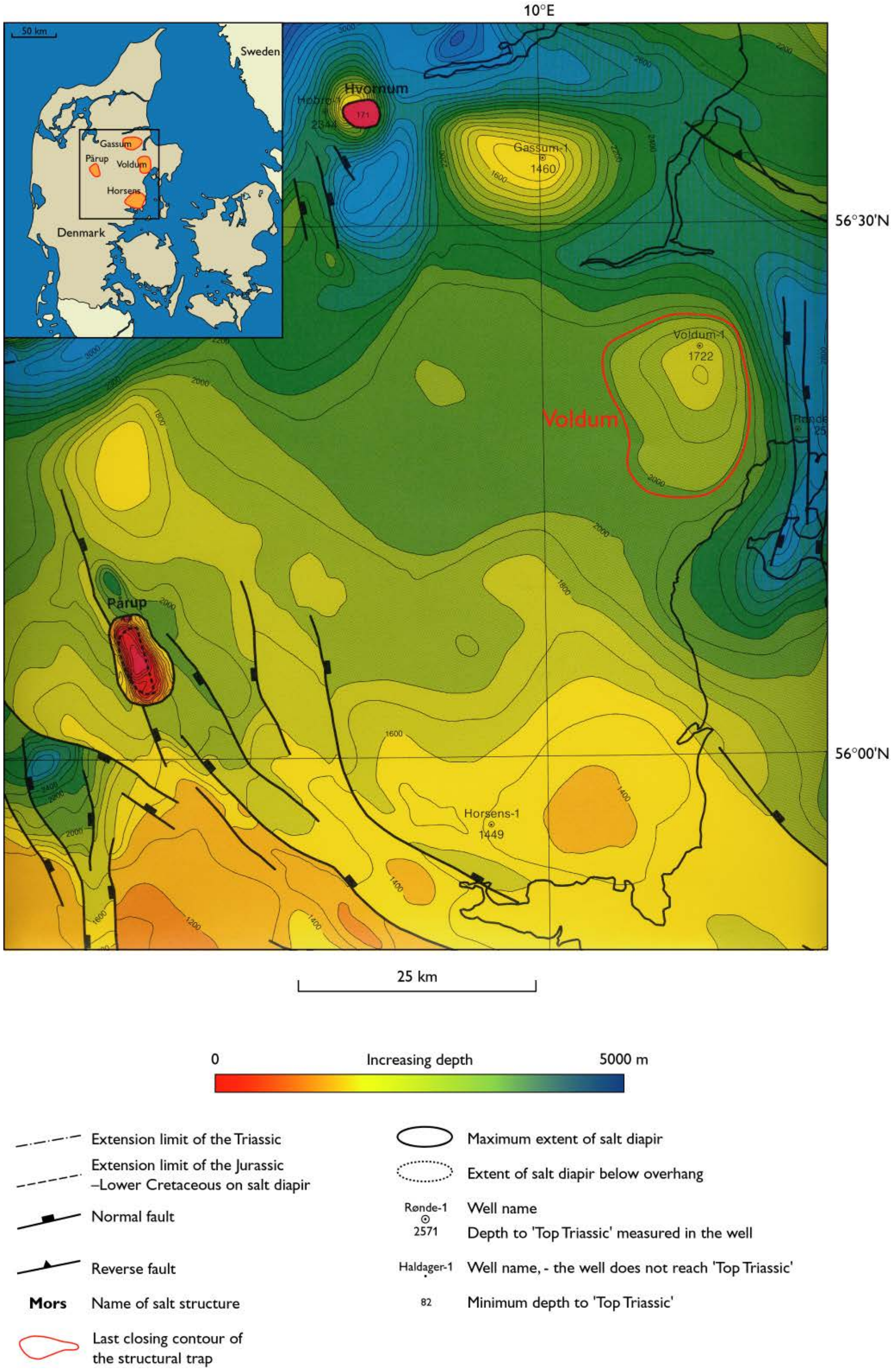

Figure 36. *Outline of the structural trap defining the potential storage site at Voldum. The structure is interpreted from the depth structure map of the "Top Triassic" as defined by Japsen and Langtofte (1991).*

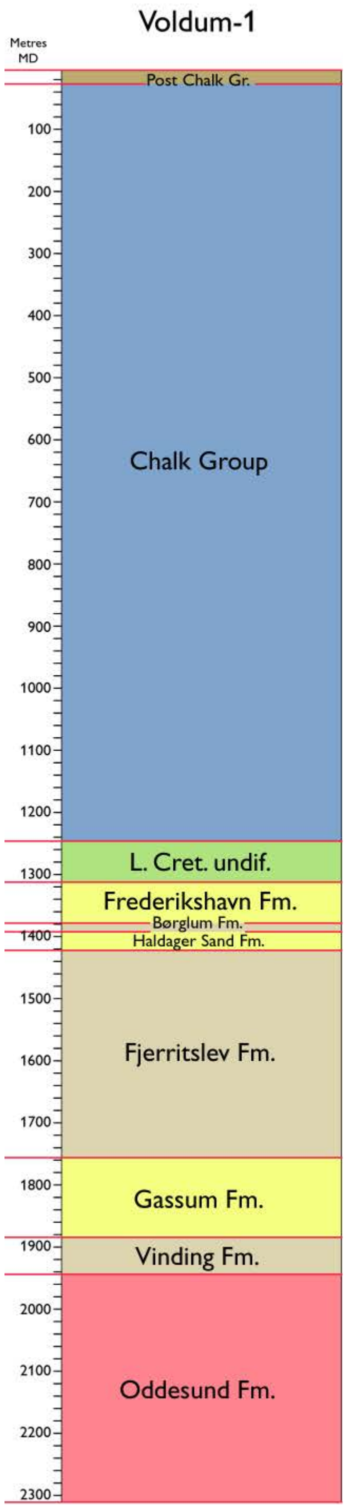

Figure 37. *Stratigraphic depth section of the Voldum-1 well showing the lithostratigraphic units and their thickness. The main reservoir is sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).*

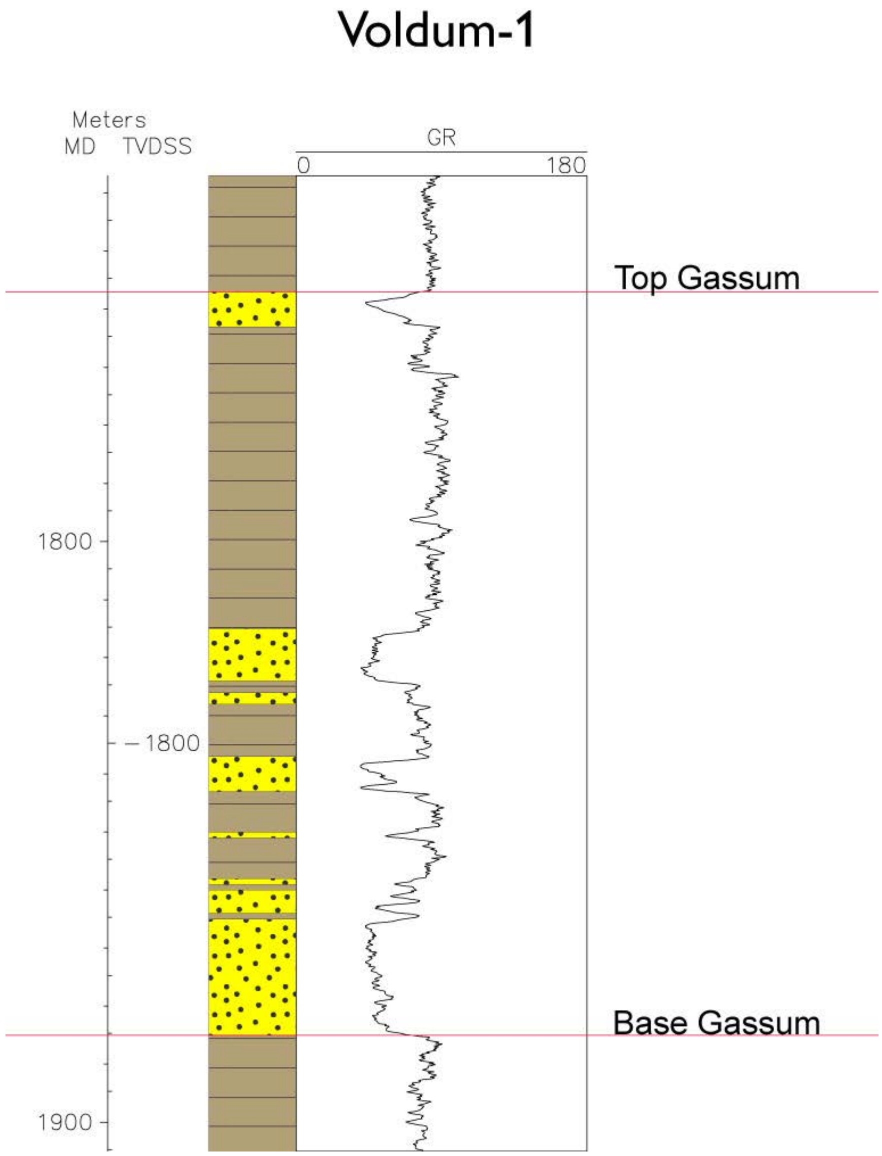

Figure 38. *Petrophysical well logs of the Voldum-1 well showing the interpreted sand/shale intervals and lateral variability of the primary reservoir unit. The top and base of the reservoir is based on interpretations given in Nielsen & Japsen (1991).*

Voldum	Stratigraphic units with possible reservoirs			Reservoirs					
Wells	Name	Depth b. msl m	Gross Reservoir Thick m	Sand Cut-off Value	Net Reservoir Thick m	Sand/Gross Ratio	Porosity %	Permeability mD	Temp. °C
Voldum-1	Lower Cretaceous undiff.	1212-1278	66						
	Gassum Fm.:	1722-1850	128	71.5 API GR	30	0.23	F-15 (avg. 8%)		

Table 13. *Table listing the wells drilled at the structure and reservoir characteristics of stratigraphic units with potential for storage of CO_2 . The porosity values are given by F: porosity based on FDC log, C: porosity measured on core. The permeability values are given by G: air permeability measure on core, L: liquid permeability measured on core. Based on Michelsen (1981).*