DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/46**

Capture, Storage and Use of CO_2 (CCUS)

Evaluation of the CO_2 storage potential in Denmark

Lars Hjelm, Karen Lyng Anthonsen, Knud Dideriksen,
Carsten Møller Nielsen, Lars Henrik Nielsen
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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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Late 2019, GEUS was asked to lead research initiatives in 2020 related to technical barriers for Carbon Capture, Storage and Usage (CCUS) in Denmark and to contribute to establishment of a technical basis for opportunities for CCUS in Denmark. The task encompasses (1) the technical potential for the development of cost-effective CO_2 capture technologies, (2) the potentials for both temporary and permanent storage of CO_2 in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the CO_2 usage potentials, including business case for converting CO_2 to synthetic fuel production (PtX). The overall aim of the research is to contribute to the establishment of a Danish CCUS research centre and the basis for 1-2 large-scale demonstration plants in Denmark.

The present report forms part of Work package 5.1 and focuses on revision of previous known structures and documentation of new identified structures suitable for CO_2 storage. The evaluation presented here presents the revision on known high-ranking structures, but evaluation is still work in progress as additional potential has been identified on other stratigraphic levels and in new structural settings.

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Dansk sammendrag

Denne rapport præsenterer den aktuelle status for evalueringen af potentialet for CO_2-lagring i det danske område. Rapporten omtaler mulighederne for lagring af CO_2 i geologiske strukturer på land og nærkyst områderne, i udtjente olie-gas felter i Nordsøen, i lag af basalter, saltkaverner og i hældende saline akviferer under havbunden. Tyngden i rapporten er langt på undersøgelse af kendte strukturer i undergrunder på land og i nærkyst områder.

Undersøgelsen leverer et estimat for lagerkapacitet for flere strukturer, der er blevet revideret, gentolket eller identificeret under denne evaluering. Da usikkerheden forbundet med kapacitetsestimatet for disse strukturer er stærkt påvirket af varieret datakvalitet, er usikkerhedsspændet for de volumetriske input-parametre estimeret for at kunne afsøge kapacitetsusikkerhedsområdet ved hjælp af Monte Carlo-simuleringsmetoder. Dette er blevet anvendt til at undersøge hele spektret af de potentielle kapaciteter, men også for at give særlig opmærksomhed på det nedre kapacitetsestimat for at vurdere om dette er et risikoelement, som bør lede til yderligere undersøgelse.

Forståelsen af den danske undergrund er udfordret af lav seismisk tæthed og dominans af meget dårlige til dårlige seismiske data. Usikkerheden, manglen på datakvalitet og den lave datadækning sandsynliggør, at flere større strukturer ville kunne identificeres, hvis nye data blev indsamlet. Det samlede potentiale for CO_2-lagring i den danske undergrund må derfor formodes at være større end præsenteret her.

Det gennemsnitlige ikke-risikovurderet potentiale er beregnet til 12 Gt CO_2 (> 6 Gt CO_2-risikovægtet) for de udvalgte strukturer der er evalueret, men det forventes at potentialet vil være større, da yderligere strukturer vil kunne identificeres med mere detaljeret kortlægning.

Desuden findes lagringsmuligheder i kulbrintefelter, hældende akviferer og saltdomer og diapirer. En screening har vist en stor åben/semi-lukket hældende akviferer i Skagerrak (Gassum Fm) (Fawad et al. 2011), som er blev evalueret mht. CO_2-lagring i NORDICCS-projektet. Simuleringer på basis af en heterogen geologisk model indikerer, at op til 1 Gt CO_2 kan lagres i det modellerede område.

Et skøn over den samlede CO_2-lagringskapacitet i de danske kulbrintefelter i Nordsøen er blevet evalueret i EU GeoCapacity-projektet til at være c. 810 Mt, og en opdatering med 2020 tal har beregnet et lagringspotentiale på ca. 900-1300 Mt (kun felter med kalk-reservoir). Nye estimater for felterne i Siri Canyon (Cecilie, Nini og Siri) (felter med sand-reservoir) fra INEOS giver en samlet lagerkapacitet på 150 til 500 Mt for hele Siri Canyon komplekset. Da størstedelen af de danske kulbrintefelter er placeret i kridt-reservoir med lav permeabilitet, kan injektion af CO_2 være en udfordring. Sandstenfelterne i Siri Canyon har højere permeabiliteter og kan være bedre egnede kandidater. Det forventes, at der er et stort lagringspotentiale i Nordsøen, både i strukturer og i hældende akviferer, som bør evalueres detaljeret med basis i GEUS' dataarkiv. Dataarkivet omfatter data fra samtlige dybe boringer og seismiske undersøgelser fra den danske del af Nordsøen foruden relevante data fra tilgrænsende områder.

I en CCUS-sammenhæng vil den mest oplagte anvendelse af saltkaverner være midlertidig lagring af CO_2 på grund af et relativt lille lagringsvolumen for de enkelte karverner, men også fordi det giver mulighed for hurtig injektion og evt. efterfølgende produktion af CO_2 sammenlignet med injektion i en vandmættet porøs sandsten.

Vulkanske eller vulkaniklastiske lag primært fra Perm eksisterer i den danske undergrund i 2-6 km dybde med lagtykkelse på op til ~700 m. Bjergarterne er rige på Mg, Ca og Fe og antageligvis velegnet til mineral karbonisering. Det er dog sandsynligt, at lav permeabilitet vanskeliggør injektion af opløst CO_2 og etablering af god kontakt mellem opløst CO_2 og bjergart.

English summary

This report presents the current status and evaluation of the CO_2 storage potential in Denmark. The report discusses the storage potential of selected subsurface structures onshore Denmark and in near coast areas, as well as the potential in depleted North Sea oil-gas fields, beds of basalts, salt caverns and in dipping offshore saline aquifers. The main emphasis has focused on investigation of known structures in the Danish on- and nearshore area.

The study delivers storage capacity estimations for several structures that has been revised, reinterpreted or identified in this evaluation. As the uncertainty associated with the capacity estimation for these structures is severely influenced by varied data quality, uncertainty ranges have been addressed for volumetric input parameters in order to assess the capacity uncertainty range using Monte Carlo simulation methods. This has been applied to investigate the full range of potential capacities, but also to give special attention to the low-side capacity estimate to highlight, if this is a risk element for further investigation.

The understanding of the Danish subsurface is challenge by low seismic density and a majority of very poor to poor seismic data. The uncertainty, lack of quality and sparse amount of data suggest that many additional structures could be identified if new data where acquired and consequently the potential for CO_2 storage should be considered larger than presented here.

For the few high-ranking structures currently evaluated, the mean un-risked potential is calculated to 12 Gt CO_2 (>6 Gt CO_2 chance weighted). It is expected that the full potential will be larger as additional structures could be identified with more detailed mapping than allowed based on the existing seismic survey database.

Additional storage options are in hydrocarbon fields, dipping aquifers, and salt domes and diapirs. A screening has revealed large open/semi-closed dipping aquifers in the Upper Triassic Gassum Formation (Fawad et al. 2011) which was evaluated for CO_2 storage in the NORDICCS project. Simulations on a heterogeneous model indicate that up to 1 Gt CO_2 can be stored in the modelled area.

An estimate on the total CO_2 storage capacity in the Danish North Sea hydrocarbon fields has been evaluated in the EU GeoCapacity project to be *c*. 810 Mt, and updated estimates in 2020 indicate a storage potential of c. 900-1300 Mt (only chalk fields). New estimates for the fields in the Siri Canyon (Cecilie, Nini and Siri) (sandstone fields) by INEOS give a range

of 150 to 500 Mt total storage capacity for the entire Siri Canyon complex. As the majority of the Danish hydrocarbon fields are situated in reservoirs of low permeability chalk the injectivity for CO_2 can be a challenge. The sandstone fields in the Siri Canyon have higher permeabilities and may be more suitable candidates. It is expected that a large storage potential is present in the North Sea in structures and in dipping aquifers, which may be evaluated in detail based on the current database available from GEUS´ files. GEUS´ archive keeps data from all wells and seismic surveys in the Danish North Sea area in addition to some relevant data from the neighbouring areas.

The most obvious use of salt caverns in a CCUS context would be temporary storage, due to a relatively small storage volume for the individual caverns and excellent opportunities for fast injection and possible production of CO_2 compared to injection into a water saturated porous rock.

Volcanic or volcaniclastic deposits mainly from the Permian exists in the Danish underground at 2-6 km depth. The successions have a thickness of up to ~700 m and the rocks are rich in Mg, Ca and Fe, suggesting that they can be used for mineral carbonation. It is, however, likely that low permeability will complicate injection of dissolved CO_2 and establishment of extensive contact between the dissolved CO_2 and the rocks.

Introduction

This chapter present the work carried out in subtask 1 under the CCUS2020 project WP5 - Validation of storage complexes. Several structures in the Danish onshore and offshore subsurface has been identified as potential targets for temporary or permanent storage of CO_2. As for this sub-task, earlier efforts to map and quantify structures has been reviewed and updated in order to incorporate new knowledge, dive further into the structural interpretation and provide further maturation to identified structures.

The major challenge for mapping and evaluating possible CO_2 storage sites and calculating of storage capacities are distribution, density and quality of the available geological data (seismic surveys and well data). In Denmark, the majority of geological data are acquired due to hydrocarbon exploration since the 1950ies and the data distribution are naturally governed by prospective areas for hydrocarbons. Younger data, typically after 2000, are often related to areas with potential for geothermal energy production and these data usually have a higher quality.

The first assessment of the Danish CO_2 storage resources was part of the EU Joule II project and the total storage capacity was estimated to 5,600 Mt for onshore aquifers and 590 Mt in hydrocarbon fields (HC-fields) offshore in the Danish part of the North Sea (Halloway et al. 1996). In 2003 the GESTCO project made a more detailed assessment of the storage capacity for 11 geological structures (traps) and the North Sea HC-fields. The capacity was estimated to 16,867 Mt in 11 structures and 629 Mt for the HC-fields (Larsen et al. 2003; Schuppers et al. 2003). These number was reused with minor editions in the later EU GeoCapacity project, and the total storage capacity in structures was estimated to 16,672 Mt and 810 Mt in HC-fields (Vangkilde-Petersen et al. 2009) and the NORDICCS project (Anthonsen et al. 2013). Additionally, the NORDICCS mapped offshore storage options in southern Denmark, summing up to 3,473 Mt CO_2 in 13 structures, and a dynamic storage estimate of a dipping aquifer in Skagerrak predicted to at least 1,000 Mt storage capacity (Anthonsen et al. 2014; Lothe et al. 2015).

The mapping of structures and static calculations of the storage capacity in GESTCO, EU GeoCapacity and partly in NORDICCS were based on earlier work of interpreted and mapped formation surfaces. The present study provides revised interpretation of previous identified structures as well as identification of new ones and deliver insights into their geological configuration and their storage capacity potential and associated uncertainty.

Geological framework

The geology of Denmark is characterised by a thick cover of sedimentary rocks of Late Paleozoic – Cenozoic age. In the Norwegian-Danish Basin (NDB) the sedimentary succession is up to 10 km thick (Figure 1). The basin is bounded to the north and northeast by Sorgenfrie-Tornquist Zone and Skagerrak-Kattegat Platform (the Fennoscandian Border Zone) and to the south and east by the basement high, Ringkøbing–Fyn High (RFH), where the sedimentary cover is relatively thin (1–2 km). The North German Basin (NGB) is situated south of the

RFH with sediment thickness comparable to the NDB, but only the northern rim of the basin is located within the Danish area.

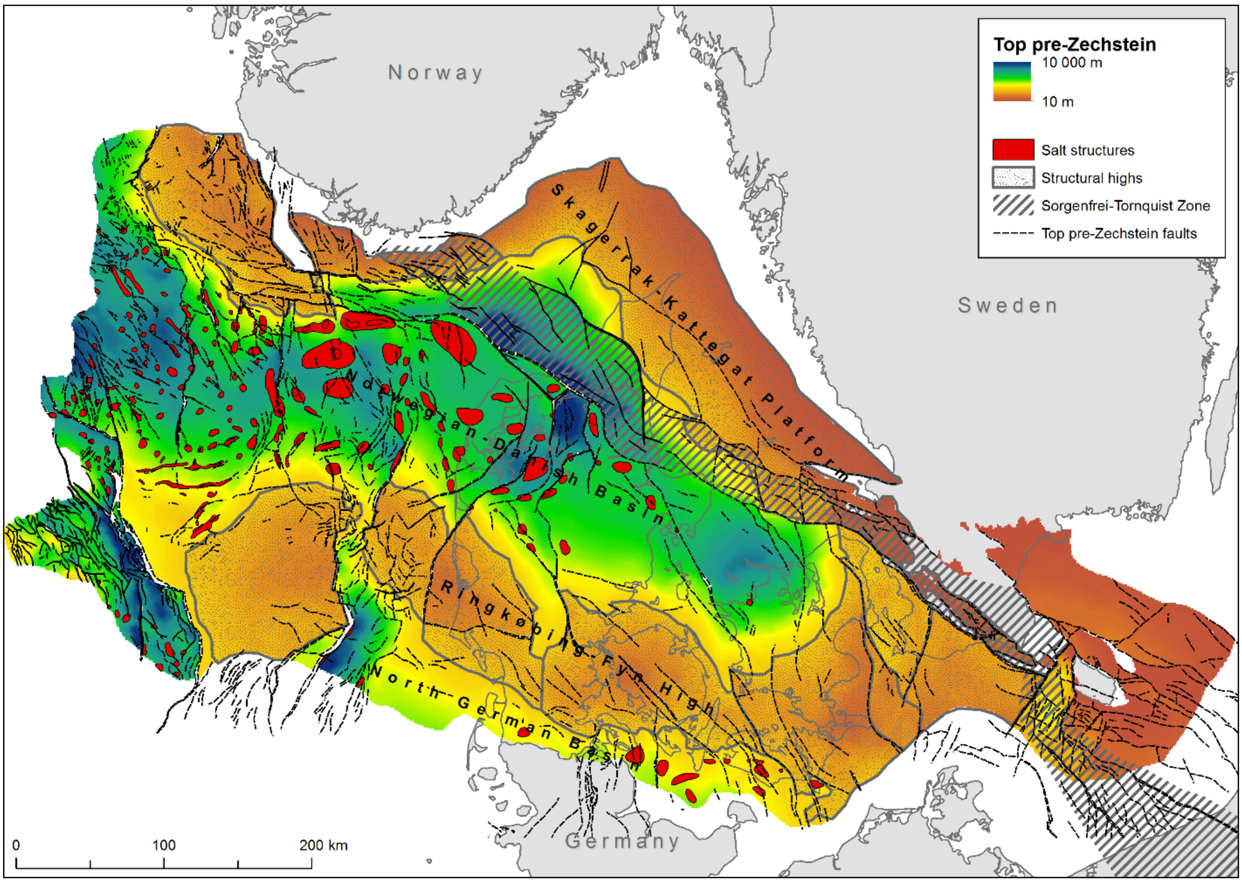


Figure 1. Map with major structural elements and depth to top Pre-Zechstein in Denmark. Modified from Vejbæk & Britze (1984).

The sediments are affected by mainly northwest–southeast striking normal faults. In the NDB and the NGB 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 salt domes and diapirs, and minor faults often accompany the salt structures.

CO_2 storage formations

The primary CO_2 storage option in Denmark is sandstone layers. Key geological selection criteria for sandstones with potential for CO_2 storage include reservoir depth, thickness, porosity, permeability, seal integrity and salinity (Chadwick et al. 2008) (Table 1).

	Positive indicators	Cautionary indicators
RESERVOIR EFFICACY		
Static storage capacity	Estimated effective storage capacity much larger than total amount of CO_2 to be injected	Estimated effective storage capacity similar to total amount of CO_2 to be injected
Dynamic storage capacity	Predicted injection-induced pressures well below levels likely to induce geomechanical damage to reservoir or caprock	Injection-induced pressures approach geomechanical instability limits
Reservoir properties		
Depth	>1000 m < 3000m	<800m >3000m
Reservoir thickness (net)	>50m	<20m
Porosity	> 20%	< 10%
Permeability	>500mD	<200mD
Salinity	> 100 gl^{-1}	< 30 gl^{-1}
Stratigraphy	Uniform	Complex lateral variation and complex connectivity of reservoir facies
CAPROCK EFFICACY		
Lateral continuity	Stratigraphically uniform, small or no faults	Lateral variations, medium to large faults
Thickness	>100m	<20m
Capillary entry pressure	Much greater than maximum predicted injection- induced pressure increase	Similar to maximum predicted injection-induced pressure increase

Table 1. Key geological indicators for storage site suitability (Modified from Chadwick et al. 2008).

Based on their relative high content of sandstone layers the most prospective formations for CO_2 storage in Denmark are (Figure 2):

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

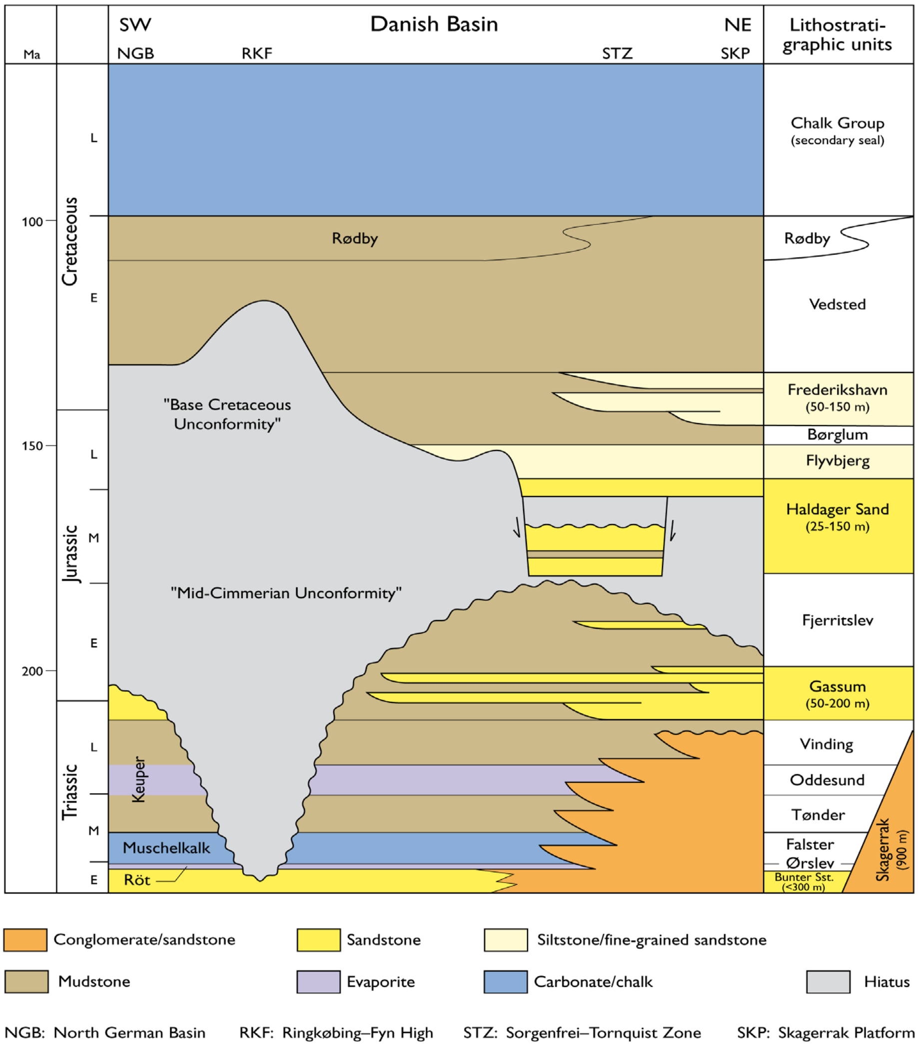


Figure 2. Simplified stratigraphy and lithostratigraphy of the sedimentary succession in the Danish part of the Norwegian-Danish Basin. (Based on Bertelsen 1980; Michelsen & Clausen 2002; Michelsen et al. 2003).

Bunter Sandstone Formation and Skagerrak Formation (Triassic)

The Bunter Sandstone and Skagerrak Formations are present throughout the Danish area. Lower Triassic sandstones of the Bunter Sandstone Formation are dominant in the southern, western, and central part of the Danish area and are gradually replaced by the Skagerrak Formation encompassing most of the Triassic sediments towards the north eastern basin margin.

The sandstone dominated succession of the Bunter Sandstone Formation forms a wide-spread unit with thickness around 300 m, although it may reach 900 m in the central part of the Danish Basin. The thickness of the individual sandstone intervals may be up to 30–50 m (Weibel et al. 2020). It is anticipated that no strong primary hydraulic barriers exist within the sheet sandstone (Sørensen *et al*. 1998). The succession is thin and locally absent across the Ringkøbing–Fyn High.

Core analyses show that several sandstones layers in the Bunter Sandstone Formation have porosity of 15–35% and a corresponding permeability of 10–3000 mD (Weibel et al. 2020).

The Skagerrak Formation is present in the Norwegian–Danish Basin where it locally occurs with thicknesses up to 5000 m (Bertelsen 1980; Liboriussen et al. 1987). Onshore wells penetrating the Skagerrak Formation are limited but show that individual sandstone-dominated intervals may exceed 200 m. The sandstone-dominated intervals consist primarily of clayey sandstones and the reservoir permeability is generally quite low (Weibel et al. 2020). The low permeability assessment is primarily based on analysis of well test data.

Gassum Formation (Upper Triassic–Lower Jurassic)

The formation is widely distributed in the Norwegian–Danish Basin and shows a remarkable continuity with thickness between 50 and 150 m throughout most of Denmark, reaching a maximum thickness of 300 m in the Sorgenfrei-Tornquist Zone. Locally it may be missing due to uplift and erosion related to vertical salt movements and it is generally lacking over the Ringkøbing–Fyn High, though it is patchily preserved south of the high (Nielsen & Japsen 1991; Nielsen 2003). It further occurs with reduced thicknesses on the Skagerrak–Kattegat Platform.

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 2003). In general, the reservoir properties are excellent with porosities ranging from 10–35% (maximum 36%) and permeability up to 10000 mD.

In the eastern onshore and nearshore parts of the Norwegian–Danish Basin, the formation may reach up to–150 m in thickness and shows 5 to 20 sandstone layers. The thickness of the individual sandstone-dominated intervals varies between 5 and 60 m, and about half of the gross sand equals reservoir-quality sandstone having high porosity and permeability (Weibel et al. 2020).

Haldager Sand Formation (Middle Jurassic)

The formation is present in the eastern onshore and nearshore parts of the Norwegian–Danish Basin, in the Sorgenfrei-Tornquist Zone and on the Skagerrak-Kattegat Platform. It is absent on and along the Ringkøbing-Fyn High and is thin and patchy in large parts of the basin except for in rim-synclines to salt structures. The formation has the largest thickness of aprox. 150 m in wells in the Sorgenfrei-Tornquist Zone and shows a general thinning toward north on the Skagerrak-Kattegat Platform and toward south in the central part of the basin. According to the results of the core analysis, the porosity of the sandstones is mainly 10–35% and with varying permeability of 1–2000 mD (Weibel et al. 2020).

The Haldager Sand Formation consists of thick beds of fine- to coarse-grained, locally pebbly sandstones intercalated with thin siltstone, claystone and coal beds. Deposition was locally affected by movements of underlying salt structures.

Frederikshavn Formation (Upper Jurassic–Lower Cretaceous)
The formation is present in the northern part of the Norwegian–Danish Basin and reaches a maximum thickness of more than 230 m in the Sorgenfrei-Tornquist fault zone. Local faults and salt tectonics mainly control thickness variations. The formation consists of siltstones and fine-grained sandstones forming 2–3 coarsening-upwards units separated by claystones (Michelsen *et al.* 2003). The reservoir zones of the Frederikshavn Formation consist mainly of fine-grained and rather clay-rich sandstones, which affect reservoir properties in a negative direction. For a particular porosity, the permeability is commonly only half the permeability of the Haldager Sand and Gassum Formation sandstones (cf. data from well-specific core analysis reports available from the GEUS subsurface archive).

Caprock/seal formations

Storage of CO_2 is not only dependent 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 mud rocks, evaporites and carbonates. The most important sealing rock type in the Danish area is marine mudstones, which are 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.

Ørslev/Röt Formation (Lower Triassic)
The formation is time-equivalent and transitional to parts of the coarse-grained deposits of the Skagerrak Formation forming the northern edge of the depositional system. The fine-grained formation reaches 100–400 m in thickness in the North German basin south of the Ringkøbing-Fyn High.

Muschelkalk /Falster Formation (Middle Triassic)
The formation is described as a unit characterised by intercalated limestones, claystones and halites (Bertelsen 1980). Fine-grained sandstones are locally present in the upper part of the formation. The formation reaches 100–200 m in thickness and forms a secondary seal for the Bunter Sandstone Formation in the Rødby and Tønder structures. It is time equivalent to parts of the Skagerrak Formation.

Keuper /Oddesund Formation (Upper Triassic)
The formation is described as a unit characterised by calcareous, anhydritic claystones and siltstones intercalated with thin beds of dolomitic limestone (Bertelsen 1980). 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 local up lift of the underlying Zechstein salt and reaches a maximum thickness of 1500 m. It is time equivalent to parts of the Skagerrak Formation.

Fjerritslev Formation (Lower Jurassic)
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 north-eastern and eastern, marginal areas of the Norwegian-Danish Basin (Michelsen 1975, 1978, Michelsen *et al*. 2003, Nielsen 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.

Flyvbjerg and Børglum Formations
The Flyvbjerg Formation consists primarily of siltstones and fine-grained sandstones with poor reservoir quality and is neither regarded as a prime reservoir formation nor as a 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 (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 Fjerritslev Fault. It rapidly thins towards the northeast, south and southwest.

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

Chalk Group (Upper Cretaceous – Lower Palaeocene)
In most of the Danish area, a several kilometres thick succession of carbonate rocks forms a possible secondary seal. The sealing effect is dependent on chemical reactions between dissolved CO_2 and the generally low permeable carbonate rock.

Database

The database consists of most available seismic and well data within the Danish area and has been made available for this study in a Petrel© (V. 2017.4) project. The data utilised in the study is shown in Figure 3 and consist of 190 wells[1], 78 different seismic surveys consisting of a total of 1832[2] seismic profiles.

Well database

190 wells reside in the database for this study (see Appendix A). For this subtask, the primary utilisation of well data has been time-depth relations for key surfaces using the formation pick framework established by Nielsen and Japsen (1991) with additional later adjustments and additions. These provide key information for ties to the seismic interpretations and essential

[1] Including side-track wells
[2] Some seismic profiles are reprocessed of older profile

input to time-depth conversion. It should be noted that only a few wells have seismic check-shots data available from the original source, and thus depth conversion is heavily depending on time-depth relations defined by Nielsen and Japsen (1991) and the difficult correlation across widely spaced wells (Figure 3).

Seismic database

For this study almost all available conventionally deep seismic data from the Danish on- and off-shore has been utilised (Figure 3). This include 78 different surveys with a total of 1832 seismic profiles amounting to grand total of 42.800 line-kilometre (See Appendix A).

A key element to bear in mind for this evaluation and for the recognition and mapping of subsurface structures is the density of the seismic lines and the quality. To further illustrate and accentuate the seismic quality and coverage in Figure 3, a map illustrating the seismic density and quality across Denmark is shown in Figure 4. The maps show green colours where seismic data of good quality are densely spaced compared to the reddish colours where no data are available and yellow/orange colour where data density or the quality is challenging. The map demonstrates to some degree that the identification of geological structures will depend on data presence, and perhaps several of the reddish areas[3] could potentially contain non-imaged structures suitable for CO_2 storage. It should in this connection also be mentioned that experience from hydrocarbon exploration, that structure size to some degree is dependent on seismic line spacing, i.e. in area where only few data are available the structure will tend to be appear larger than they are.

Another important element to notice is how the seismic quality effect the interpretation and identification of structures. For the onshore portion, the Danish seismic data are ranging from very good to very poor depending on the various vintages of acquisition. Below are a few examples of how the seismic line quality may vary and examples of profiles can be seen in Appendix B:

- Scanned old paper sections where the digital source is unknown or no longer available. For these data simple information like polarity, datum and e.g. processing workflow are to some degree unknow. Scanning of wiggle traces does not always render good results and the data are challenged further as some lines display pulling of the paper section during scan and show time indicators drifting with more than 40ms +/-

- Some lines are acquired with dynamite source data. The quality may vary with depth and range from poor to fair, as data are low fold and carry an acquisitional footprint for the shallow part.

- Some modern vibroseis lines show very good illumination of the subsurface, but these are unfortunate not very well represented in the database.

[3] Perhaps not in the Ringkøbing-Fyn High.

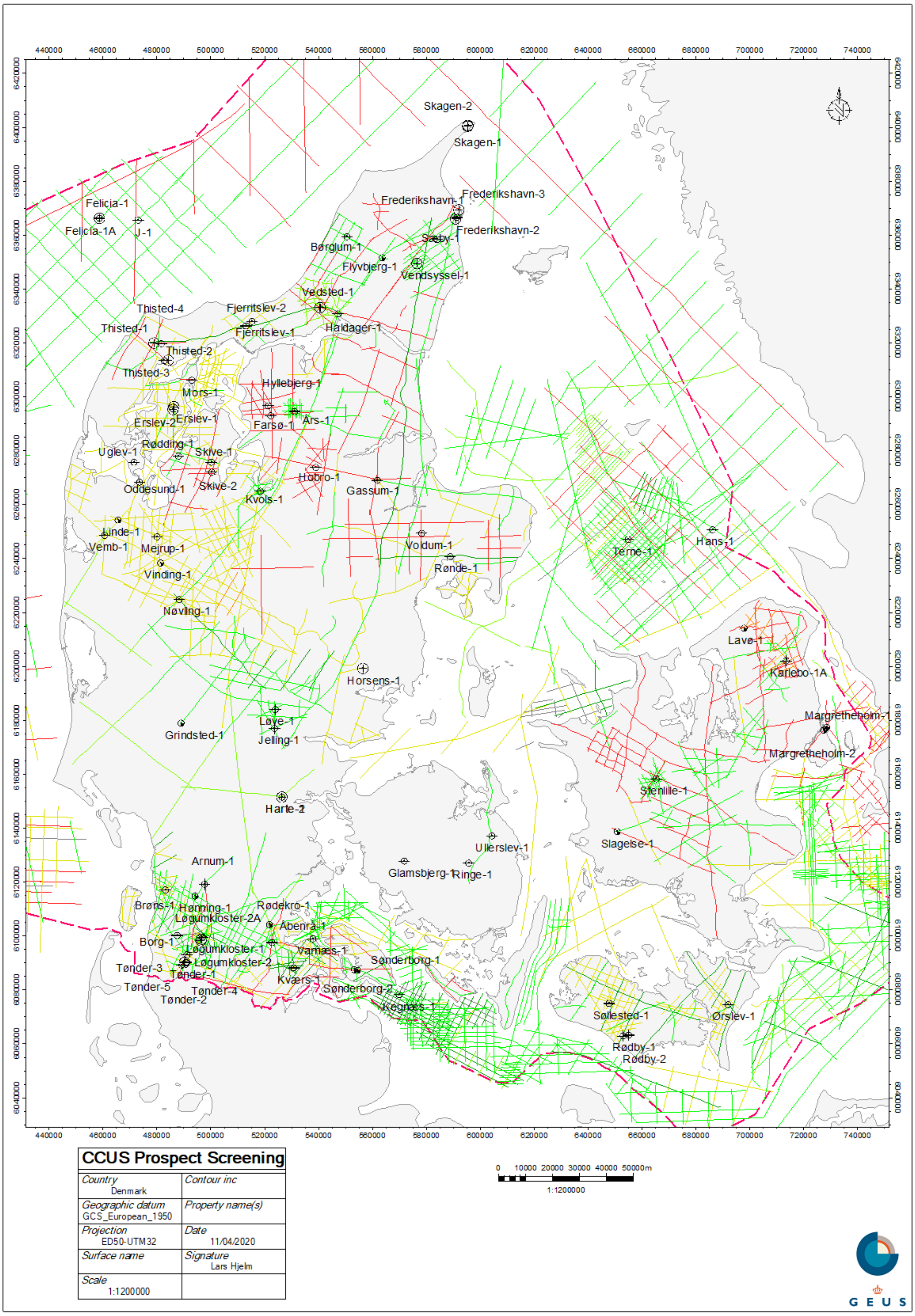


Figure 3. Spatial distribution and quality of available well and seismic surveys. The Seismic line colour reflect the quality of the lines: Red: very poor, yellow; poor/fair, Green: Good, Dark green: Very Good. Colour codes also apply for Figure 5. The variable data density and quality across Denmark affects where structure are identified and their size.

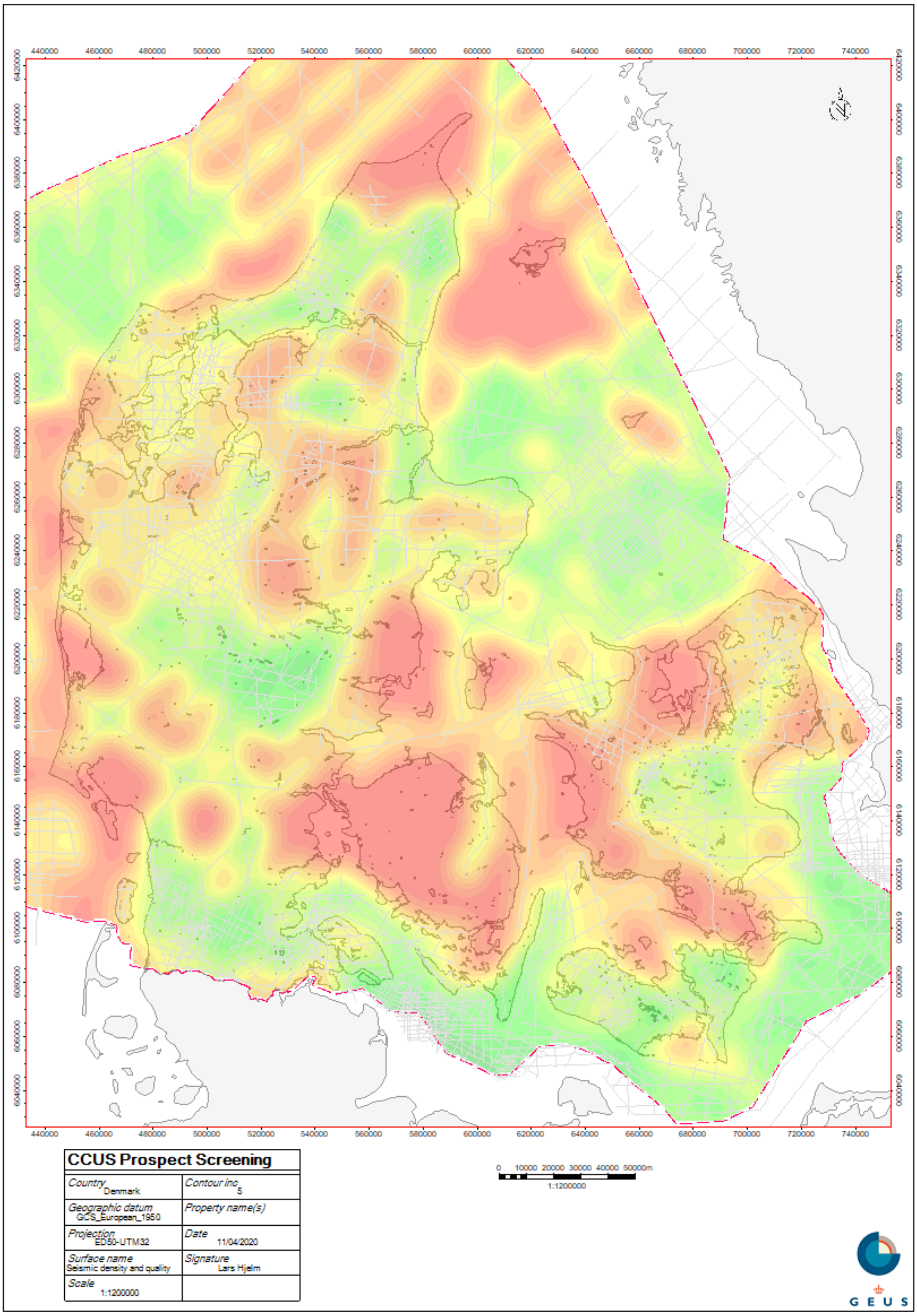


Figure 4. Seismic line density and quality map illustrating how well the Danish subsurface can be illuminated with the currently available data. The colours range from red, yellow to green and reflects how well the certainty of the subsurface interpretation can be and how well structures can be identified and defined. Red: No data, Yellow/Orange: Sparse and/or low-quality data cover and Green: Fair to Good control of the subsurface.

The seismic quality has for most profiles been subjectively ranked by their quality as shown in Figure 3 and Figure 5. For the entire database more than 2/3 of the seismic profiles are of ‘good’ or better quality. However, when working with onshore data only a 1/3 of the data has been evaluated to be ‘good’ or better and thus points to a significant challenge for this study. As almost 2/3 of the onshore data are ‘poor’ or ‘very poor’ leaves the question whether the data is sufficient for giving a reliable picture of the CO_2 storage potential. The poor-quality affects depth conversion and thus impedes structural definition, and it is believed that many structures are simply not identifiable with the current data quality and leaves a potentially underestimation of the total storage potential.

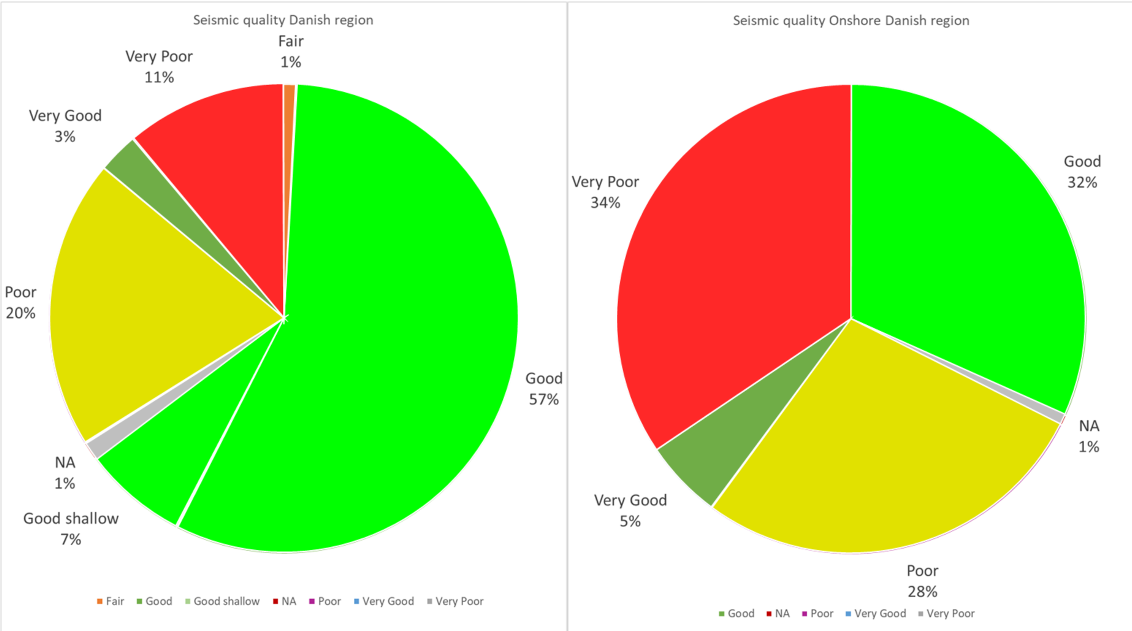


Figure 5. Chart illustrating the subjective evaluation of the seismic quality as pr. seismic line-km. On a regional scale (left) c. 2/3 of the seismic line-km have a good to very good quality, whereas this is only 1/3 for the Danish onshore part (right). This is a significant challenge that needs to be considered in the evaluation and quantification of the subsurface.

Work package results

Seismic interpretation

For this study, earlier work and a regional framework interpretation has been adapted and locally modified to support the structural definition of suitable features. The regional interpretation framework constitutes a set of rough horizon interpretations that were established for geothermal and other investigation purposes and screening projects with various objectives. In this study, local reinterpretations over already identified structures was carried out ensuring horizon consistency and paying special attention to spill points and general structural geometry and definition. For some structures, a re-definition of the overburden was needed as the local interpretation was too coarse for local depth conversion. The important local structural definition in depth is important for smaller structures and different compared to regional consideration, where wide grids and smoothed maps are fit for that purpose. Some new structures are also identified, and the reinterpretation has in several places redefined structures, as the subsurface geometry has been modified. More work is needed to get the full perspective on the structural potential for both the Gassum Formation and the Bunter Sandstone Formation and for additional targets as the Skagerrak Formation, the Haldager Sand Formation and for possibly the Miocene sands in the North Sea. Figure 6 shows a structure map with the current status of the Gassum Formation top, but further refinement of this horizon and others is recommended.

The seismic interpretation is, as mentioned above, very challenging on the numerous low-quality profiles. To illustrate this, Figure 7 shows two uninterpreted seismic profiles running parallel (within kilometres of each other) where the difference in seismic quality of vintages is significant. The selected example is located in a fairly structural quiet region to illustrate how much seismic facies and reflector consistency differs. In areas with additional structural complexity, the interpretation of faults and associate ambiguity in reflector displacement adds an additional element of complexity/uncertainty.

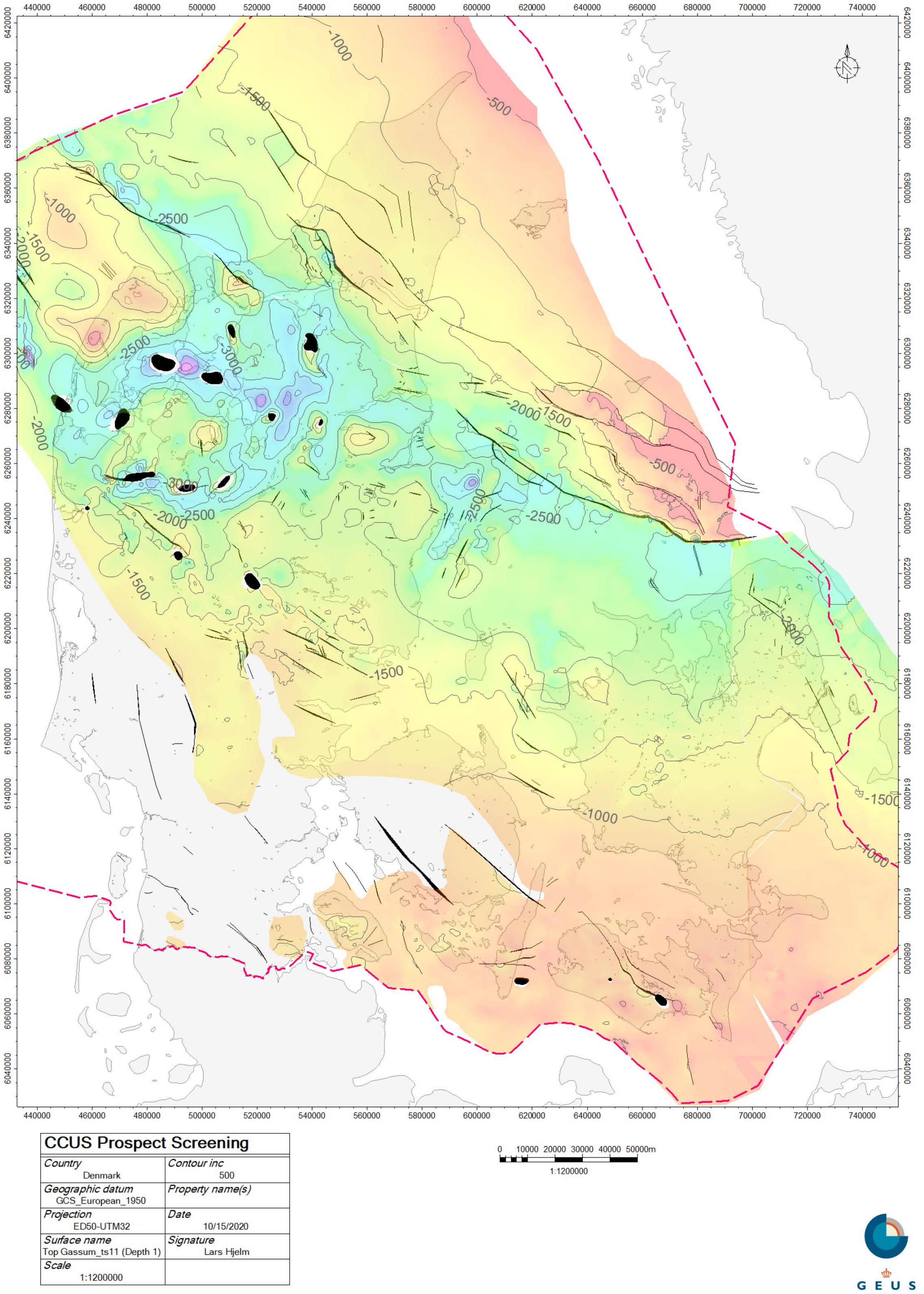


Figure 6. Structural depth map showing the current interpretation status of the Gassum Fm. Some fault definition are Non-QC adaptations from previous studies. Due to the time transgressive nature of the Gassum Fm., this surface is a merge of the Gassum Fm. sequences TS9(Central), TS11(N-NE) & TS15(East).

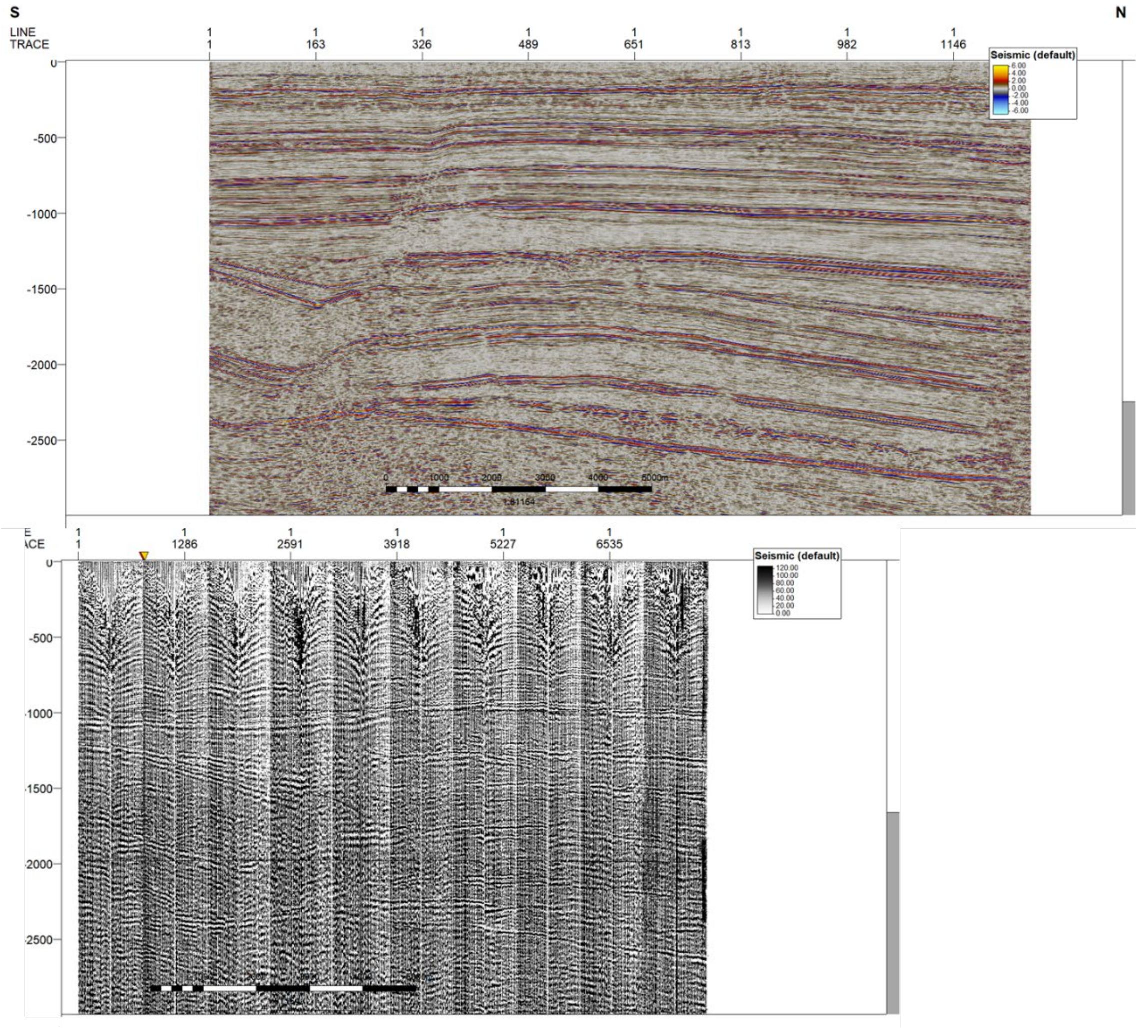


Figure 7. Example of two uninterpreted N-S running seismic profiles (almost spatially overlying) just south of the city of Ikast. The upper profile is categorized as 'Very Good' and the lower one as 'very poor' (one of the better 'very poor' profiles). The quality difference demonstrate how interpretation across very poor seismic data is challenging as poor definitions of faults, acquisition footprint, processing artefacts, seismic reflector recognition/continuation and lack of seismic facies can introduce misinterpretations, subsurface risk, and structural uncertainty.

Storage capacity estimation

The amount of CO_2 than can be stored in a subsurface feature is very much depending on the media for storage and the needed control on injected CO_2. For subsurface aquifers or permeable geological formation, a Storage Assessment Unit (SAU) can be defined as the regional extent of the aquifer and as having an upper limit defined as the depth where supercritical CO_2 phase no longer is possible (approximately at 800m depth depending on temperature and pressure conditions). The lower limit for storage is depending on porosity and permeability of the host rock, and an acceptable lower boundary is very much depending on acceptable injection rates in the projects (lower limit is usually described as 3-4 km Figure 8) (Brennan et al 2010). The Storage Capacity of a SAU can in general terms be describe as the pore volume of the aquifer within the SAU definition multiplied with a storage efficient factor, (fraction of the pore space where CO_2 'can' be injected) and multiplied with the CO_2 density at the reservoir P-T conditions.

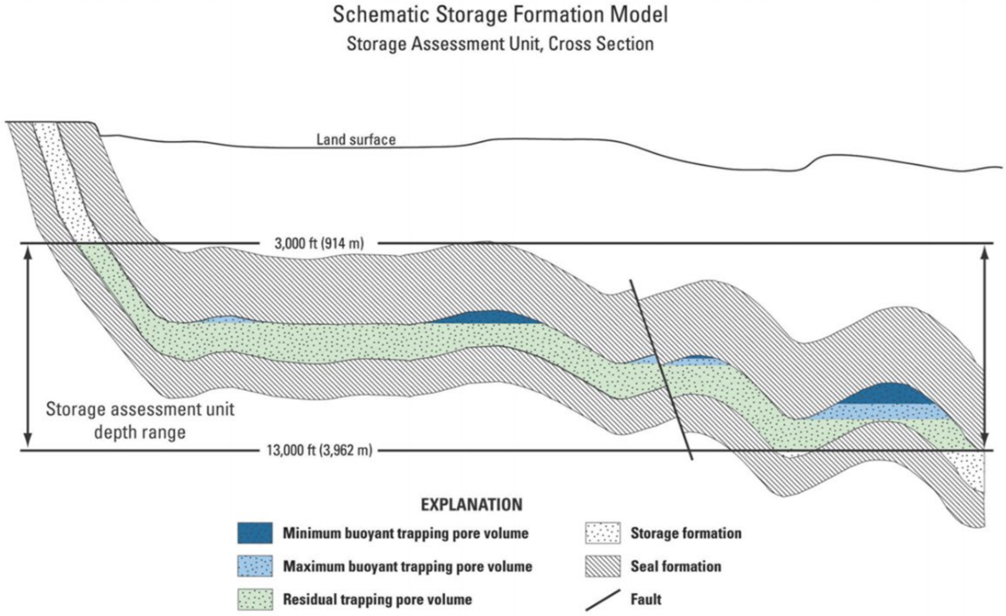


Figure 8. Conceptual profile across a potential reservoir unit suitable for CO_2 storage and illustrates elements of the storage assessment unit (SAU) as defined by Brennan et al (2010).

Two general trapping mechanism are generally considered within a SAU; residual trapping and buoyant trapping and the amount of trapped CO_2 can be assess via the equation below and the calculation workflow illustrated in Figure 9.

A large potential for residually stored CO_2 is believed to be available in the Danish subsurface reservoirs. However, only the storage potential of buoyant trapped CO_2 in well-defined geological structures is considered and quantified for this part, as the confidence in confinement and subsequent monitoring of the CO_2 in these structures is associated more certainty.

The storage capacity estimation of structures with buoyant trapping is estimated via this equation:

$$\mathrm{SC} = A \times h \times GCF \times N{:}G \times \varphi \times \rho_{CO2R} \times S(Eff.)$$

SC	Storage Capacity
A	Area of aquifer within trap. This is the area of the deepest closing contour from where spillage from a trap will occur. This is also the potential area of the CO_2-water contact
h	Average height or gross thickness of reservoir unit (including non-net reservoir). The thickness must correspond to the selected N:G and φ.
GCF	Geometric Correction Factor. Geometric compensation for the volume below CO_2-water contact when the A x h methodology is applied. The parameter is estimated by considering thickness vs structural relief and the overall shape of the structure

using geometrically calculated geometry relationships shown by Gehman (1970) (see Figure 10)

N:G Average net to gross reservoir ratio of aquifer across trap

φ Average effective reservoir porosity of aquifer within trap

ρ_{CO2R} CO_2 density at reservoir conditions across all of trap. The density is calculated using Span and Wagner (1996) using average temperature and pressure assumption for the entire trap.

$S(Eff.)$ Storage efficiency factor relates to the fraction of the available pore volume that can actually store CO_2 within the trap. This fraction depends on the size of storage domain, heterogeneity of formation permeability, porosity, compressibility, but is also strongly influenced by different well designs and injection schemes (Wang et al. 2013). Rule of thumb estimates for storage efficiency factor is also given by Brennan et al. (2010) (see e.g. Figure 11).

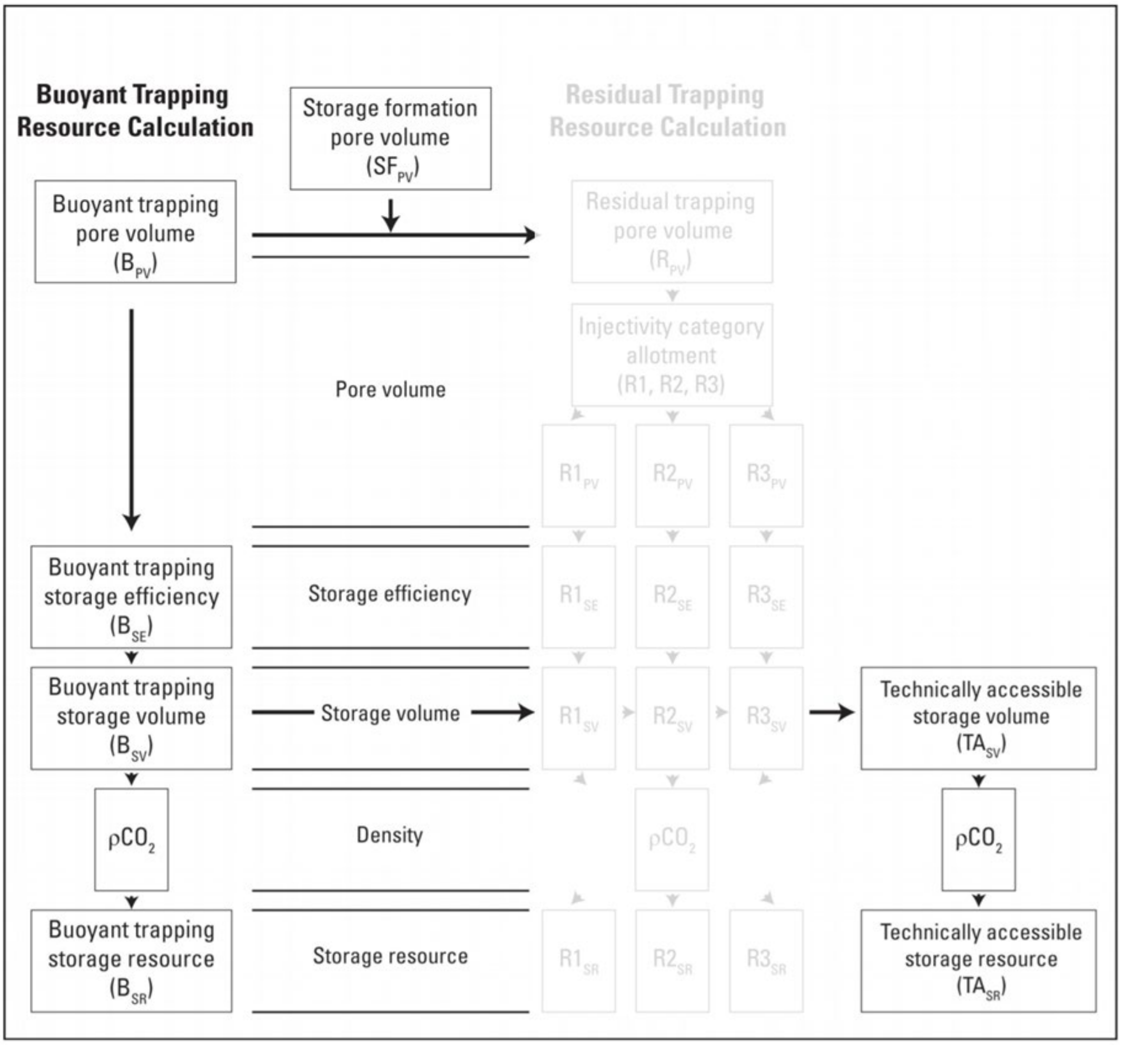


Figure 9. Terminology, methodology and flow chart for estimation the total storage potential/resource of a SAU in terms of both the residually trapped (greyed out) and the buoyant trapped volume (Brennan et al. 2010). For this part, only the potential of the buoyant trapping resource is addressed, but it should be noted that an un-evaluated volume (potentially huge) is available for residual trapping within the Danish subsurface aquifers.

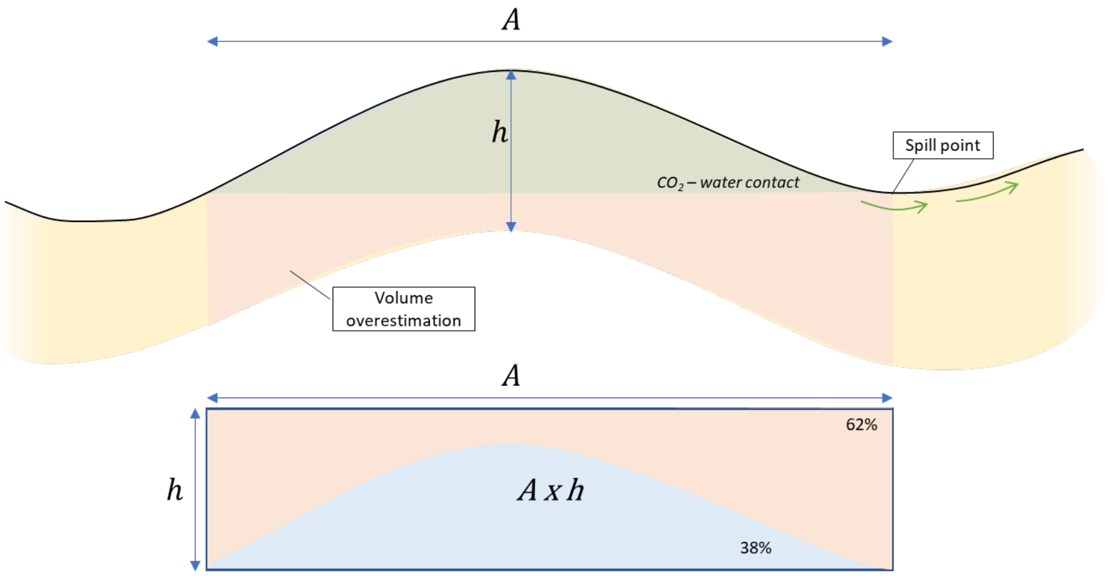


Figure 10. Conceptual profile across a potential structure illustrating the application of Geometry Correction factor (GCF). As multiplication of structural area(A) and the reservoir thickness (h) is applied, the overestimation of volume needs to be corrected as some of the volume will be situated below the spill point and the CO_2 -water contact. This is done by applying a GCF that constitute the fraction of volume above CO_2 -water contact divided with (A x h). Here the GCF is very low (38%) to illustrate the point, but thin reservoirs in high relief structures will have GCFs near 90-95%.

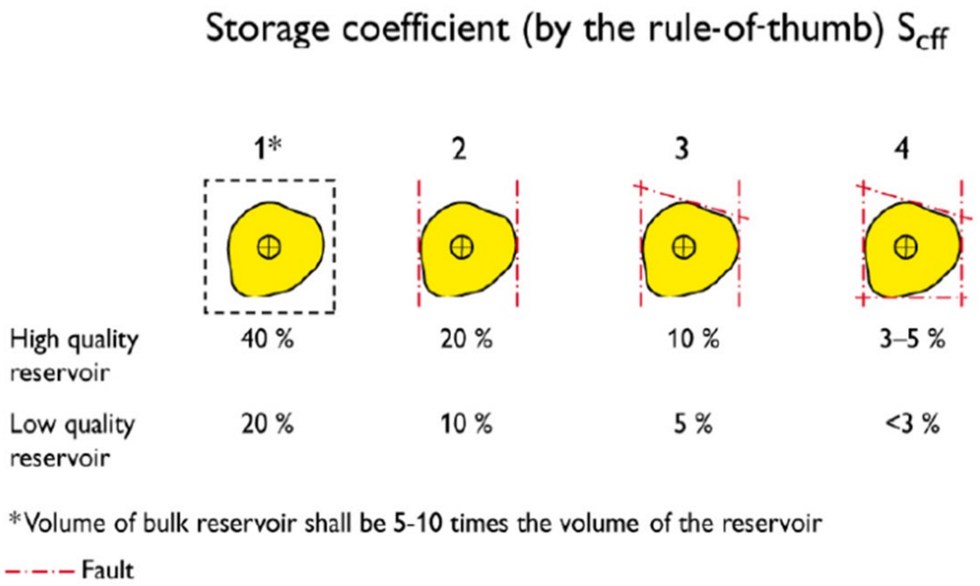


Figure 11. Potential variability and 'rule of thumb' estimate of the storage efficiency for different structural configuration. From Brennan et al (2010).

The storage capacity can be calculated with best estimates for all input parameters, but for screening projects the uncertainty of input is incorporated to produce a storage capacity range for each structure.

Uncertainty in estimating capacity input parameters

With the available data, lack of analogues (except the Stenlille gas storage facility) and uncertainty in interpretations, the storage capacity estimate for a given structure should be associated with large uncertainty. Below are descriptions of key uncertainty elements to consider in the calculation.

Gross rock volume (A x h x Geometry Correction Factor (GCF))

Seismic data quality:	Large variations in the data quality affects several input parameters due to lack of interpretational certainty. Data might indicate an anticline which potentially could be seismic noise (very seldom considered the case), but the quality affects the structural definition, and thus area, the reservoir thickness and the total understanding of the structural geometry. Processing of seismic data (poor velocity picks and poor migration) may affect how structures are interpreted and can lead to uncertain definition of the areal limit of a structure, the relief and depth to the spill point. Seismically picked depth to structural apex is also affected and could introduce risk on whether super critical CO_2 phase is possible for shallow located structures. Figure 12 conceptually show how structure geometry can vary and cause uncertainty of the interpretation of area, thickness and GCF.
Seismic interpretation:	Interpretations may be subjective (particularly for poor quality seismic). Uncertainty is thus introduced for all structural geometry parameters and to some of the elements describe above.
Seismic density:	Interpretation and mapping in an open grid leaves great uncertainty on gross rock parameters. Selection of different gridding algorithms create very different structures and a simple test in this study shows that max. area for a structure could vary up to 25% depending on the selected gridding algorithm only. Fault interpretation (fault polygon definition on maps) will have an impact on area of a structure as the gridding is guided by the interpreted polygon length and orientation.
Seismic well tie:	Tying interpretations to well data can be problematic over large distances and across very poor data. The situation might arise where it is uncertain whether a given reflector truly represents the interpreted top of a given reservoir. It could be situated shallower or deeper or it could even be truncated and represent something completely different.
Depth conversion:	As the depth conversion have a very important influence on final structural geometry, it is critical that the depth conversion is associated with large uncertainties in some areas. The final structural geometry is affected by how overburden is interpreted (cumulative

uncertainty of the horizons above), data uncertainty in well ties and the associated velocity approximation. The current velocity model is not detailed, and some uncertainty is accepted as no data could support a more detailed model.

Thickness: Thickness has not consistently been mapped across the different structures in this study. It is however considered that the interpretation of the base reservoir is affected by the same uncertainties as mentioned above, but that nearby well data can provide an equally good estimate for the thickness. Well data and interpretation of logs provide guidance to thickness assumptions. Some uncertainty needs to be considered to capture whether the wells are representative for the structure in question.

Estimation method: For this screening study, the gross rock volume is calculated with the A x h x GCF method. This is not a precise method but fast and easily updateable compared to other methods. A key uncertainty issue is the estimation of the GCF that usually will be guided with a subjective approximation.

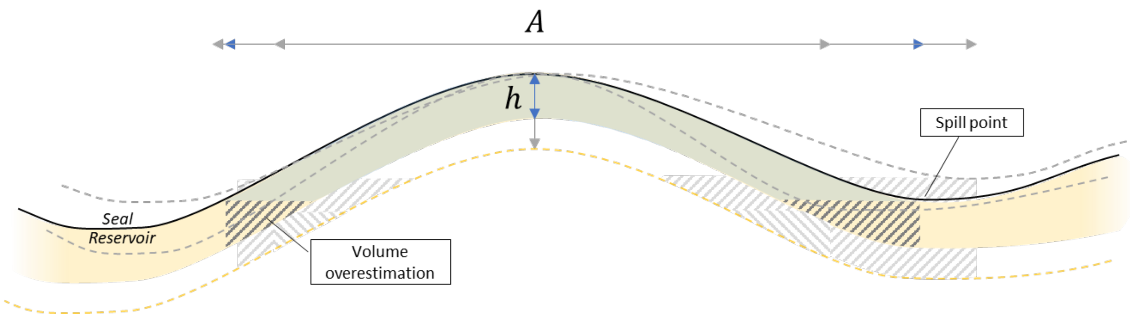


Figure 12. Conceptual figure illustrating how uncertainties in depth conversion, seismic mapping, data quality and sub-CO_2-water-contact volume affects possible trap configuration (compare to (Figure 8). The uncertainty is addressed by applying uncertainty on area(A), Reservoir thickness (h) and Geometry Correction Factor (GCF) that compensate the volume overestimation in the A x h methodology

Reservoir parameters (φ x N:G)

Well log interpretation: Some uncertainty in estimation of reservoir parameters is associated with interpretation of the petrophysical logs. The quality of the logging tools (especially for old wells) and selection of cut-off thresholds all affect the accuracy and confidence of the reservoir quantification.

Well extrapolation: In some cases, wells have already been drilled on the structures being evaluated, but other structures rely on nearby offset well data. With further distance to a well a larger uncertainty is introduced in the porosity and N:G input. The large-scale lateral facies development can be modelled and give good estimates; but it is emphasised that it is a model. Seismic interpretation uncertainty also increases away from the wells.

Well representativeness: Extensive local facies variability may be present as demonstrated by the Gassum Fm in areas with several wells, i.e. the Himmerland Graben (Farsø-1, Hyllebjerg-1, Aars-1 wells), the Thisted structure (Thisted-1 through Thisted-5 wells) and the Stenlille area where some wells show huge variability. Finding a representative average value for φ and N:G can be difficult, even for structures with one or several wells and good well-log quality and solid interpretation. Some wells may also be located in a position which is not representative for the average lithology for the entire structure, and thus considerations on how to average well results across the entire structure is hampered.

Depth dependency: Using well results directly should be done with care as porosity is depending on maximum burial depth. Well porosity should therefore be calibrated to the depth of the evaluated structures. The porosity input needed in capacity calculations are average porosity, which can be difficult to estimate as some structures have more than 800m relief and a poorly known or even unknown volume distribution across the different depth. The input porosity will usually be a (reasonable) guess with some uncertainty associated.

Fluid parameters (ρ x S_{eff})

Depth assumption: Temperature and pressure assumptions are based on the mapped depth and therefor already have some primary uncertainty associated.

Temperature assumption: A structures average temperature can be established from estimated geothermal gradients. However, geothermal gradient may vary across a region of interest, as structural configuration and variation of the surrounding geology may vary significantly. The resulting CO_2 density at reservoir depth based on a geothermal gradient of 20°C/km instead of 35°C/km can affect the storage volume.

Pressure assumption: Density estimates depend on pressure and this can vary locally as minor overpressures can occur.

CO_2 purity: Impurities in the injected CO_2 means that the actual CO_2 density range may deviate from pure CO_2 (lower density typically)

Storage efficiency:	Certainty of the storage efficiency is very difficult. The fraction has some physical constraints such as size of the injected structure, formation permeability, porosity and compressibility. But some of the uncertainties also depend on selected injection strategy i.e. the well design, well density and distribution, injection rates etc.

Monte Carlo methodology in capacity assessment

The main purpose for using the Monte Carlo methodology in this study, is to emphasise the considerable uncertainty in the storage capacity estimation. The approach can generate results that answers the question; ‘how big could it be’, but more importantly gives insights into low end capacity values that should be considered in risk management discussions.

To describe the uncertainties quantitively and calculating the potential range in storage capacity, a simple Monte Carlo simulation tool has been built in MS Excel®. Monte Carlo simulation is a computational algorithm that utilise repeated random sampling to obtain numerical results. The underlying concept is to use randomness to solve the calculations involving the multiplication of the 7 different probability distribution for each of the input parameters used here. In practical terms, the building of uncertainty distribution for each of the volumetric input parameters, the PERT[4] distribution was selected as a general versatile distribution that can accommodate this simplistic modelling and utilise the range assessment very easily into normal and naturally occurring distribution sets. The PERT distribution belongs to a family of continuous probability distributions defined by the minimum, most likely (mode) and maximum values, and importantly the distribution can be skewed toward both the low - and high end (Figure 13). The distribution is easily transformed into the four-parameter Beta distribution that is available in Excel®. To achieve stable and sufficient statistical representation of both input distribution and result output, 10.000 trials are calculated for each simulation. For each trial, a random picked value from each input distributions is multiplied to give a ‘random’ output result for pore volume, effective storage volume and CO_2 storage capacity.

[4] See Glossary for further information

Parameter	Assumption Min	Mode	Max
Area (km^2)	105	210	273
Geometric corr. factor	0,6	0,68	0,85
Gross Thickness (m)	100	130	150
Net/Gross	0,27	0,32	0,45
Porosity	0,08	0,1	0,15
Storage effect.	0,2	0,35	0,4
Insitu CO_2 density (kg/m^3)	584,25	615	645,75

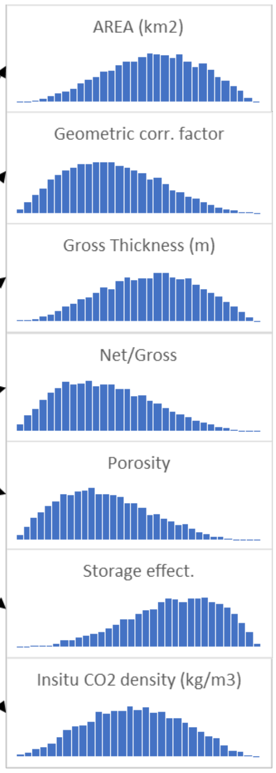


Figure 13. For the Monte Carlo simulation in Excel® the input distributions are built from the range assessment of min., mode and max. for each volumetric element as shown in the table. The PERT distribution is built from 10.000 trials for each element and result in the input distribution shapes seen to the right.

Limitations of current Monte Carlo method setup

Excel® is not the perfect Monte Carlo simulation tool, but iis considered to be adequate for this screening effort.

The model is restricted in functionality with respect to:

a. Correlations of input parameters have not been incorporated. This means that if a correlation between e.g. thickness vs GCF or $S_{eff.}$ vs Area is believed to be present this cannot be incorporated. Other associations like inverse correlation between thickness vs. GCF or porosity/perm vs. storage eff. cannot be incorporated either.
b. One may argue that the Excel® 2003 random number generator does not fulfil the basic requirements for a random number generator to be used for scientific Monte Carlo purposes. However, for practical rough estimates as in this case, it is considered that the approach is suitable.
c. Only a few statistical distribution functions are available in Excel®. The Pert-Beta distribution is considered to be sufficient for this level of evaluation, although it could be argued that extreme values are not represented in the calculation.

Input parameters for this study

To address the storage capacity uncertainty of the structures, the ranges for the volumetric input parameters has been assessed and selected. In general terms, each structure has been given individually evaluated input ranges, but general concepts for the parameter selection has been applied, ensure consistency and comparability across the structures. The input parameters used for this study are shown in Table 2.

The various input ranges have been given the following concepts and considerations:

Area: As area uncertainty is dependent on confidence in the seismic interpretation, the depth conversion and density and quality of the seismic lines, this parameter must be regarded as having large uncertainty. Experience from Oil industry exploration have shown from performance tracking that sparsely data supported prospects (successful) were ranging from 50% to 130% of their original assessed prospect area. This oil industry 'rule of thumb' has been adapted for this study to quantify uncertainty, but application of an even larger uncertainty range has been considered to accommodate the relatively poor data quality; however, the justification for this may be challenged.

h: The thickness range for the reservoir units is selected based on knowledge from nearby well averages. Mapping of the base of the reservoir unit has not been applied and may be difficult to impossible in certain areas. The range is picked using a most likely estimate considering all uncertainties and then setting a min./max. range usually +/-20% or larger if e.g. wells are far from the structures. The reservoir thickness (h) parameter in the capacity equation represents the average thickness (across the prospect) and therefor the value range should encompass regional understanding, representativeness of local wells and local thickness variation across structure.

GCF: Geometry correction factor is picked using the calculation methodology described by Gehman (1970) for the selection of Mode (Figure 14). The low side of the range is calculated using max. estimated reservoir thickness wheras the high end of the range is picked fairly high to represent a scenario where multiple reservoir units are stacked and not in pressure communication.

Net to Gross: Similar to reservoir thickness the N:G mode is selected based on offset well information. The range is usually +/-20% from best estimate, but distance to wells and regional variation in facies is incorporated in the range estimation.

Porosity: The porosity mode is selected incorporating offset well information. In addition, the porosity value also incorporates the entire depth range for the structure. Usually a +/- 20% min./max. range is adapted from the mode, but local considerations may deviate from this.

Storage efficiency: Various styles of top-site development, financial investment and local subsurface confinement strongly influence the storage efficiency as suggested in Figure 11 (e.g. Brennan et al. (2010) and Wang et al. (2013). With the insufficient database presently available from the Danish subsurface or even with global analogues, it is difficult to evaluate in realistic ranges for storage efficiency factor for the various structures. Therefore, for this study it has been chosen to use a fixed 40% efficiency following the previous GESTCO project. However, it is emphasised that further investigations of subsurface and development scenarios are needed to fully understand the potential storage efficiency ranges.

CO2 density: As density primarily is depending on pressure and temperature of the supercritical phase injected, the uncertainty range tries to incorporate as much knowledge available on these elements. The pressure for the studies structures is assumed to be hydrostatics a over pressures have not been observed onshore Denmark, and therefor only depth top structure uncertainty is incorporated. Temperature estimates for the structures is based on the temperature modelling by Fuchs et al. (2020) as this study models direct temperature estimates for both the top Gassum Fm and the Bunter Sandstone Fm (Figure 15). For the Skagerrak Fm structures slightly warmer estimates than for Gassum Fm at same location has been selected as the Skagerrak Fm is situated slightly deeper. For the selected P & T estimations the density range has been established using the conversion method suggested by Span and Wagner (1996).

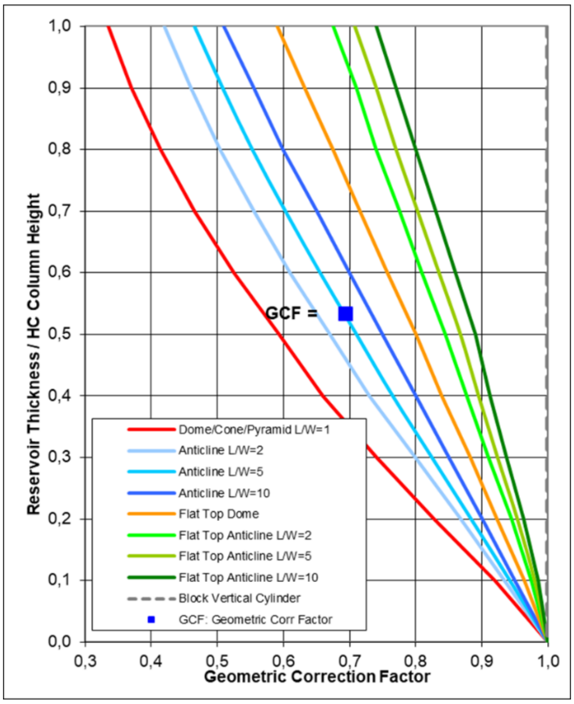


Figure 14. Graphical representation of the approximation of GCF for various structural geometries with relation to their reservoir/relief high. Here an anticlinal elongated structure where the Length / Width = 10 and the Reservoir thickness / Relief high = 5,4 the GCF is c. 70%. Uncertainty in structural geometry (depth conversion /interpretation etc.), reservoir thickness and the potential for stacked reservoir units can be incorporated to get an estimation of the uncertainty range on GCF. The method is derived from oil industry methods. Modified after Gehman (1970).

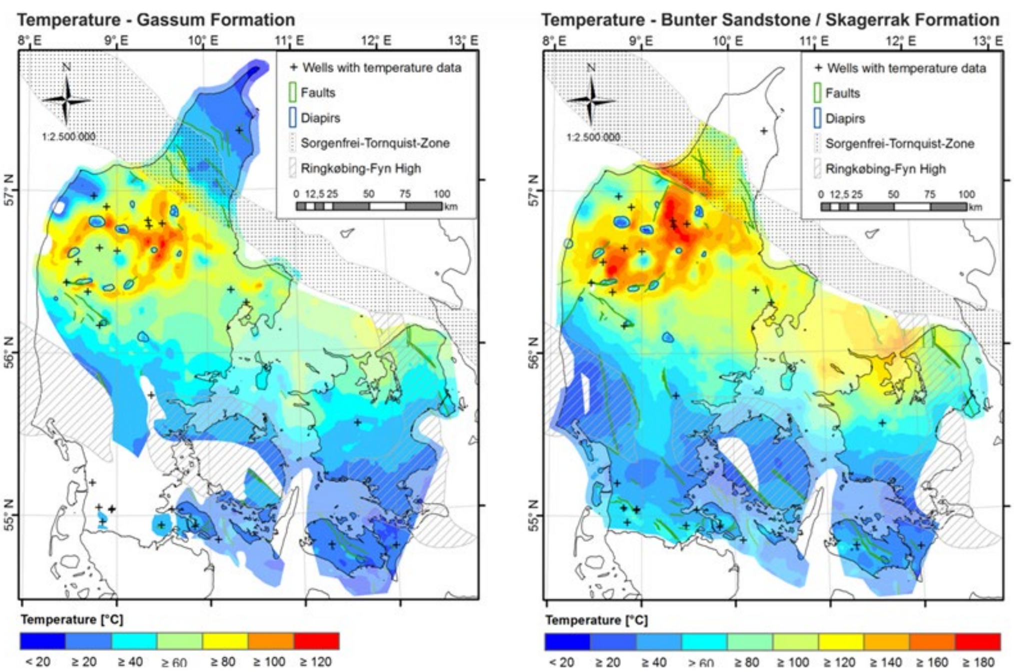


Figure 15. Temperature modelling results for the Gassum - and Bunter Sandstone Fm. From Fuchs et al. (2020). The temperatures are affected by salt presence and structural configuration. Temperature variations at constant depth may vary as much as 30°C across the study area (Fuchs et al. (2020). Temperature from these maps provide input to CO_2 density estimation.

Structure	Area			Geometric corr. Factor			Gross Thickness (m)			Net/Gross			Porosity			Storage Eff. Factor			Insitu CO2 density (kg/m3)			Average res. depth	Permeability (mD)		
Name	**min**	**mode**	**max**	**min**	**mode**	**max**	**min**	**mode**	**max**	**min**	**mode**	**max**	**min**	**mode**	**max**	**min**	**mode**	**max**	**min**	**mode**	**max**	**m**	**min**	**mode**	**max**
Gassum GF	117	233	303	0,50	0,80	0,85	100	130	150	0,27	0,37	0,45	0,15	0,25	0,30	0,40	0,40	0,40	714	752	790	-1802	49	461	1024
Havnsø GF	59	119	154	0,40	0,46	0,75	140	200	240	0,35	0,46	0,73	0,15	0,22	0,25	0,40	0,40	0,40	610	629	793	-1500	49	263	461
Hanstholm GF	182	364	473	0,55	0,64	0,80	200	250	300	0,32	0,40	0,48	0,16	0,20	0,35	0,40	0,40	0,40	550	687	720	-959	65	173	2011
Rødby BF	69	138	179	0,55	0,60	0,80	205	256	307	0,19	0,24	0,31	0,17	0,24	0,29	0,40	0,40	0,40	630	700	770	-1300	81	385	856
Thisted SF	116	231	300	0,40	0,42	0,70	598	747	896	0,42	0,52	0,68	0,14	0,20	0,24	0,40	0,40	0,40	700	750	810	#REFERENCE!			
Voldum GF	280	560	728	0,70	0,78	0,90	102	128	154	0,18	0,23	0,50	0,08	0,25	0,30	0,40	0,40	0,40	573	637	701	-1898	3	461	1024
Tønder BF	29	59	77	0,45	0,47	0,90	162	203	244	0,59	0,74	0,90	0,16	0,20	0,24	0,40	0,40	0,40	558	620	682	-1735	65	173	385
Vedsted GF	5	11	48	0,40	0,42	0,80	156	195	234	0,45	0,56	0,73	0,16	0,20	0,24	0,40	0,40	0,40	488	542	596	-1789	65	173	385
Torning GF	105	210	273	0,60	0,68	0,85	100	130	150	0,27	0,40	0,50	0,08	0,18	0,21	0,40	0,40	0,40	584	615	646	-1670	3	109	215
Røsnæs GF	59	119	155	0,45	0,58	0,80	100	200	250	0,23	0,45	0,70	0,20	0,25	0,30	0,40	0,40	0,40	670	715	790	-1463	173	461	1024
Hanstholm SF	167	334	435	0,35	0,42	0,70	598	747	896	0,42	0,52	0,68	0,14	0,20	0,24	0,40	0,40	0,40	700	750	830	-1343			
Legin SF	112	225	292	0,35	0,42	0,70	400	500	750	0,42	0,52	0,68	0,14	0,20	0,24	0,40	0,40	0,40	700	750	810	-1050			
Skive SF	37	73	95	0,65	0,90	0,95	162	203	244	0,59	0,74	0,90	0,08	0,12	0,14	0,40	0,40	0,40	740	770	800	-2238	3	18	41
Sletterhage GF	103	206	268	0,40	0,65	0,75	102	128	154	0,18	0,23	0,50	0,08	0,25	0,30	0,40	0,40	0,40	720	785	840	-1899	3	461	1024

Table 2. Input parameter ranges for the selected structures (GF: Gassum Fm, SF: Skagerrak Fm, BF: Bunter Fm). The input parameters are selected as described in the text. Average reservoir depths are geometrical mean between apex and max. closing contour depth. Permeability estimates are calculated using regression trends from Kristensen et al. (2016), see Figure 16.

As permeability is an input parameter needed for further simulation, modelling the average permeability for the structures has been modelled from input porosity selections. Here relationships established by Kristensen et al. (2016) for Gassum Fm are shown in Figure 16. For the Gassum Fm. the regression below has been use for permeability ranges:

$$K = 0{,}000347 * (\varphi * 100)^{(4{,}38)}$$

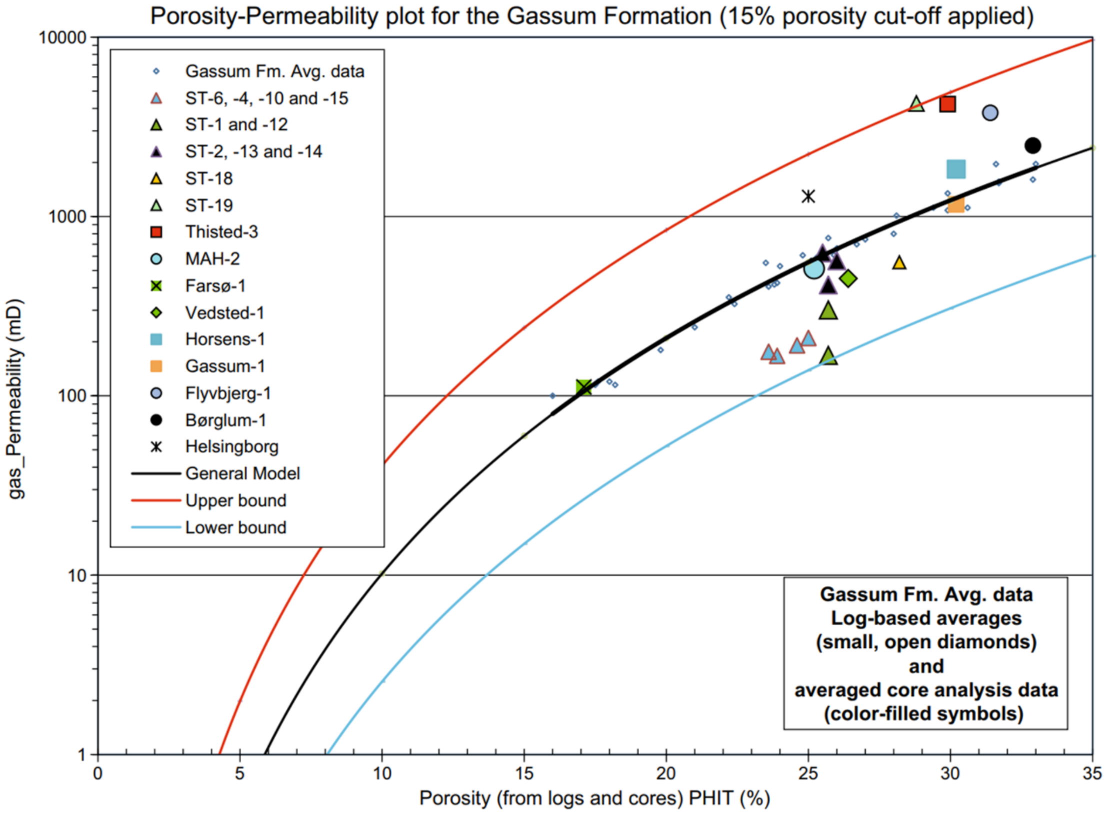


Figure 16. Generalized Porosity vs Permeability relationship. From Kristensen et al. (2016)

Capacity estimation progression

A few comments should be added on the progression of the capacity estimation and how in particular uncertainty is evolving during the life of a potential structure from early screening until termination of injection.

Figure 17 illustrates how the various assessment phases of the storage capacity of a potential site will vary as maturity and data certainty evolves. As an example, in the early Danish evaluation phase of potential sites (e.g. GESTCO project in 2003), an approach to investigate a scoping potential (deterministic values without quantification of the uncertainty) for sites was made fully acknowledging the large uncertainty related to sparsely available data. The present study brings the evaluation a step further by initiating attempts to quantify the capacity uncertainty range by assessing the uncertainty on input parameters resulting in a large output range. For selected structure subjected to further analyses including acquisition of new seismic and/or well data, the maturation process may be further progressed. Further constraints will be added to the evaluation as additional investigations are carried out on e.g. reservoir modelling and in particular when new data is acquired. With new additional data gathering over specific sites the uncertainty range will be narrowed as data will be targeted for specific purposes and new wells will provide reservoir performance data. This continues as sites and structures are developed and more well performance data is collected, and iterative modelling with history matching is carried out during injection. The capacity range will continue to narrow until injections are eventually terminated, and the exact capacity is established.

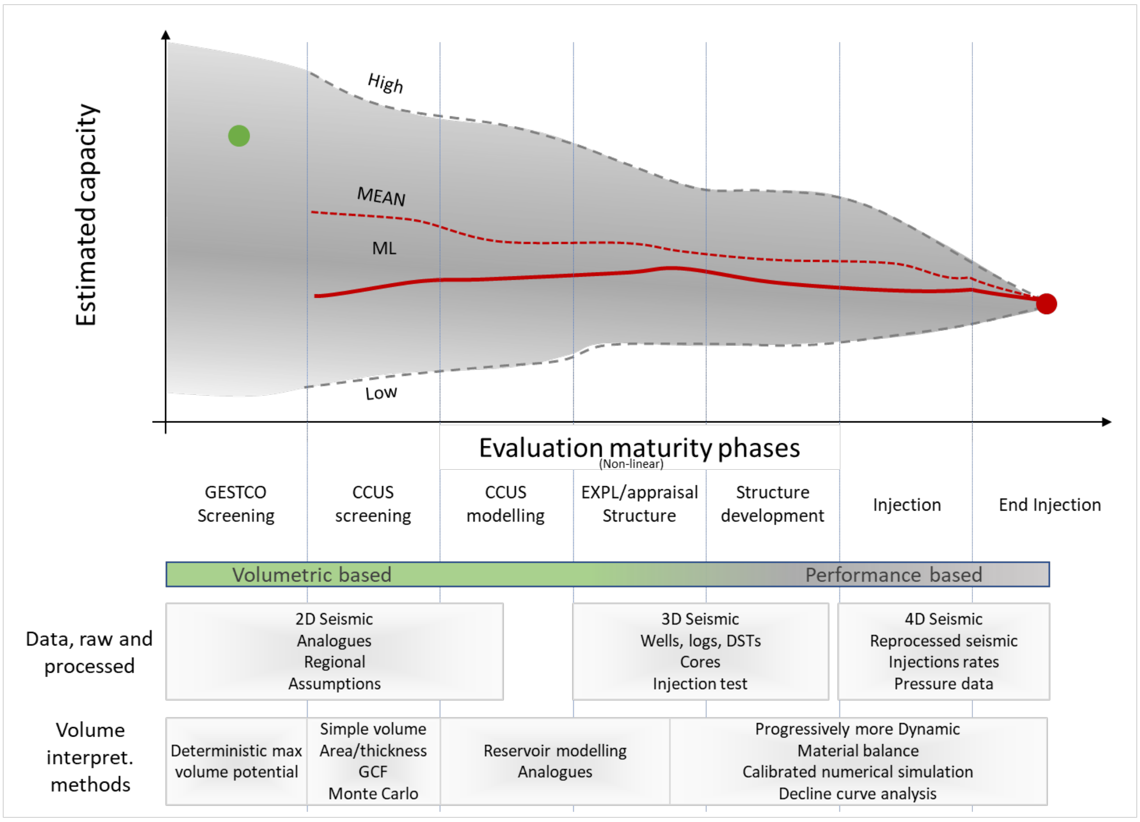


Figure 17. Schematic illustration of the evolution of the uncertainty on storage capacity through the various evaluation phases. See text for explanation. This study (CCUS Screening phase) introduces the quantification of the uncertainty range. Adapted from oil industry experience (Otis and Haryott 2010).

Simulation results

Understanding simulation results

The Monte Carlo simulation results in 10.000 trials or unique storage capacity calculations. The many results can be regarded statistically and described in various ways, but here the results are presented with P10, P50 and P90 percentiles and the harmonic Mean value[5]. The percentile value is to be understood as exceeding values, i.e. described here for the 'P90' value: 'The P90 percentile represent 90 percent probability of exceeding 758 Mt CO_2' (Table

[5] The resultant Mode or Most Likely are not shown as Excel® does not have a built-in Mode approximation algorithm.

3). The numbers in the table are conditional value in the sense that they are given that the structure is considered as a geological and engineering success. Values are all conditional of success unless stated otherwise.

Results	P90	P50	P10	Mean
Pore vol (km^3)	3,850	5,211	6,792	**5,271**
Eff. storage volume (Km^3)	1,226	1,730	2,321	**1,759**
Storage capacity Mt CO_2	758	1070	1443	**1090**

Table 3 Result table of Monte Carlo simulation of capacity of a potential structure.

The Monte Carlo results can also be represented graphically as illustrated in Figure 18, where all percentile values are represented for both un-risked and chance weighted estimates.

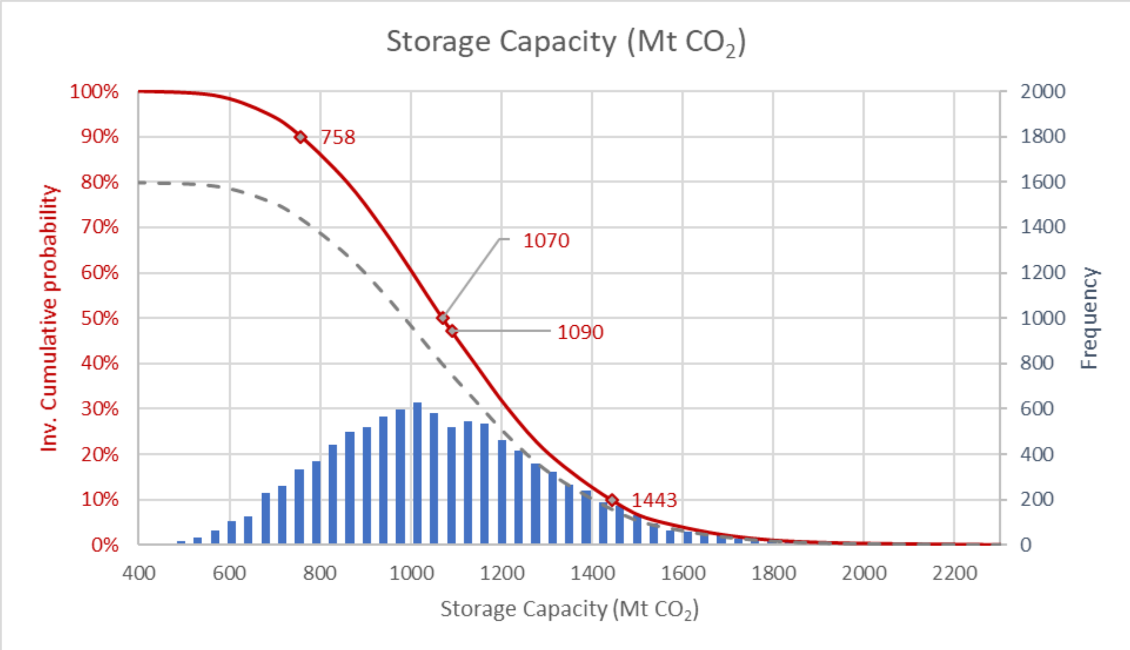


Figure 18. Graphical representation of the buoyant trapped storage capacity for a given structure. Solid red line displays the inverse cumulative probability of exceeding a given storage capacity volume. Values for P90, P50; P10 percentile are shown as well as the mean value (here 1090 MT @P48). Grey stippled line is the chance weighted inverse cumulative probability (here there is 80% chance of the structure being suitable for CO_2 storage). Blue bars represent the frequency of trials within given volume ranges.

For each of the structures assessed in this study, a detail documentation of inputs and results can be found in Appendix B.

Storage capacity of the selected and evaluated structures

The storage capacity has been assessed for 14 potential targets. Evaluations have primarily been carried out on structures already identified by e.g. the GESTCO project. Several new structures have been added, and some have been downgraded after remapping. In Figure 19 some of the identified structures are shown, but it should be stressed that more work needs to be carried out to get the full understanding of the storage potential. Capacity numbers presented here do not represent the full potential in Denmark.

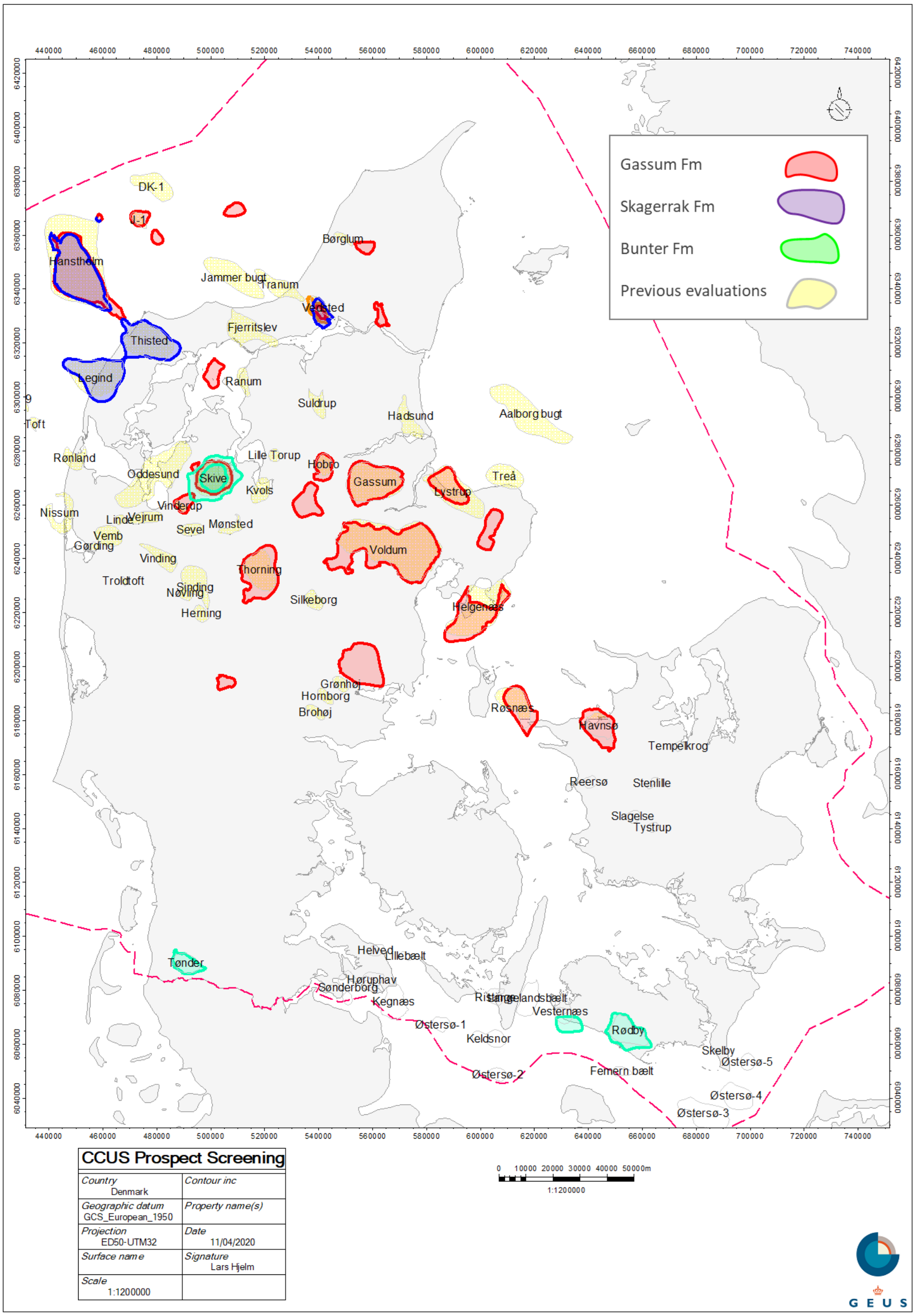


Figure 19. Overview of some of the structures identified in the Danish area. Structures reviewed and defined in this study so far involve structures at Gassum Fm level (red), Skagerrak Fm level (dark purple) and Bunter Fm level (Green). GESTCO structures and additional later identified structures are shown in yellow (multiple stratigraphic levels). Notice that structural outlines may differ from this study.

Using new or updated interpretations and the input range assessment for the structures as documented in Appendix B and shown in Table 2, the capacity estimations have been carried out. A summary of the calculated conditional storage capacities is shown in Table 4

Structures	**Probability**	**Storage capacity Mt CO2**				**GESTCO**	**This eval.**
Name	***%***	**P90**	**P50**	**P10**	**Mean**	**Mean**	**% div.**
Gassum GF	*80%*	412	574	777	**586**	631	-7%
Havnsø GF	*80%*	204	294	423	**306**	923	-67%
Hanstholm GF	*80%*	927	1293	1801	**1333**	2752	-52%
Rødby BF	*64%*	242	334	449	**341**	151	126%
Thisted SF	*48%*	1703	2367	3198	**2418**	5593,5	-57%
Voldum GF	*48%*	531	817	1224	**854**	288	197%
Tønder BF	*80%*	162	224	304	**229**	93	147%
Vedsted GF	*60%*	18	35	64	**39**	161	-76%
Thorning GF	*56%*	202	290	397	**296**	90	229%
Røsnæs GF	*57%*	264	410	617	**429**	NA	
Hanstholm SF	*48%*	2376	3352	4630	**3441**	NA	
Legin SF	*29%*	1090	1564	2222	**1619**	5593,5	-71%
Skive BF	*43%*	241	329	434	**334**	NA	
Helgenæs GF	*32%*	187	292	447	**307**	NA	

Table 4. Storage capacity estimates of the current evaluated structures (GF: Gassum Fm, SF: Skagerrak Fm, BF: Bunter Fm). Structures are described in Appendix B. Each structure has a preliminary (non-QC'ed) probability assigned to indicate likelihood of geological and engineering success. Mean capacities for this study are compared to GESTCO max. estimates. Unrisked mean combined capacity of these structures exceeds 12 GT CO_2 (6,3 Gt CO_2 chance weighted[6]).

For comparison between the structures, the full volumetric ranges are illustrated in un-risked inverse cumulative probability plots shown in Figure 20 and for chance weighted comparison and aggregation in Figure 21. The probability (Probability of Success) values presented here are preliminary assessments of some of the geological and engineering risks associated the individual structures.

[6] Chance as in the Probability of Success (POS = 1 – probability of failure). 'Chance weighting' refers to the accumulation of volumes from different structures taking into account the probability of the structure working successfully as a storage).

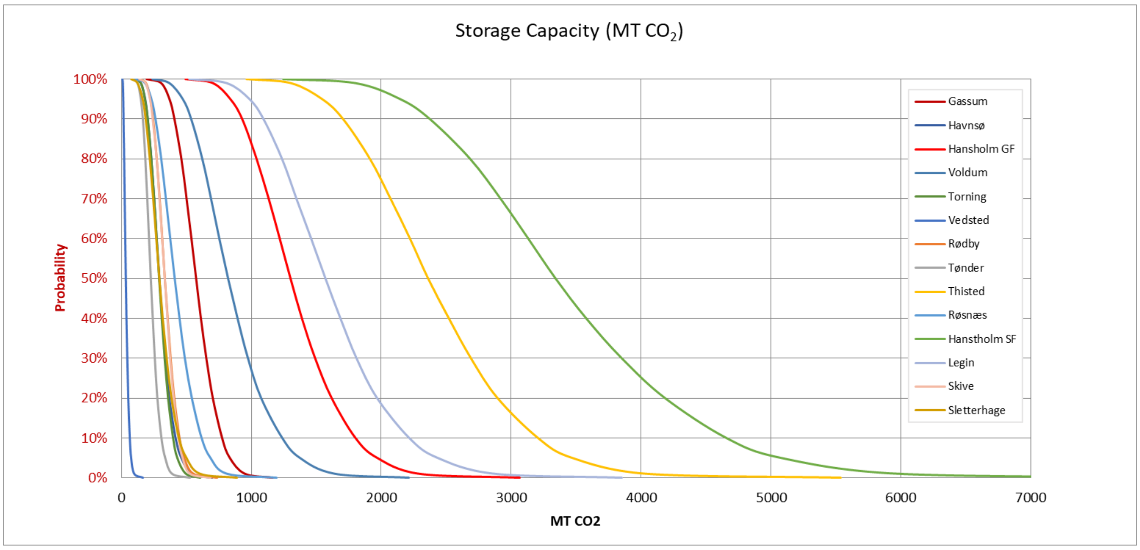


Figure 20. Graphical representation of the inverse cumulative probability functions for storage capacities of various structures in this study. All range are 'un-risked' or conditional of the structures being suitable for storage and show how Hanstholm-Thisted-Legin structural complex with the current evaluation by far surpasses all other Danish structures.

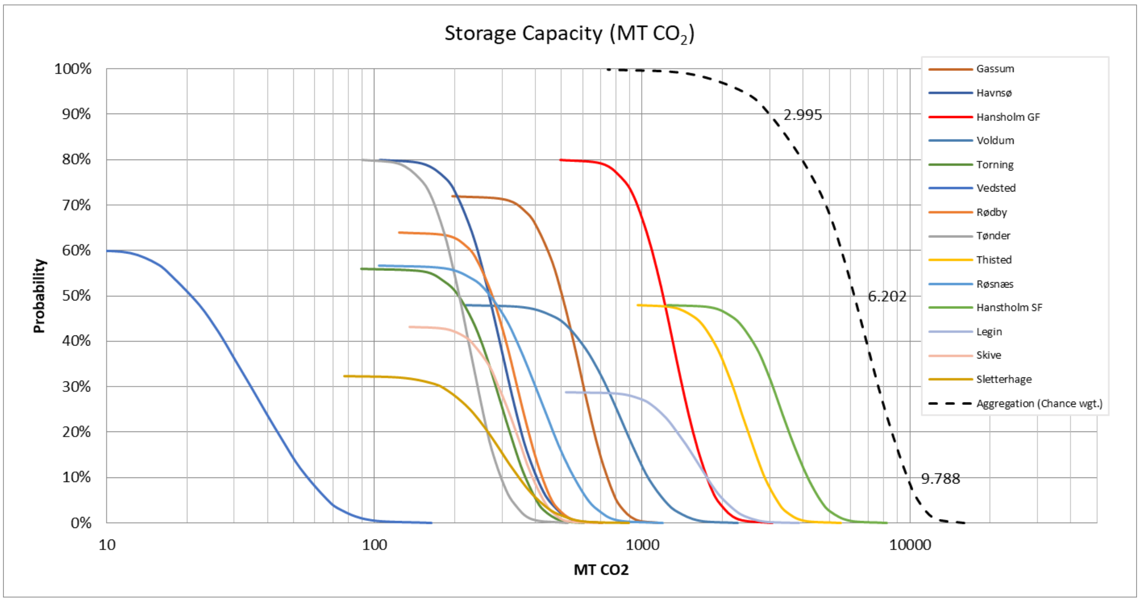


Figure 21. Graphs illustrating the 'risked' or chance weighted inverse cumulative probability function for storage capacities of the evaluated structures. The height of a curve relates to the likelihood of a given structure being suitable for storage (i.e. the Probability of success) and the curve describes the probabilities of exceeding a given storage capacity volume. Note the logarithmic scale. The black stippled line shows the 'risked' or chance weighted aggregation of all evaluated structures (values shown in Table 4 and 5). The Hanstholm-Thisted-Legin structural complex is very large but also associated higher risk (low probability of success).

Aggregated storage capacity

Although the currently evaluated structures only constitute a part of the structures available in the Danish area, the sum of the structure has been aggregated table 5.

Total	Probability	Storage capacity Mt CO2			
Type	**%**	**P90**	**P50**	**P10**	**Mean**
Aggregation (Un-Risked)	NA	10679	12172	13898	**12249**
Aggregation (Chance wgt.)	99,99%	3022	6236	9737	**6317**

Table 5. Combination of the capacity estimations of the currently evaluated 14 structures. The un-risked aggregation combines all distributions regardless of risk whereas the chance weighted aggregation combines the structures incorporating their probability of success. Several structures are not yet incorporated in this summary (work in progress) and the total Danish potential is believed to significant larger.

The full stochastically combined range for both un-risked and chance weighted distributions are shown in Figure 22.

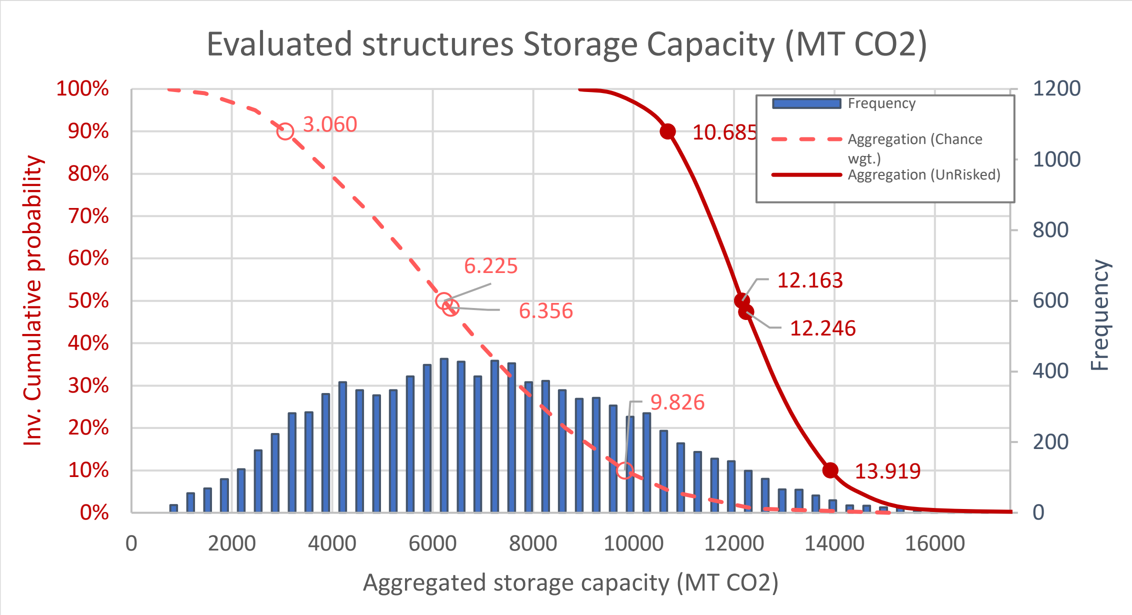


Figure 22. Graphical representation of the combined volume potential of the evaluated structures. Solid line illustrates the distribution given that all structures are success (un-risked). The stippled line displays the chance weighted capacity potential incorporating preliminary risk assessment of the structures.

Key takeaways from this capacity assessment:

- Comparing the capacity values from this study to those of e.g. GESTCO (Larsen et al. 2003) is not applicable in a one to one sense.
  - The GESTO project assessed reasonable max. or scoping potential, whereas this study tries to address the entire uncertainty range and initiate risk assessment of the structures.
  - Earlier capacity calculation was carried out on smoothed regional maps whereas this study includes revised local structural mapping for the resource calculation.

    - The storage capacity calculation in this study only carries the volume potential above the structural spill point (buoyant trapping volume). A residual potential is believed to provide an upside to buoyant trapping potential, but this is depending on individual development scenarios and not addressed here. In the volume calculations the Geometry Correction Factor is included to give the gross rock volume for the buoyant trapping geometry, whereas the GCF has not been implemented in earlier scoping volumetrics.
    - Different volumetric scenarios involving different fault sealing scenarios has also been included in this capacity estimation (e.g. for Vedsted structure). The incorporation of fault seal leakage risk in the volumetrics has not been address in earlier studies as detailed fault identification was not included in the studies. Capacity estimates in this study are in general terms smaller than previous studies. Reasons for this is the incorporation of the geometry correction factor and detailed mapping[7] (smaller grids).
- The selected structures, currently in the portfolio, have been selected with a preference for 4-way dip closures with no faults within the closure. However, with this mapping, several of these structures have been associated with minor crestal faults that were not identified in the mapping foundation for the GESTCO study.
- Only two 3-way fault supported structures are incorporated here, but many more are to be evaluated although they carry larger risk than 4-way structures.
- Several potential areas could contain large stratigraphic traps, but as these would be associated with larger risk they have not yet been evaluated.
- This study only assesses buoyant trapping potential. There is a huge potential in residual trapping that has not been evaluated here. For some structures, injection points could be located deeper and away from the structural spill point and an additional upside could be added from the residual CO_2 left from the injection plume. This kind of assumptions however require additional reservoir modelling and injection simulation.
- Many additional structures have been identified but have not yet been evaluated with regards to risk and capacity estimation. Many structures could potentially be hidden in areas with no or sparse data coverage and in areas between seismic lines.
- Several structures have potential in both the Gassum, Skagerrak and Bunter Fm. Dual target evaluations has only been carried out for the Hanstholm structure so far, but several structures could potentially carry dual or even triple targets.

Sensitivity analysis on capacity results

Simple sensitivity analysis has been carried out to investigate what input elements drives and controls the final storage capacity result.

As illustrated in Figure 23, various structures can have different volume controlling input elements, but a few generalizations can be deducted from tornado plots.

1. Structural gross rock volume elements such as area (A), reservoir thickness(h) and Geometry Correction Factor (GCF) appears to be most important for the resultant capacity.

[7] Some structures became larger than previous studies

2. Reservoir elements such as net:gross and porosity have some influence on the capacity estimate. This is particularly important when the porosity estimate is very small as the sensitivity to the final capacity then increases (e.g. 8-12 % porosity range)
3. Test shows that Storage efficiency factor can have a smaller influence on capacity range, but for this study it has been decided to keep S_{eff}. constant until further work has been carried out for this element.
4. Ranges on CO_2 density have only little impact on final storage capacity volumes.

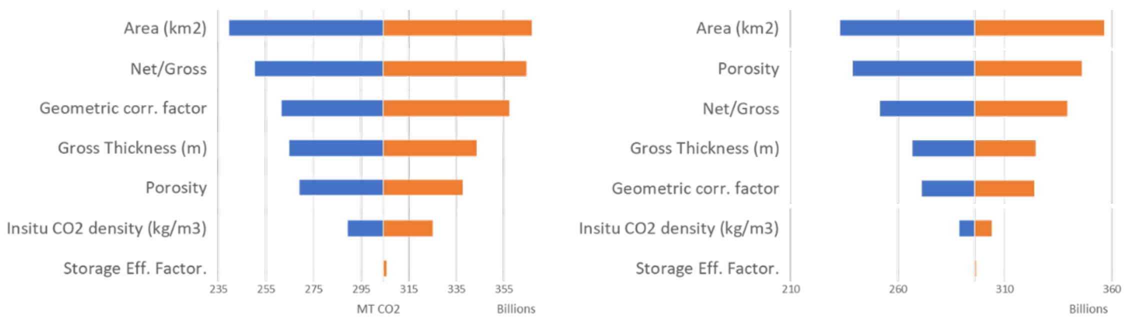


Figure 23. Tornado plots showing the sensitivity in the input range for two different structures (Havnsø (left) and Thorning (right)). The horizontal bars for each of the input parameters indicate change in storage capacity given that only that parameter is changed leaving all other constant. Blue signify volumes smaller than the mean estimate and orange is larger than.

From this analysis it is suggested that in order to mitigate risk and uncertainty of storage capacity of a structure, the primary elements to address are the gross rock volume assessment via better seismic data to constrain the structural definition, identification of possible spill points and careful interpretations of top and base reservoir via good ties between seismic and well data. Secondarily, revised input into reservoir parameter distributions across a structure could be beneficial and potentially statistically modelled, or even better, geophysical modelling of reservoir parameters if the seismic data coverage allows. Studies of temperature and pressure could give insights into better range constrains on CO_2 density at reservoir conditions, but an effort to understand the injection and storage efficiency via reservoir simulation would give better constrains of the final capacity range.

Additional storage options

CO_2 storage in geological structures are based on present knowledge considered the preferred storage option. Alternatives storage options are described in the sections below.

Open saline aquifers

Geological background
The possibility for injecting and storing CO_2 in subsurface saline aquifers in addition to storage in well-defined subsurface closed structures is briefly discussed in this section. The discussion is here limited to the onshore and relatively nearshore areas in the mid-eastern part of the Norwegian-Danish Basin and the northernmost rim of the North German Basin. Several sandstone dominated lithostratigraphic units with reservoir potential occur within the upper

Paleozoic-Mesozoic and Cenozoic successions in the greater North Sea Basin. However, an analysis of the storage potential in the saline aquifers in the western Danish offshore areas such as the Outer Rough, the Central Graben and Horn Graben, and the platform areas between the grabens are beyond the scope of this report and is only briefly described below.

Saline aquifers in the North Sea
In addition to the reservoirs of active and depleted hydrocarbon fields in the Central Graben, several potential reservoirs are known from the areas between the hydrocarbon fields in the Graben. Potential storage is also present on the Outer Rough platform west of the graben, and in the westernmost part of the Norwegian-Danish Basin from the Coffee Soil Fault to the Horn Graben. The Mesozoic succession, in particular the Middle and Upper Jurassic contains several regional sandstone bearing formations of which the Bryne and Heno Formations are the most promising in terms of CO_2 storage. Also, the Cretaceous Chalk succession known to be oil and gas bearing in places may have a storage potential. Paleocene sands from the Siri Canyon are likely to have a storage potential between the known hydrocarbon fields. Sands with a storage potential are also known from the Miocene succession. As this very brief overview indicates, it is expected that a large storage potential is present in the North Sea in structures and in dipping aquifers, which may be evaluated in detail based on the current database available from GEUS´ files.

Onshore and nearshore
In the Danish onshore and nearshore subsurface, several saline sandstone aquifers are widely distributed. The most significant are the Lower Triassic Bunter Sandstone Formation, the Triassic Skagerrak Formation, the Upper Triassic-Lower Jurassic Gassum Formation, the Middle Jurassic Haldager Sand Formation, and the Upper Jurassic-Lower Cretaceous Frederikshavn Formation (Bertelsen 1978, 1980; Michelsen et al. 2003; Nielsen 2003) (Figure 24).

The Bunter Sandstone Formation is present along the northern flank of the North German Basin south of the Ringkøbing-Fyn High, on parts of the high and in central parts of the Norwegian-Danish Basin north of the high. Laterally the formation passes into the much thicker Skagerrak Formation, which takes over closer to the northern and north-eastern basin margins. While the Bunter Sandstone Formation only encompasses Lower Triassic sandstones, which in places are overlain by potential seals comprising various fine-gained units, such as mudstones, carbonates and halites, the Skagerrak Formation consists mainly of a thick succession of various sandstones with intervals of mudstones representing most of the Triassic period. The potential reservoir sandstones are overlain in places by the Oddesund and Vinding Formations containing mudstones and halites forming potential seals. Towards the basin margins to the north and northeast, the Oddesund and Vinding Formations are wedging out and the top of the Skagerrak Formation and the formation gets directly overlain by Rhaetian sandstones of the Gassum Formation. The seal capacity related to storage in the Skagerrak Formation therefore needs specific attention in parts of its area of distribution.

The Gassum Formation is widely distributed and is penetrated by some 50+ wells. In the Danish part of the North German Basin, its distribution is patchy and shallow due to uplift and erosion, and in most of the area the formation is located too shallow. Its presence on the

Ringkøbing-Fyn High is limited and poorly known due lack of seismic and well data. In contrast, the formation is widely distributed in the Norwegian-Danish Basin within the preferred depth interval of 800-3000 m documented by many wells and seismic sections (Figure 24). In most of its distribution area, the Gassum Formation is overlain by marine mudstones of the Fjerritslev Formation, which in general have good sealing capacity.

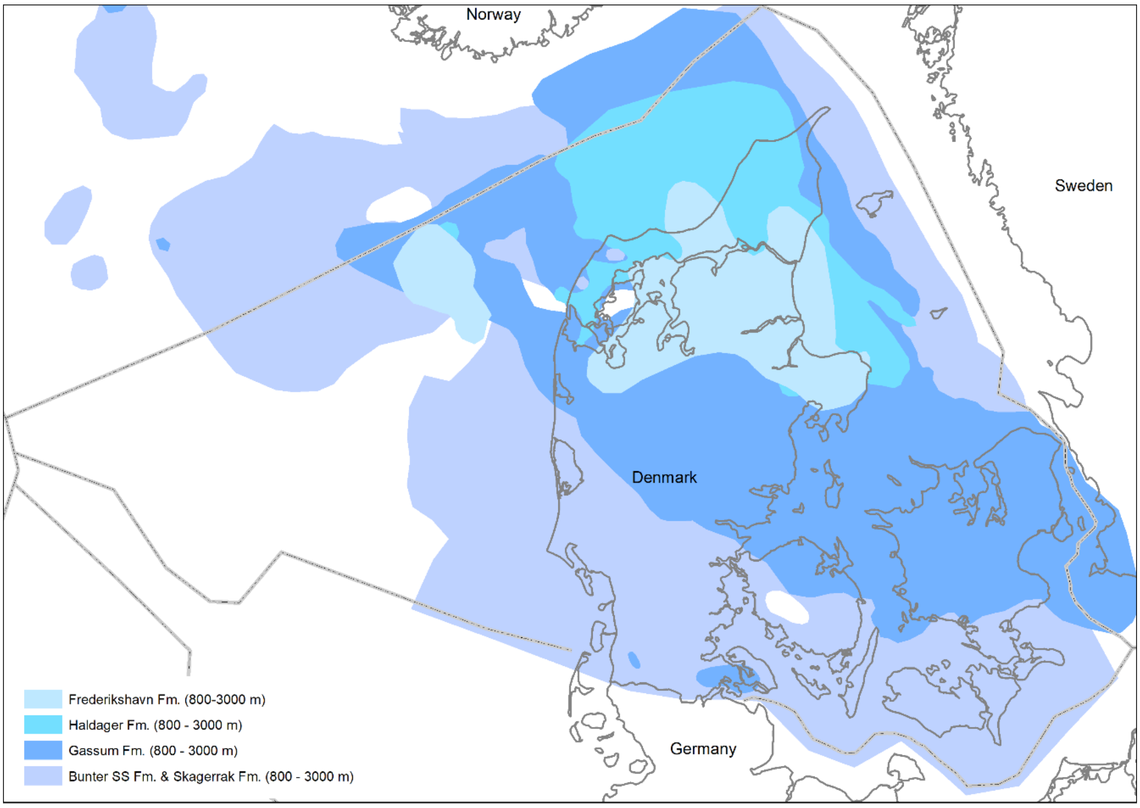


Figure 24. Distribution of formations with saline aquifers in the depth interval 800-3000m. Note that in some areas the formations are overlapping offering the possibility to develop multi-target storage.

The Haldager Sand and Frederikshavn Formations have a more restricted distribution limited to the northern part of the onshore and nearshore areas. The possible seals for these two potential storage aquifers are marine mudstones of the Flyvbjerg, Børglum and Vedsted Formations, which show a similar restricted lateral distribution.

In addition to these four reservoir formations, the Permian-Mesozoic succession of the Norwegian-Danish Basin contains further units, which may represent additional storage potential – most notable are probably Rotliegendes sandstones, lower-middle Triassic sandstones in the southern parts of the Danish area close to the Ringkøbing-Fyn High, and sandstones of the upper Jurassic Flyvbjerg Formation in the northern part of the basin. These potential storage aquifers are not considered further here.

Estimates of storage potential

The EU-funded GeoCapacity project (Assessing European Capacity for Geological Storage of Carbon Dioxide) that was concluded in 2009 investigated the potential regional storage capacity of the four reservoirs presented above. Based on regional considerations as discussed in and by applying a simple and general formula, the regional “bulk” storage capacity M_{CO2} may be calculated as (Bachu et al. 2007):

$$M_{CO2} = A \times h \times N/G \times \phi \times \rho_{CO2} \times S_{eff}$$

where A and h corresponds to the area and height of the aquifer, respectively; N/G expresses the net to gross ratio; ϕ is the average reservoir porosity; ρ_{CO2} is the CO_2 density at reservoir conditions and S_{eff} is the storage efficiency factor. The GeoCacity study applied a general and low S_{eff} of 2% for the bulk calculations following results of studies performed by the US DOE.

The estimates indicate a regional storage capacity of 16 Gt CO_2 in the Bunter Sandstone Fm/Skagerrak Fm, 5.5 Gt CO_2 in the Gassum Formation, 0.75 Gt CO_2 in the Haldager Sand Formation and 0,075 Gt CO_2 in the Frederikshavn Formation corresponding to a total regional storage potential of more than 22 Gt CO_2 in the four aquifers.

These numbers indicate a large regional storage capacity for the Bunter Sandstone/Skagerrak Formations and the Gassum Formation in particular. The estimates of storage capacity may be substantiated and qualified for local and closed structures as done in other sections of this report. The above regional estimates indicate that large storage capacity may be present in open aquifers in addition to that of the closed structures.

A screening has revealed large open/semi-closed dipping aquifers in the Upper Triassic Gassum (Fawad et al. 2011) which was evaluated for CO_2 storage in the NORDICCS project (2012-2015) (Figure 25). Simulations based on the heterogeneous model indicate that up to 1 Gt CO_2 can be stored in the modelled area. Extrapolating this result to include the whole North-Eastern part of the Gassum Formation (Figure 26) would give a maximum storage capacity of 3.7 Gt CO_2. However, different topography, heterogeneity and dip in the regions not simulated will affect this estimate.

The main results indicate that the north-eastern part of the Gassum formation on the Danish side is the most promising target for injection of CO_2. This is based on the observation that all the injected CO_2 is capillary trapped or dissolved within the model boundaries; the injection pressure is thought to be in the safe pressure range. The location is still worth investigating further since small changes in flow parameters can change the maximum plume size of the injected CO_2. These parameters are at the present uncertain and more data is needed for better characterization of the target formation (Lothe et al. 2015).

These studies indicated a large and safe storage potential in the Gassum Formation aquifer. Based on the regional geological models of the Norwegian-Danish Basin, it is likely that several suitable aquifers may be identified offshore adding to the potential storage volumes in the Danish area.

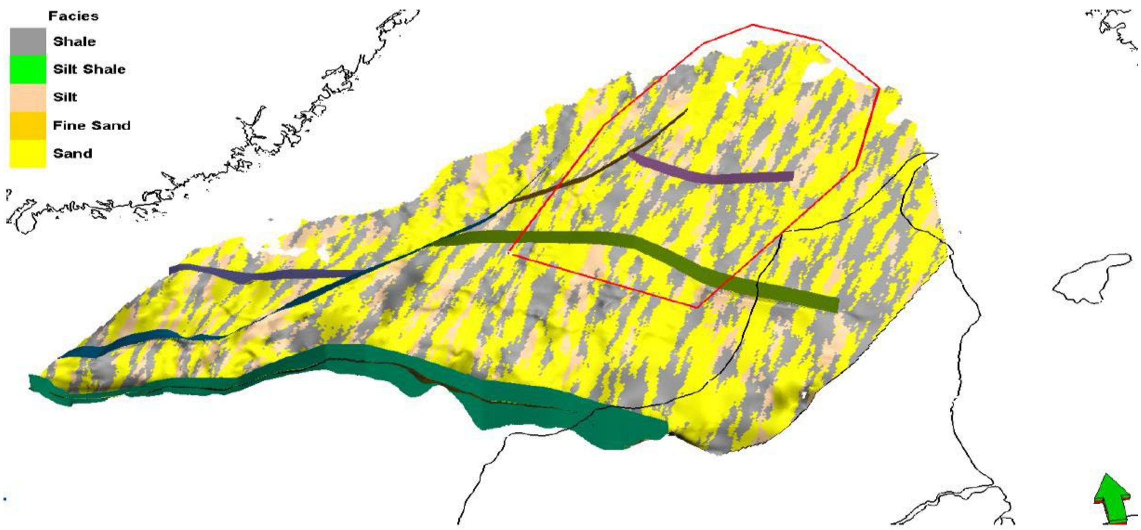


Figure 25. The figure shows facies model for the North-Eastern Gassum Formation. The main facies are sand, silt and shale (Lothe et al. 2015).

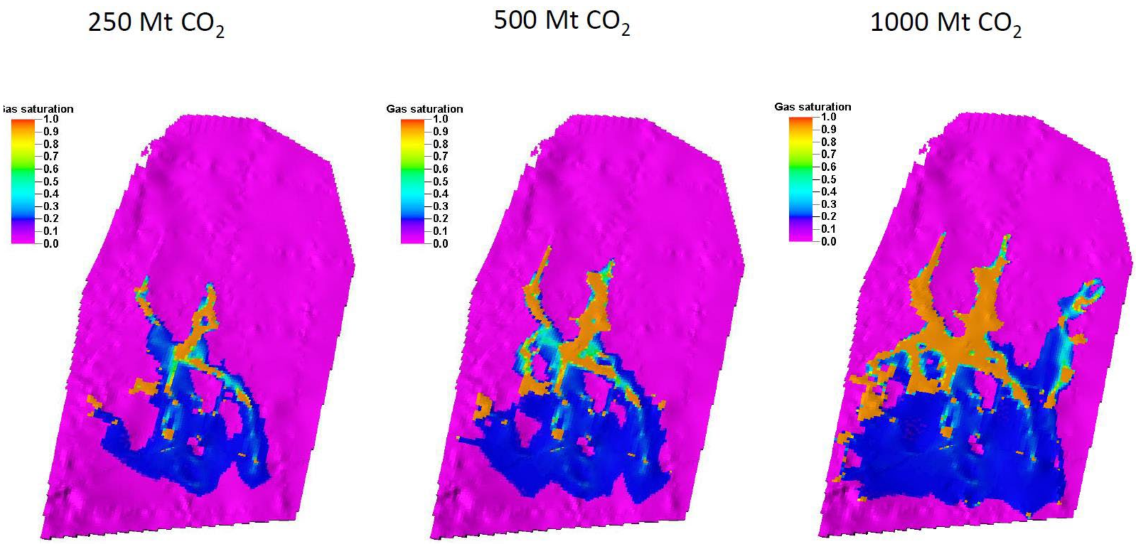


Figure 26. The model area is marked by a red line on figure 25. Distribution of the injected CO_2 after 4000 years, for 250 Mt, 500 Mt and 1000 Mt CO_2. The injection rate is 10 Mt CO_2 per year. The colour scale shows gas saturation where 1 (red) is fully saturated (Lothe et al. 2015).

Hydrocarbon fields

Abandoned hydrocarbon fields or fields on decline can potentially be used for permanent storage of CO_2. In Denmark, all hydrocarbon fields are located offshore in the Danish sector of the North Sea. Most of the producing fields are past peak production but with substantial tail end production. Three fields have stopped production (Dagmar, Regnar and Svend) but are not yet abandoned, 17 fields are still on production. The new national agreement on not to implement the 8th Licencing Round and not extending any production beyond 2050 has put a deadline on oil and gas exploitation leaving the North Sea open for other subsurface exploitation.

A majority of the fields are located in the salt dome province of the Central Graben and are 4-way dip closures situated in the chalk sequence. Three fields are located to the Northeast in the Siri Canyon complex, where the reservoirs are Palaeocene marine sandstones. The Danish oil and gas infrastructure and field locations are illustrated in figure 27.

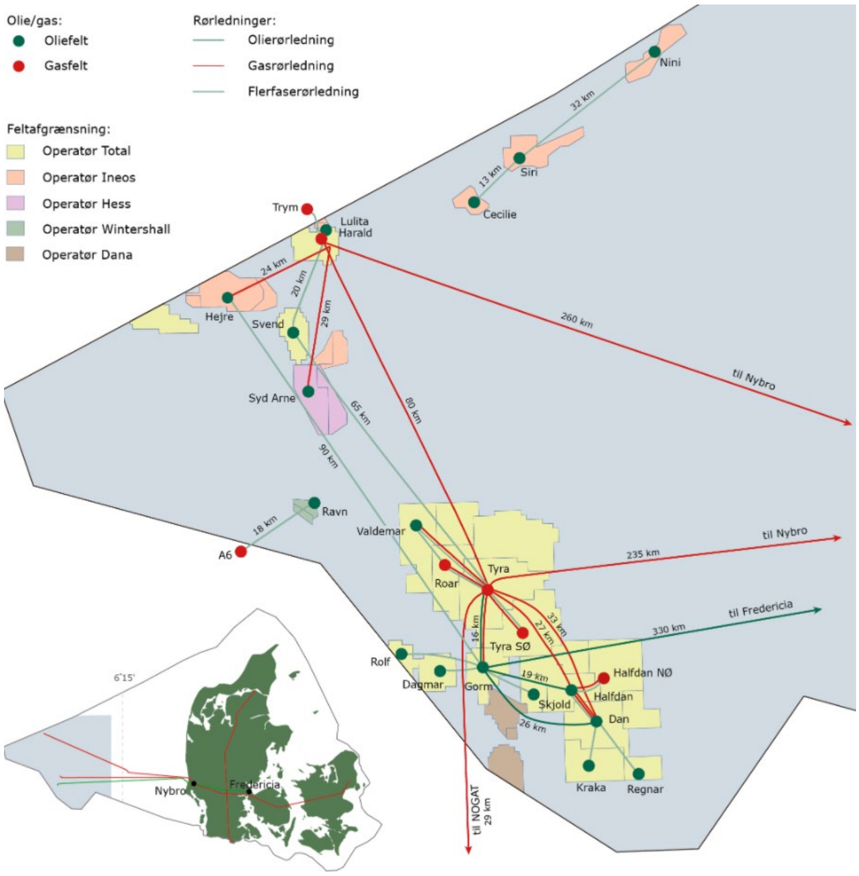


Figure 27. Danish oil and gas infra-structure (Danish Energy Agency) figur_1_anlaeg_i_nordsoen_dk1.png (2063×2097) (ens.dk)

All Danish oil and gas fields are in depths of more than 1000 m and have proven to accumulate hydrocarbons for several millions of years, so in principal they all qualify to be candidates for CO_2 storage. The deepest fields are in Jurassic sandstones at approximate 3500 m (Harald West and Lulita). Fields in the chalk interval are in the typical depth range of 1200 m to 2700 m and comprise the former DUC fields (now operated by Total) and the South Arne field. Fields in the Siri Canyon are in the depth range 1600 m to 2200 m (Cecilie, Nini and Siri). The deepest fields are not necessarily the most suitable; the largest reduction in the CO_2 volume will occur at approximate 800 m of depth, and below that depth the volume reduction will only be minor as the CO_2 will be in the supercritical phase due to pressure and temperature. Porosity and permeability typical decreases with increasing depth (and pressure) thereby decreasing both storage capacity and injectivity.

An estimate on the total CO_2 storage capacity in the Danish North Sea hydrocarbon fields has been evaluated in the EU GeoCapacity project (Shuppers et al. 2003) to be *c*. 810 Mt.

These estimates have been updated in 2020 based on the Danish Energy Agency inventory for production and resources (Energistyrelsen 2020, Ressourceopgørelse og Prognose[8]). The storage capacity based on produced volumes until January 2020 is 925 Mt, if the expected and risked future resources is included the capacity is 1170 Mt, and estimates where the "possible resources" are included gives a storage capacity of 1250 Mt.

New estimates for the fields in the Siri Canyon (Cecilie, Nini and Siri) by INEOS give a range of 150 to 500 Mt total storage capacity for the entire Siri Canyon coplex (pers. com. Johan Byskov Svendsen, INEOS).

Use of abandoned oil and gas fields possesses advantages and disadvantages, and must be assessed and weighted before decisions are made for development of CO_2 storage in a specific field.

Advantages for use of abandoned hydrocarbon fields
Reservoir characterization of the CO_2 storage complex (reservoir and seal) is vital for an efficient and secure storage operation. Through exploration, development and production phases field operators have proven that the HC fields are able to accumulate and deliver oil and gas. This, often extensive knowledge on field behaviour and acquired field data can help de-risking decisions for a future development for CO_2 storage application.

The detailed knowledge of the dynamic field behaviour during production of hydrocarbons can with some modifications be transformed to the process of injecting CO_2. Careful reservoir modelling and simulation can help to assess the different processes. Field operators often have very detailed and history matched (calibrated) models. This gives high confidence in forecasting the behaviour of the injected CO_2 plume in the reservoir and helps to optimize a potential development for CO_2 storage.

CO_2 storage capacity estimation for hydrocarbon fields can to some extend be guided by the operators estimate for the *hydrocarbon initial in place* for the individual fields. The reservoir pore space will initially contain two (water and oil) or three (water, oil and gas) phases, which complicates an initial estimation of the pore volume accessible for CO_2. The volume estimates are subjected to some uncertainty but tends to be more constrained through the production period of the fields.

Disadvantages for use of abandoned hydrocarbon fields
The majority of the Danish hydrocarbon fields are situated in reservoirs of low-permeability chalk. This can challenge the injectivity for CO_2, and thereby the storage efficiency (injection speed). The sandstone fields in the Siri Canyon have higher permeabilities and may be more suitable candidates. Proper well completion *e.g.* fracturing the near well bore area can increase the injectivity.

Abandoned hydrocarbon fields will even after long and extensive production of oil and/or gas still contain considerable volumes of hydrocarbons. These volumes can interact with the injected CO_2. CO_2 can dissolve in the oil phase, thereby lowering the phase viscosity and

[8] Microsoft Word - Ressourcer og prognoser 20200831 DK.docx (ens.dk)

getting the oil phase to swell. This will increase the mobility of the oil phase, which is the primary driver in CO_2 EOR (Enhanced Oil Recovery) processes, where the aim is to increase oil production by increased phase mobility. For permanent storage of CO_2, the aim is opposite; the injected CO_2 should over time become more and more immobile to secure permanent and safe storage.

During hydrocarbon production the reservoir pressure will decrease over time causing some subsidence in the overburden. A subsequent injection of large volumes of CO_2 for storage will reverse the pressure development, which could have adverse impact on the geomechanical properties in the overburden resulting in potential leakage pathways for CO_2 through the sealing rocks.

The sealing rocks above the reservoir sections of Hydrocarbon fields have obviously been penetrated by several wells, which can potentially be leakage points for the injected CO_2. Development of the Danish oil and gas production commenced in the early 1970'ties meaning that a considerable number of the wells are 2 to 4 decades of age. Risk assessments on well integrity are crucial, including both steel and cement qualities and best drilling/abandonment practices.

Retrofitting of existing infrastructure to withstand CO_2, especially wet CO_2, most be evaluated. At the top facilities it may be possible to keep the CO_2 dry and less corrosive, but in the subsurface, where water is present this will not be possible.

Salt domes and diapirs

Salt caverns are at present in use for seasonal storage of natural gas in the northern part of Denmark at Ll. Thorup. The storage plant is operated by Energinet.dk, who also operates the Stenlille gas storage plant located in mid Zealand. The Stenlille plant stores gas in a saline aquifer. Both storage plants are used to balance seasonal fluctuations between domestic gas demand and gas delivery from the North Sea.

Salt caverns could potentially be used for storage of CO_2. Salt rocks have excellent sealing capabilities and some positive mechanical properties, such as self-healing when damaged or cracked. The most obvious use of salt caverns in a CCUS context would be for temporary storage, due to a relatively small storage volume of the individual caverns. Further the simple storage compartment provides excellent opportunities for fast injection and withdrawal of the CO_2 compared to injection into water saturated porous rock.

The caverns at Ll. Thorup are typical in the depth range of 1000 - 1700 m. Each cavern is 200 - 300 m of high with a diameter span of 40 - 60 m. This returns an estimate of a storage capacity for supercritical CO_2 of approximate 0.3 Mt/cavern, under the assumption that cavern pressure and temperature are equilibrated to ambient conditions. The density of the CO_2 phase will be almost one order of magnitude higher than the natural gas at the present conditions, meaning that the overpressure at the top of a gas filled cavern will be considerably lower when filled with CO_2.

Technical feasibility rock mechanics studies together with chemical reaction studies must be conducted and evaluated before any implementation of salt caverns in a CCUS context. This is beyond the present project.

Salt domes are present in northern Jutland and the most southern parts of Denmark (Figure 28).

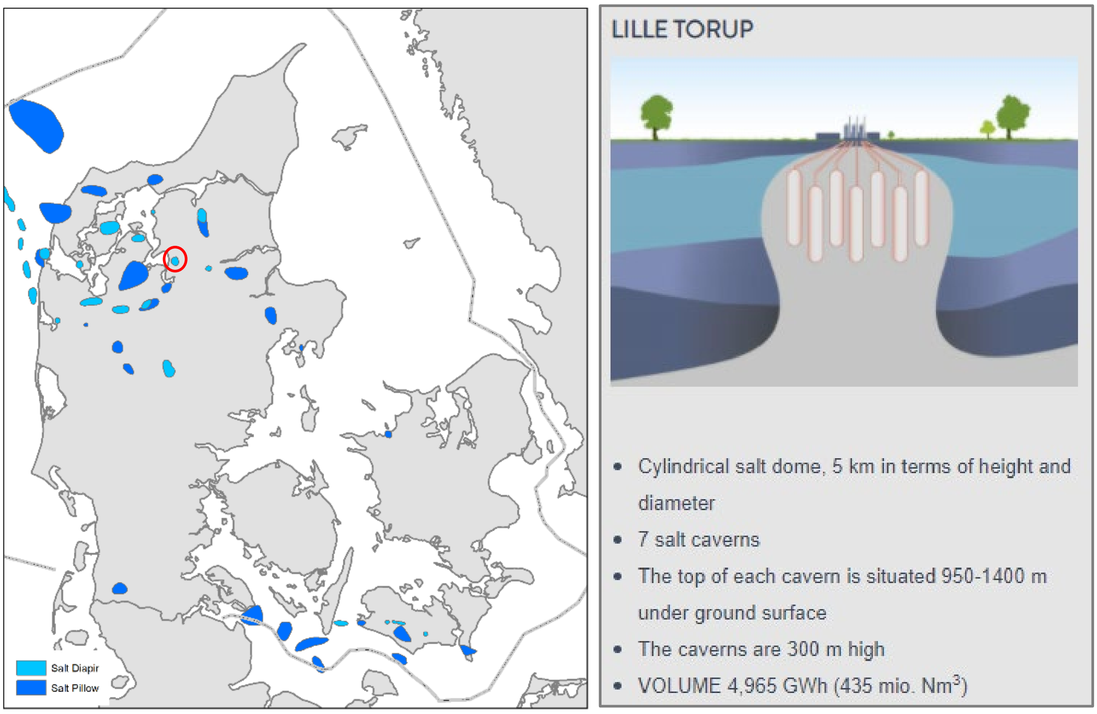


Figure 28. Location of salt domes and diapirs. Only onshore sites will be attractive as CO_2 storage. Basic information of the existing natural gas storage in Lille Torup (red cirkel on the left figure) are given on the right figure (Our storage | Gas Storage Denmark A/S)

Potential for use of deeply situated basaltic rock for CO_2 storage

Recent results show that injected CO_2 can be rapidly and safely stored as solid carbonate minerals in basalt, because of the high reactivity of the rock (e.g., Matter et al., 2016). This type of CO_2 storage is based on mineral carbonation. It relies on geochemical interaction between dissolved CO_2 and rock, which causes dissolution of Mg-, Ca- and Fe(II)-silicates and formation of the corresponding carbonates. This process is Nature's slow regulation of atmospheric CO_2 pressure, but it can be hastened by engaging basalt rich in reactive silicates and by increasing pressures of CO_2 (e.g. Matter et al. 2016; McGrail et al. 2017; Clark et al. 2020).

Traditionally, geological storage of CO_2 builds on 1) structural capturing of CO_2, 2) capillary immobilization of CO_2, 3) solubility trapping of CO_2, and 4) formation of minerals with CO_2 (mineral carbonation) to an extend governed by the presence of Mg-, Ca- and Fe(II)-silicates. These four trapping mechanisms evolve slowly over time, increaseing the storage safety (Figure 29). Targetted mineral carbonation in basalt has several advantages compared to traditional geological storage, where buoyant, supercritical CO_2 is injected in siliclastic rocks:

1) CO_2 is dissolved in water during injection (Sigfusson et al., 2015), so it no longer rises towards the surface (Figure 29); 2) trapping of CO_2 as minerals occurs much faster; and 3) basalt is hospitable to acid gas impurities (e.g., 25% H_2S; e.g. Matter et al. 2016). This decreases the risk of CO_2 leakage and makes requirements for monitoring programs and mitigation strategies less strict, which lower costs of the storage. Despite these advantages, mineral carbonation is not widely recognized as a viable alternative. Doubt remains if operations aimed at mineral carbonation can be upscaled by orders of magnitude from current operation at ~15.000 tons of CO_2/year; little is known about the actual storage capacity or its relationship with CO_2 injection rate, which precludes estimation of total storage cost; and it is unknown if rocks, that are geochemically suitable but difficult to access, can be used.

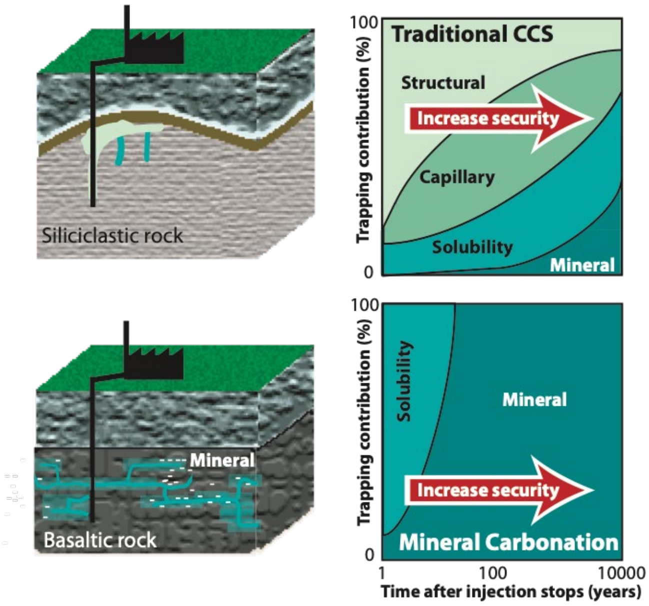


Figure 29. The storage concept and trapping mechanisms for traditional CCS and mineral carbonation (based on Snæbjörnsdóttir et al. 2017).

Use of basalts requires that large amounts of CO_2 and water can be injected simultaneously (Sigfusson et al. 2015; ~30 ton of water per ton of CO_2, with water possibly stemming from the storage formation itself), and that the dissolved CO_2 can interact with the rock (e.g. Snæbjørnsdottir et al. 2020). These two aspects depend on different properties of the basaltic rock. Injection necessitates permeability but the presence of a fracture network could suffice. In contrast, the extent of mineral carbonation depends on rock reactivity and the surface area in contact with the CO_2 bearing water. This is a complex function of a range of parameters, such as fluid flow (Clark et al. 2020), the interconnectedness of fractures and pores (Zahasky et al. 2018), dimension of fracture and pore throats, diffusion into blind porosity, spatial distribution of minerals with variable reactivity, and confounding between fluid flow and volume changing, geochemical reactions, which affect permeability. Consequently, accurate estimation of storage capacity is complicated. Current methods for estimation of storage capacity are simple and rely largely on assumptions about the amount of porosity, that can be filled with carbonate minerals. Estimations for a given site vary by two orders of magnitude from 0.6 to 70 $MtCO_2/km^2$, depending on the method used (Sigfússon et al. 2017). This range of values could entail utter failure of an operation or outstanding performance. Thus, new and much better methods would be needed for determining storage capacity at a Danish site and assess if use of the basalt for CO_2 storage is achievable.

In Denmark, volcanic or volcaniclasitc rocks are located in wedges at 2-5 km depth, possibly as part of the ~300 Ma Skagerak Centered Large Igneous Province or somewhat later magmatic events (Aghabawa, 1993, Stemmerik et al. 2000; Heeremans and Falliede 2004). Figure 30 shows the estimated original extent of the volcanic rock as delineated by Torsvik et al. 2008. However, subsequent subsidence and erosion means that only some of the material remains, emplaced in half-grabens (Stemmerik et al. 2000; Nielsen 2003). Offshore in the North Sea, the rock forms the bulk of the Karl Formation (Stemmerik et al. 2000). It has been encountered in several deep wells in the Danish area (some indicated by red dots in Figure 30), and a maximum known thickness of 678 m occurs in the R-1 well. In addition, the Hans-1 well in Kattegat penetrated ~750 m of rock in two intervals, interpreted to be volcanic or reworked volcanic rock (Michelsen and Nielsen 1991). From the relatively little we know, the rock consists of lava flow and volcaniclastic rock with variable chemical composition. Overall, the material is dominantly basic and rich in Ca, Mg and Fe (Aghabawa 1993). The plagioclase, for example, frequently have anorthite content of above 50. These characteristics are favourable for mineral carbonation. However, the primary minerals are often altered (Aghabawa 1993; Lundmark et al. 2018), meaning that reactivity has most likely decreased compared to when pristine.

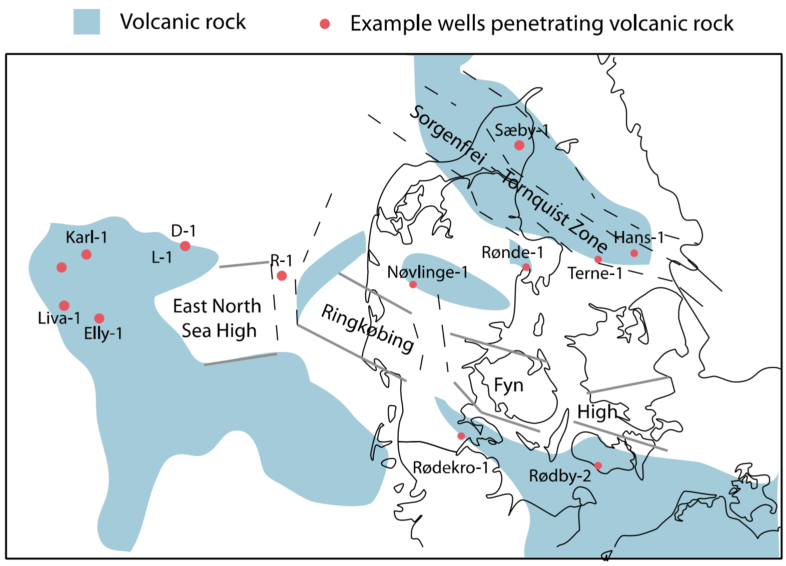


Figure 30. Estimated extend of volcanic rock at time of formation (based on Torsvik et al. 2008), and location of some of the wells penetrating volcanic or volcaniclastic rock.

For such deeply situated and old rocks, diagenesis would have decreased permeability and porosity, in particular when they are basaltic. Ongoing work at GEUS on a Greenlandic outcrop analogue, that has been buried to ~6 km depth, shows that porosity of basaltic rocks is < 3%, compared to adjacent mixed siliciclastic-volcaniclastic rock which have porosities of up to 10% (Weibel et al., in preparation). Assuming that the basaltic lava flow in Denmark display similar qualitites, mineral carbonation would not be trivial and might well have to rely on fracture networks of either natural or induced origin. Data from a deeper injection in Iceland into natural fractures in altered basalt suggests that mineral carbonation might nevertheless be possible (Clark et al. 2020). Modelling of tracer data indicate an effective porosity of 0.2 to 3.5%, yet field data covering 3.5 years of operation shows mineralisation of 50 to 60 % of the injected CO_2, depending on injection rate. However, it is currently unknown if such carbonation rates largely reflect increased reaction rates at the high temperature (>250 °C) at the Icelandic site. As an alternative to the lava flow, basaltic, volcaniclastic rock might also be targetted. Potentially, such rock might have increased permeability (Berger et al. 2009). To conclude, there is a very real possibility that the cooler, but very deep Danish volcanic rocks are not suitable for large scale storage of CO_2. To assess if suitable or not, more work is required to 1) characterise the composition and mineral assemblage of the rock, its petrophysical properties, and its distribution; and 2) use geochemical reactive transport modelling to estimate storage capacity and rate.

Suggestions for supplementary investigations and research

This section summarises suggestions for further work and is focused on the challenges described in this study and how they could be addressed by further investigations.

Acquire regional seismic data

The quality and density of the Danish onshore seismic database is of a state where model driven interpretations and guesswork is required to generate maps. The confidence in the maps should therefore always be questioned, but the uncertainty and the risk in the presented maps are difficult to communicate and it may give a false sense of 'knowledge' that is not supported by data. More regional data is needed to build a more certain framework of the subsurface.

It is believed that many additional structures could be present within the current database, both hidden in the very poor-quality profiles, but also in the space 'between' the very open grid of seismic lines. A regional effort to get high quality seismic across all of Denmark, could benefit mapping of the CO_2 storage potential, but also profit Denmark in general in the mapping for green-tech solutions such as various types of energy storage, geothermal investigations, depositories etc.

Geothermal projects in The Netherlands has realize that seismic surveys are very important for the understanding and de-risking of the subsurface, and initiatives to allocate 90M € to new regional seismic projects has been granted. Similar initiatives are much needed in Denmark.

Seismic database revision and optimisation

1. Shallow seismic data sets (1000ms) targeted for groundwater or similar shallow targets, are not yet incorporated as these do not reach potential reservoir target. However, some of these data could help in delineating Chalk Gr. surfaces in the shallow subsurface and thus improve time to depth conversion.
2. All data currently loaded have been assigned seismic datum in 0 ms. It is, however, not certain whether some of the vintage data has been topographically corrected and

assigned a fixed datum (and whether this is at 0 ms), so it is recommended that seismic datum assumptions should be revisited if possible.

3. The Danish onshore seismic database is very inhomogeneous as it comprises many surveys acquired over a long-time span for different purposes and by different companies, and seismic processing flows, velocity picking etc. varies from survey to survey. Seismic ties across profiles both within and across different surveys are poor to bad and could be investigated further. This might be an impossible task, but interpretations suffer from poor line correlation.
4. Reprocessing of seismic profiles with new modern processing techniques and methods possibly including revised velocity could potentially improve seismic quality and optimizing line correlations in some areas. The uplift from this is however unknown and in areas where this is really needed the raw data might not be available.

Acquire structure specific seismic data

To properly map and define individual known structures acquisition of additional seismic data is needed. Particularly for CO_2 storage, a much denser 2D grid across structures are needed and perhaps only 3D will be sufficient to give the confidence needed in the structural assessment and for certification of a storage site. Reservoir performance at a potential storage site is also a key element, and perhaps geophysical modelling and assessment of the reservoir quality via modelling of rock-physics is required, preferably from new 3D seismic data designed with this in mind.

A feasibility study or even a test acquisition would be very beneficial as proof of concept for further investigations. Acquisition across structures such as the Havnsø or Hanstholm could provide important insights.

Revised depth conversion

Seismic time to depth conversion is not a trivial process, particular for the Danish onshore, the onshore/offshore transition and to some degree for parts of the Danish offshore. For large parts of the Danish area a working seismic velocity model is available, but the model is designed for screening purposes and is very rough, not covering the entire AOI and is associated with large known uncertainties. Several challenges are present in both the subsurface and the available data (or lack thereof) and it cannot be ruled out that the uncertain velocity model both could introduce unreal structures and potentially eliminate smaller real structures. It is therefore highly recommended to initiate the large task of revising and updating the Danish velocity model for both the onshore, offshore and in particular for the on- and offshore transition. This task would involve incorporating work on revising interpretations of particularly the shallow parts of the Chalk group and the pre-Quaternary. Constraining the Chalk group is seen as a key issue here.

As many DK wells carry uncertainty with regards to velocity data, an effort to revise the seismic well ties and well tops would be most beneficial.

Shallow seismic data sets (<1000ms) are available in parts of the Danish onshore. Incorporation of these data could perhaps assist in better interpretation of the Chalk Gr.

Refined structural interpretation model
For some of the investigated structures the structural complexity is difficult to unravel due to sparse data and poor imaging. A comprehensive interpretation, structural model creation and QC have not been possible as this level of detail has not been the scope of this study. But detailed fault interpretation and detailed displacement analysis could potentially lead to better interpretation and definition of structures.

On a regional scale the structural framework is complex. There are several indications of a very complex kinematic evolution with several tectonic events superimposed on each other. For several areas different tectonic dynamics are observed, concerning complex fault evolution, reactivation, fault decoupling (salt) and transition from brittle to ductile deformation. The Danish area in general, could benefit from a thorough structural review and QC of fault definitions both locally but also on a regional scale.

This process is time consuming with lots of trial and error iterations but should be carried out for some of the structures moving forward.

Play fairway mapping and Yet-To-Find analysis
As data coverage and identification of structures is challenging, methods from oil industry exploration could be utilised for getting an estimate of the total storage potential. Methods such as ‘Play-Fairway Mapping’ and ‘Yet-to-Find’ analysis as described by Rose (2001) and Brown and Rose (2001) could assist in getting a statistical founded estimate of the regional potential.

The method includes:

- Identifying areas that have the same associated risk or likelihood of having reservoir, seal, traps and injection likelihood and assigning these into common risk part-play areas. For each of these a chance probability is assigned
- The storage capacity is then estimated for each Part play. This is done by aggregating the capacity potential of identified structures with the evaluated potential from unidentified structures.
    - The capacity of the identified structures is calculated using similar method as described in this report
    - The unidentified potential is estimated by approximating the number of unidentified potential structures in the part-play using for an area analogue structural density (e.g. from where data is good or from a global identified analogue). For each unidentified structure, a capacity is the assigned using probability distribution from capacity analysis.
- Stochastic modelling of Yet-to-find potential is best estimated using Monte Carlo simulation as large uncertainty are expected for both identified, the potential number of un-identified structures and their potential capacity, but also for modelling the risk these will be associated all structures.
- For all identified part plays the probabilistic aggregated storage capacity is estimated and can be compared with neighbouring part plays.
-

The key outcome from the analysis will be to point out areas that have larger potential than others and the steer the exploration effort forwards in these high potential areas.

Improve volumetric assessment

This study provides very simplistic stochastic estimates the storage capacity. Moving forward several initiatives could improve the capacity estimation.

1. Building a more solid Monte Carlo simulation model would benefit estimates and estimate ranges. Utilisation e.g. commercial software such as @Risk®, ModelRisk® or Crystal Ball®, with more robust randomness via better sampling from eg. latin hypercube so similar, could improve stability and the statistical foundation. These softwares also have the benefit of superior control of important correlations and dependencies and provides better documentation of results etc. for both regional assessment and structure specific evaluations
2. More detailed volumetric calculations methods could potentially narrow the uncertainty range and give better confidence in results by e.g. moving away from A x h x GCF gross rock volume method and applying the better Area vs. Depth, or similar, methods could provide better insights into the capacity potential.
3. Calibration of stochastic result against result from reservoir modelling and dynamic flow simulations could constrain volumetric models even further.

Storage Efficiency Factor estimation

The storage efficiency factor could potentially prove to be a vital element in the capacity estimation. Currently very little is known on the topic and further analysis should be carried out to get a better feel for the parameter and its uncertainty related to the Danish context. Full field simulation and investigation into development scenarios should be tested. If knowledge from analogues is available these should be investigated although the statistical foundation is considered to be low. On the other end of the scale it should be investigated whether it is feasible to carry out special core analysis for further insights into CO_2 flow, saturation etc. to help constrain $S_{eff.}$

Multi-target evaluation

Several of the structures are developed on top of the Zechstein halites and as the halokinesis is fairly late, the structures formed e.g. over a salt pillow will form on multiple levels ranging from the Triassic to the Cretaceous (and perhaps even younger strata). The means that structures identified on e.g. Gassum Fm. level may also have associated structures on older and deeper reservoir levels. The capacity of these levels should be evaluated in further work if they are not situated to deep. Only the Hanstholm potential at both Gassum and Skagerrak has so far been evaluated, but several other dual or multi target structure at believed to be present.

Possible future work evaluating basaltic rocks

In the case that work on CO_2 storage in basalt is deemed promissing within a future CCUS project, a number of activities would be needed to allow us to assess if targeted mineral carbonation in Danish basalts could be feasible, safe and cost efficient. The work is divided in 4 stages.

In Stage 1, the spatial distribution of basaltic rock and the locations of potential storage sites would be mapped using existing information from well logs, seismic surveys, etc. The mapping would include chartering of earthquake density, with high concentration indicating active faults and a surrounding damaged zone with microfractures and possibly elevated permeability. Based on evaluation of the data, the most promising locations for sites would be selected for further studies.

In Stage 2, site characterisation and 3D geological models would be developed for the most promising sites. The work includes characterisation of petrology, mineralogy, permeability/porosity, fracture networks and hydrology. The analysis would be based on existing material from drill cuttings and, where they exist, cores from the target formation, adjacent formations and from other, tectonically and compositionally similar sites. 3D geological models with fracture networks would then be constructed for the most suitable storage site(s) to enable reactive transport computations in Stage 3.

In Stage 3, dual porosity/permeability reactive transport modelling would be conducted using the 3D geological models to compute the storage capacity and determine the influence of injection rates on results. This work would rely on mainly continuum modelling, but potentially, porescale calculations could be performed to derive the averaged parametes for fracture and matrix transport required in the continuum calculations. As part of the calculations, we would consider if the storage can be coupled with geothermal exploitation to lower costs. From the modelling, we could predict the rate of CO_2 injection and the corresponding storage capacity.

In Stage 4, the costs of the operation would be estimated in terms of capital and operational expenses. Finally, the safety of the storage operation would be assessed, including risks of substantial induced seismicity.

If the rock is deemed suitable, further work could ensue with laboratory experiments on the interaction between dissolved CO_2 and basalt, and, eventually, pilot field tests.

References

Aghabawa M. A. (1993). Petrology and geochemistry of the Rotliegendes volcanic rocks in Denmark and their tectonic implications: Dynamisk/stratigrafisk analyse af Palæozoikum i Danmark. Geological Survey of Denmark, Client report 35, 335 pp.

Anthonsen, K.L., Aagaard, P., Bergmo, P.E.S., Erlström, M., Faleide, J.I., Gislason, S.R., Mortensen, G.M., Snæbjörnsdottir, S.Ó. (2013). CO_2 storage potential in the Nordic region. Energy Procedia 37, p. 5080-5092.

Anthonsen, K.L., Bernstone, C., Feldrappe, H. (2014). Screening for CO_2 storage sites in the Southeast North Sea and the Southwest Baltic Sea. Energy Procedia 63, p. 5083-5092.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Christensen, N.P., Holloway, S., Mathiassen, O.M. (2007). Estimation of CO_2 Storage Capacity in Geological Media – Phase 2. Work under the auspices of the Carbon Sequestration Leadership Forum (www.cslforum.org)

Berger A., Gier S., Krois P. (2009). Porosity-preserving chlorite cements in shallow-marine volcaniclastic sandstones: Evidence from Cretaceous sandstones of the Sawan gas field, Pakistan. AAPG Bulletin 93, 595–615.

Bertelsen, F. (1980). Lithostratigraphy and depositional history of the Danish Triassic. Geological Survey of Denmark. Series B 4, 59 pp.

Brennan, S.T., Burruss, R.C., Merrill, M.D., Freeman, P.A., Ruppert, L.F. (2010). A probabilistic assessment methodology for the evaluation of geologic carbon dioxide storage: U.S. Geological Survey Open-File Report 2010–1127, 31 PP., available only at http://pubs.usgs.gov/of/2010/1127.

Brown, P.J., and Rose, P.R. (2001). Plays and concessions – a straightforward method for assessing volumes, value and chance. Search and Discovery Article no. 40024 (adapted for online presentation from poster session presented at AAPG Annual Meeting, Denver, CO, June 5, 2001).

Clark D. E., Oelkers E. H., Gunnarsson I., Sigfússon B., Snæbjörnsdóttir S. Ó., Aradóttir E. S., Gíslason S. R. (2020). CO_2 and H_2S mineralization during 3.5 years of continuous injection into basaltic rocks at more than 250 °C. Geochim. Cosmochim. Acta 279, 45–66.

Fawad M., Sassier C., Jarsve E.M., Aagaard P., Faleide J.I., Nielsen L.H., Kristensen L. & Bergmo P.E.S. A. 2011. Potential CO_2 Storage Play in Skagerrak – Depositional Environment and Reservoir Geology of the Gassum Formation. Poster presentation at TCCS-6, Trondheim 2011.

Fuchs, S., Balling, N., Mathiesen, A. (2020). Deep basin temperature and heat-flow field in Denmark – New insights from borehole analysis and 3D geothermal modelling, Geothermics, ISSN: 0375-6505, Vol: 83, 101722 PP.

Gehmann, H.N. (1970). Graphs to Derive Geometric Correction Factor: Exxon Training Materials (unpublished), Houston.

Hamberg, L. and Nielsen, L.H. (2000). Shingled, sharp-based shoreface sandstones and the importance of stepwise forced regression in a shallow basin, Upper Triassic Gassum Formation, Denmark. In: Hunt, D. & Gawthorpe, T.L. (eds): Sedimentary responses to forced regressions. Geological Society Special Publication (London) 172, p. 69–89.

Heeremans M. and Falliede J. I. (2004). Late Carboniferous-Permian tectonics and magmatic activity in the Skagerrak, Kattegat and the North Sea. In: Wilson M., Neumann E. -R., Davies G.R., Timmerman M. J., Heeremans M. and Larsen B. T. (eds). Permo-Carboniferous Magmatism and Rifting in Europe. Geol. Soc. Spec. Publ. 223, 157-176.

Holloway, S., Heederik, J.P., van der Meer, L.G.H., Czernichowski-Lauriol, I., Harrison, R., Lindeberg, E., Summerfield, I.R. Rochelle, C., Schwarzkopf, T., Kaarstad, O., Berger, B. (1996). The underground disposal of Carbon Dioxide. Joule II project No. CT92-0031, summary report, 385 pp.

Kristensen, L., Hjuler, M.L., Frykman, P., Olivarius, M., Weibel, R., Nielsen, L.H., Mathiesen, A. (2016). Pre-drilling assessments of average porosity and permeability in the geothermal reservoirs of the Danish area. Geotherm Energy 4:6 DOI10.1186/s40517-016-0048-6

Larsen, M., Bidstrup, T., Dalhoff F. (2003). Mapping of deep saline aquifers in Denmark with potential for future CO2 storage. Geological Survey of Denmark and Greenland, Rapport 2003/39, 83 pp.

Liboriussen, J., Ashton, P., Tygesen, T. (1987). The tectonic evolution of the Fennoscandian Border Zone in Denmark. Techtonophysics 137, p. 21–29.

Lothe, A., Emmel, B., Bergmo, P., Mortensen, G.M., Frykman, P. (2015). Updating estimates of storage capacity and evaluation of seal for selected aquifers. NORDICCS Technical report D6.3.1401 (D26), 86 pp.

Lundmark A.M., Gabrielsen R.H., Strand T., Ohm S.E. (2018). Repeated post-Caledonian intra-cratonic rifting in the central North Sea- Evidence from the volcanic record in the Embla oil field. Mar. Pet. Geol. 92, 505–518.

Matter J. M., Stute M., Snæbjörnsdottir S. Ó., Oelkers E. H., Gislason S. R., Aradottir E. S., Sigfusson B., Gunnarsson I., Sigurdardottir H., Gunnlaugsson E., Axelsson G., Alfredsson H. A., Wolff-Boenisch D., Mesin K., Fernandez de la Reguera Taya D., Hall J., Dideriksen K., Broecker W. S. (2016). Rapid carbon mineralization for permanent and safe disposal of anthropogenic carbon dioxide emissions. Science 352, 1312-1314.

McGrail B. P., Schaef H. T., Spane F. A., Horner J. A., Owen A. T., Cliff J. B., Qafoku O., Thompson C. J., Sullivan E. C. (2017). Wallula Basalt Pilot Demonstration Project: Post-Injection Results and Conclusions. Energy Procedia 114, 5783 – 5790.

Michelsen, O. (1975). Lower Jurassic biostratigraphy and ostracods of the Danish Embayment. Danmarks Geologiske Undersøgelse II. Række 104, 287 pp.

Michelsen, O. (1978). Stratigraphy and distribution of Jurassic deposits of the Norwegian–Danish Basin. Danmarks Geologiske Undersøgelse Serie B 2, 28 pp.

Michelsen, O. (ed.) (1981). Kortlægning af potentielle geotermiske reservoirer i Danmark. Danmarks Geologiske Undersøgelse, Serie B 5, 28 pp.

Michelsen O. and Nielsen L. H. (1991). Well records of the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark: Hans-1, Sæby-1 and Terne-1 wells. DGU Series A 29, 37 p.

Michelsen, O. and Clausen, O.R. (2002). Detailed stratigraphic subdivision and regional correlation of the southern Danish Triassic succession. Marine and Petroleum Geology 19, p. 563–587.

Michelsen, O., Nielsen, L.H., Johannessen, P.N., Andsbjerg, J., Surlyk, F. (2003). Jurassic lithostratigraphy and stratigraphic development onshore and offshore Denmark. In: Ineson, J.R. & Surlyk, F. (Eds.) The Jurassic of Denmark and Greenland. Geology of Denmark Survey Bulletin 38.

Nielsen, L.H. and Japsen, P. (1991). Deep Wells in Denmark, 1935-1990: Lithostratigraphic Subdivision, Oplag 31 af DGU series A, ISSN 0901-0270, Danmarks Geologiske Undersøgelse, 1991, 179 PP.

Nielsen L. H. (2003). Late Triassic – Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. Geol. Surv. Den. Green. Bull. 1, 459–526.

Nielsen, L.H., Larsen, F., Frandsen, N. (1989). Upper Triassic–Lower Jurassic tidal deposits of the Gassum Formation on Sjælland, Denmark. Geological Survey of Denmark. DGU Series A 23, 30 pp.

Otis, R. and Haryott, P. (2010). Calibration of Uncertainty (P10/P90) in Exploration Prospects, AAPG Search and Discovery Article #40609 (2010)

Rose, P. R. (2001). Risk Analysis and Management of Petroleum Exploration Ventures. AAPG Methods in Exploration, Series no. 12, 164 PP.

Schuppers, J.D., Halloway, S., May, F., Gerling, P., Bøe, R., Magnus, C., Riis, F., Osmundsen, P.T., Larsen, M., Andersen, P.R., Hatzyannis, G. (2003). Storage capacity and quality of hydrocarbon structures in the North Sea and the Aegean region. EU project: 005.70200/01.02.07, 77 pp.

Sigfusson B., Gislason S. R., Matter J. M., Stute M., Gunnlaugsson E., Gunnarsson I., Aradottir E. S., Sigurdardottir H., Mesfin K., Alfredsson H. A., Wolff-Boenisch D., Arnarsson

M. T., Oelkers E. H. (2015). Solving the carbon-dioxide buoyancy challenge: The design and field testing of a dissolved CO_2 injection system. Int. J. Greenhouse Gas Control 37, 213–219.

Sigfússon B., Arnarson M. Þ., Snæbjörnsdóttir S. Ó., M. R. Karlsdóttir, Aradóttir E. S., Gunnarsson I. (2017). Reducing emissions of carbon dioxide and hydrogen sulphide at Hellisheidi power plant in 2014-2017 and the role of CarbFix in achieving the 2040 Iceland climate goals. Energy Procedia 146, 135-145.

Snæbjörnsdóttir S. Ó., Oelkers E. H., Mesfin K. G., Aradóttir E. S., Dideriksen K., Gunnarsson I., Gunnlaugsson E., Matter J. M., Stute M., Gislason S. R. (2017). The chemistry and saturation states of subsurface fluids during the in situ mineralisation of CO_2 and H_2S at the CarbFix site in SW-Iceland. Int. J. Greenhouse Gas Control 58, 87-102.

Snæbjörnsdóttir S. Ó., Sigfússon B., Marieni C., Goldberg D., Gíslason S. R. and Oelkers E. H. (2020). Carbon dioxide storage through mineral carbonation. *Nat. Rev. Earth Environ.* 1, 90–102.

Span, R. and Wagner, W. (1996). A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100K at pressures up to 800 MPa, J. Phys. Chem. Ref. Data., 25, 1509-1596 PP.

Stemmerik L., Ineson J. R., Mitchell, J. G. (2000). Stratigraphy of the Rotliegend Group in the Danish part of the Northern Permian Basin, North Sea. J. Geol. Soc., London, 157, 1127-1136.

Sørensen, K., Nielsen, L.H., Mathiesen, A., Springer, N. (1998). Geotermi i Danmark: Geologi og ressourcer. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1998/123, 24 pp.

Torsvik T. H., Smethurst M. A., Burkeb K., Steinberger B. (2008). Long term stability in deep mantle structure- Evidence from the ~ 300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP). Earth Planet. Sci. Lett. 267, 444–452.

Vangkilde-Pedersen, T., Anthonsen, K.L., Smith, N., Kirk, K., Neele, F., Van der Meer, B., Gallo, Y.L., Bossie-Codreanu, D., Wojcicki, A., Nindre, YL.L., Hendriks, C., Dalhoff, F., Christensen, N.P. (2009). Assessing European capacity for geological storage of carbon dioxide–the EU GeoCapacity project. Energy Procedia 1, 2663-2670.

Vejbæk, O.V. and Britze, P. (1984). Top præ-Zechstein. Danmarks Geologiske Undersøgelse Map series 45.

Wang, Y., Zhangb, K. and Wua, N. (2013). Numerical Investigation of the Storage Efficiency Factor for CO_2 Geological Sequestration in Saline Formations, Energy Procedia, Volume 37, 2013, 5267-5274 PP.

Weibel, R., Olivarius, M., Vosgerau, H., Mathiesen, A., Kristensen, L., Nielsen, C.M., Nielsen, L.H. (2020). Overwiew of the potential geothermal reservoirs in Denmark. Netherlands Journal of Geosciences, Volume 99, e3. https://doi.org/10.1017/njg.2020.5

Zahasky C., Thomas D., Matter J., Maher K., Benson S. M. (2018). Multimodal imaging and stochastic percolation simulation for improved quantification of effective porosity and surface area in vesicular basalt. Adv. Water Resour. 121, 235–244.

Glossary

Brine: Water having a salinity higher than that of average seawater, that is, more than 35,000 parts per million (milligrams per liter) total dissolved solids.

Buoyancy: Upward force on one phase (for example, a fluid) produced by the surrounding fluid (for example, a liquid or a gas) in which it is fully or partially immersed, caused by differences in density.

Buoyant trapping: CO_2 in communication across pore space creating a column that is held in place by a top and lateral seal, either a seal formation or a sealing fault.

Buoyant trapping Pore Volume: A geologically determined, probabilistic distribution of the volume fraction of the storage formation that can store CO_2 by buoyant trapping.

Buoyant trapping Storage Efficiency: A distribution of efficiency values that describes the fraction of buoyant trapping that can occur within a volume of porous media.

Buoyant trapping Storage Capacity: Mass of CO_2 retained in the storage formation by buoyant trapping.

Buoyant trapping storage volume: Volume of CO_2 retained in the storage formation by buoyant trapping.

Capillary entrance pressure: The pressure necessary to displace a wetting fluid from a porous medium by a nonwetting phase (for example, displacing water with gas or mercury). The surface tension between the phases is a function of the radius of curvature of the interface between the phases, causing capillary entrance pressures to increase as the diameter of the pores and pore throats decreases. Very fine-grained rocks, like mudstones, have very high capillary entrance pressures allowing them to be barriers to flow (seals) for nonwetting fluids, such as oil, gas, and supercritical CO_2.

Capillary force: Capillary forces in a petroleum reservoir are the result of the combined effect of surface and interfacial tensions, pore size, geometry, and wetting characteristics of a given system.

Carbon dioxide plume: The subsurface extent, in three dimensions, of an injected carbon dioxide stream.

CO2-water contact: As supercritical CO_2 density is lower than that of brine, the density contrast will for CO_2 saturated buoyant traps create a boundary between CO_2 and water. The bounding surface in a reservoir above which predominantly CO_2 occurs and below which predominantly water occurs. Although CO_2 and water are immiscible, the contact between the two is commonly a transition zone and there is usually irreducible water adsorbed by the grains in the rock. The contact is not always a flat horizontal surface, but instead might be tilted or irregular depending on injection and pressure across the structure.

Column height: The thickness defined by the highest and lowest levels within the strata where the CO_2 phase is continuously connected. This column is held in place by top and lateral seals, and its thickness is controlled by the geometry of the closure and (or) the seal adequacy. Column high cannot exceed the structural relief of the structure.

Geologic storage of CO_2: The long-term retention of carbon dioxide in subsurface geologic formations.

Chance: The probability of an event having a successful outcome. Chance is the opposite of risk (probability of failure) i.e. Chance = 1 - Risk

Injectivity: The rate and pressure at which fluids can be pumped into the rock without fracturing the formation. Although injectivity is typically reported as a rate, this methodology addresses this requirement by using permeability values to divide the residual storage component of the storage formation into three classes.

Monte Carlo simulation: Experiments of a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. The underlying concept is to use randomness to solve problems that might be deterministic in principle. They are often used in physical and mathematical problems and are most useful when it is difficult or impossible to use other approaches. Monte Carlo methods are mainly used in three problem classes: Optimization, numerical integration, and generating draws from a probability distribution.

Permeability (k): A measure of the ability of a rock to transmit fluids, controlled by pore size and pore throat geometry. Typically reported in Darcy units.

PERT distribution: Distribution in family of continuous probability distributions defined by the minimum (a), most likely (b) and maximum (c) values that a variable can take. Developed from project schedule evaluation using the Program Evaluation and Review Technique, (hence its name), but is widely used in risk analysis to represent the uncertainty of the value of some quantity where one is relying on subjective estimates.

Porosity (φ): The part of a rock that is occupied by voids or pores. Pores can be connected by passages called pore throats, which allow for fluid flow, or pores can be isolated and inaccessible to fluid flow. Porosity is typically reported as a volume, fraction, or percentage.

Pressure gradient: The change in pore pressure per unit depth, typically in units kilopascals per meter.

Residual trapping: Discrete droplets, blobs, or ganglia of CO_2 as a nonwetting phase, essentially immiscible with the wetting fluid, trapped within individual pores where the capillary forces overcome the buoyant forces.

Residual trapping class 1 (R1): Residually trapped storage formation rock having a permeability of greater than 1 Darcy.

Residual trapping class 2 (R2): Residually trapped storage formation rock having a permeability of greater than 1 millidarcy and less than 1 Darcy.

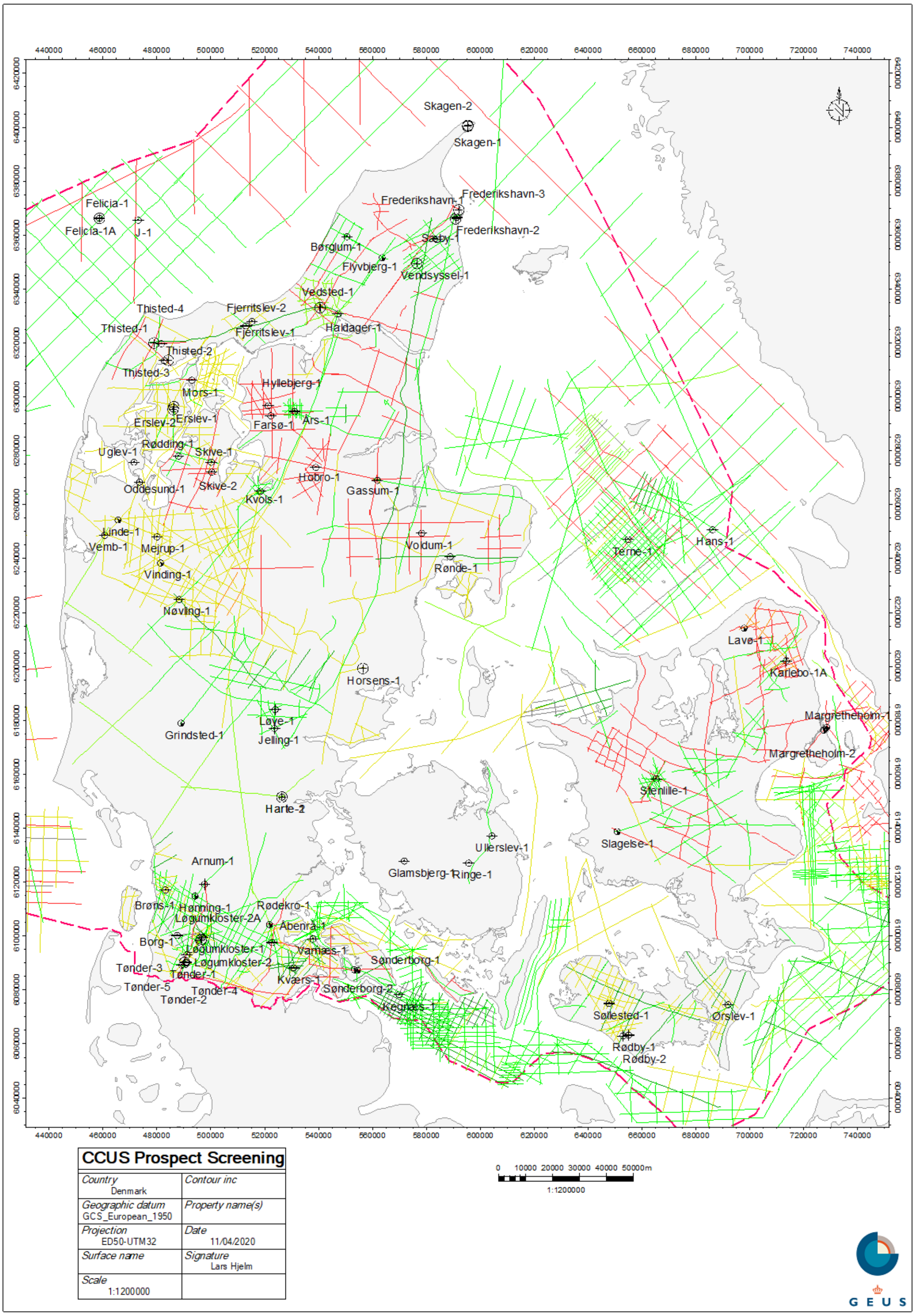
Residual trapping class 3 (R3): Residually trapped storage formation rock having a permeability of less than 1 millidarcy.

Residual trapping pore volume: A calculated value equal to the storage formation pore volume (SFPV) minus the buoyant trapping pore volume (BPV). The value represents the pore volume within the storage formation that can be used to store CO_2 by residual trapping; it is calculated during iterations of the Monte Carlo simulator after a value from the buoyant trapping pore volume distribution is chosen.

Residual trapping storage efficiency: A distribution of efficiency values that describes the fraction of residual trapping that can occur within a volume of porous media.

Residual trapping storage resource: The mass of CO_2 retained in the storage formation by residual trapping.
Residual trapping storage volume: The volume of CO_2 retained in the storage formation by residual trapping.
Salinity: A measurement of the water properties determined by the total dissolved solids, generally reported in parts per million or milligrams per liter.
Seal formation: The confining rock unit within the storage assessment unit. The seal formation is a rock unit that sufficiently overlies the storage formation and has a capillary entrance pressure low enough to effectively inhibit the upward buoyant flow of CO_2.
Seal: A geologic feature that inhibits the mixing or migration of fluids and gases between adjacent geologic units. Typically, a rock unit or a fault; it can be a top seal, inhibiting upward flow of buoyant fluids, or a lateral seal, inhibiting the lateral flow of buoyant fluids.
Storage assessment unit (SAU): A mappable volume of rock that includes the storage formation, a reservoir flow unit for CO_2 storage, and a regional seal formation.
Storage formation: The reservoir component of the storage assessment unit. The sedimentary rock layers that are saturated with formation water with total dissolved solids greater than 10,000 parts per million (milligrams per liter). In the CO_2 assessment methodology, the storage formation resource calculation is the main resource calculation and consists of two parts, a buoyant trapping resource and a residual trapping resource.
Storage formation pore volume: The available pore space in the storage formation calculated from area, thickness of the net porous interval, and porosity. This value is used in the calculation of residual trapping pore volume (RPV).
Structural Relief: The high of a subsurface structure from Apex (top) to structural Spill Point
Supercritical CO_2: Carbon dioxide is in a supercritical fluid state when both the temperature and pressure exceed the critical temperature of 31°C and pressure of 74 bars (7,400 kilopascal) at which liquid and vapor CO_2 can no longer coexist.
Technically accessible storage volume The CO_2 storage volume that may be available for CO_2 injection and storage estimated by using present-day geologic and hydrologic knowledge of the subsurface and engineering practices.
Trapping: The physical and geochemical processes by which injected CO_2 is retained in the subsurface.

Appendix A: Seismic surveys and well data



Spatial distribution available well and seismic surveys. Notice the variable data density across Denmark. The Seismic line colour reflect the quality of the lines: Grey: very poor, Purple; poor, Green: Good, Blue: Very Good.

Well data

Name	Surface X	Surface Y	Well da-tum (KB, m)	TD (TVDSS, m)	TD (MD, m)	Seismic Check-Shot [from org. source]	DepthTime [LHN+PJ 1992]	Esti. DepthTime [OtherSource]
Arnum-1	497667.10	6119439.00	42.7	1805.3	1848.0	Yes	Yes	No
Borg-1	487628.00	6100414.08	18.4	3030.3	3059.0	No	Yes	No
Brøns-1	483176.64	6117339.66	11.0	2525.0	2536.0	Yes	Yes	No
Hønning-1	494144.69	6115082.83	32.4	2456.6	2489.0	No	No	Yes
Kegnæs-1	569834.80	6078504.71	39.0	2552.0	2591.0	No	Yes	No
Kværs-1	530767.39	6088454.60	53.3	2644.7	2698.0	No	Yes	No
Løgumkloster-1	496875.80	6099655.50	19.0	2655.7	2675.0	No	Yes	No
Løgumkloster-2	496303.91	6098640.50	21.0	2769.0	2790.0	No	No	No
Løgumkloster-2A	496303.91	6098640.50	21.0	2405.9	2625.0	No	No	No
Rødekro-1	521721.75	6104497.88	52.1	1595.9	1648.0	No	No	Yes
Sønderborg-1	553832.07	6087323.97	9.6	2400.0	2591.0	No	No	Yes
Sønderborg-2	553841.34	6087327.79	9.6	1247.8	1405.0	No	No	Yes
Tønder-1	490697.16	6090513.26	13.4	3110.5	3123.9	No	Yes	No
Tønder-2	491076.24	6093294.57	17.4	3182.7	3200.1	No	Yes	No
Tønder-3	490892.39	6090296.47	12.5	1827.5	1840.0	No	Yes	No
Tønder-4	490207.87	6090452.47	15.3	1854.7	1870.0	No	No	No
Tønder-5	489237.86	6089468.61	14.0	1901.0	1915.0	No	Yes	No
Varnæs-1	537850.39	6099195.64	27.9	2207.1	2235.0	No	Yes	No
Åbenrå-1	522677.69	6097825.45	56.1	2290.9	2347.0	No	Yes	No
Grindsted-1	488919.20	6179228.21	34.9	1615.1	1650.0	No	No	Yes
Harte-1	526385.61	6151791.14	29.4	761.6	791.0	No	No	No
Harte-2	526368.07	6151791.04	30.9	1065.2	1096.1	No	No	Yes
Horsens-1	556450.11	6199508.53	56.7	1674.3	1731.0	No	No	Yes
Linde-1	465572.28	6254591.93	24.2	2218.8	2243.0	No	No	Yes
Mejrup-1	480035.60	6248278.50	47.3	2476.1	2524.6	No	Yes	No
Nøvling-1	488201.36	6225061.67	69.2	3692.8	3762.0	No	Yes	No
Rønde-1	588795.08	6240966.03	42.3	5257.7	5300.0	No	Yes	No
Vemb-1	460662.32	6248861.66	15.7	1944.3	1960.0	No	Yes	No
Vinding-1	481360.61	6238597.46	61.6	2372.5	2434.1	No	No	Yes
Voldum-1	578227.65	6249671.90	34.7	2277.3	2312.0	No	Yes	No
Jelling-1	523598.33	6177265.94	97.0	1864.9	1962.0	Yes	No	No
Løve-1	523899.60	6184270.44	95.0	2359.6	2454.8	Yes	No	No
Børglum-1	550498.13	6359647.19	22.6	1504.5	1527.1	No	Yes	No
Erslev-1	486002.66	6295590.29	25.2	3464.8	3490.0	No	No	No
Erslev-2	486280.87	6296622.14	8.2	3395.8	3404.0	No	No	No
Farsø-1	522230.86	6293254.26	25.3	2924.7	2950.0	No	Yes	No
Fjerritslev-1	513066.67	6326577.42	8.0	910.0	918.0	No	Yes	No
Fjerritslev-2	515232.68	6328254.67	8.0	2337.0	2345.0	No	Yes	No
Flyvbjerg-1	563568.27	6351899.18	47.4	1651.6	1699.0	No	No	Yes
Frederikshavn-1	591326.78	6366826.63	12.8	1304.2	1317.0	No	Yes	No
Frederikshavn-2	590820.55	6366332.75	15.5	1064.4	1079.9	No	No	No
Frederikshavn-3	592024.40	6369626.50	10.4	997.6	1008.0	No	No	No
Gassum-1	561768.03	6269278.81	57.9	3404.0	3461.9	No	Yes	No
Haldager-1	547200.23	6331031.90	5.2	1518.8	1524.0	Yes	Yes	No
Hobro-1	538946.73	6274108.59	32.4	2577.6	2610.0	No	Yes	No
Hyllebjerg-1	521266.55	6296956.76	28.0	2855.0	2883.0	No	Yes	No
Kvols-1	518385.87	6265280.02	19.2	2621.8	2641.0	No	Yes	No
Mors-1	492978.00	6306401.47	18.0	5303.0	5321.0	No	Yes	No
Oddesund-1	473537.41	6268653.06	11.0	3537.0	3548.0	No	Yes	No
Rødding-1	488041.64	6278243.47	31.4	2163.6	2195.0	No	Yes	No
Skagen-1	595300.49	6400663.66	1.8	458.1	459.9	No	No	No
Skagen-2	595392.41	6400975.21	2.1	618.8	620.9	No	No	Yes
Skive-1	500187.48	6276031.13	28.0	2290.0	2318.0	No	Yes	No
Skive-2	500361.64	6272311.44	34.0	1415.0	1449.0	No	Yes	No
Sæby-1	583970.97	6358619.78	64.3	1789.7	1854.0	No	Yes	No
Thisted-1	478919.52	6320240.35	35.7	909.3	945.0	No	No	No
Thisted-2	482715.64	6313729.05	35.9	3251.1	3287.0	No	Yes	No
Thisted-3	484220.98	6313822.02	34.2	1207.8	1242.0	No	No	No
Thisted-4	481670.52	6319942.79	37.1	3380.9	3418.0	No	Yes	No
Uglev-1	471516.17	6276028.54	35.7	1208.2	1243.9	No	Yes	No
Vedsted-1	540549.13	6333373.41	5.3	2067.7	2073.0	No	No	Yes

Års-1	531115.24	6294872.46	44.5	3356.5	3401.0	No	Yes	No
Glamsbjerg-1	571745.41	6128056.71	71.3	840.7	912.0	No	Yes	No
Hans-1	686167.49	6250983.84	23.4	2981.7	3009.1	No	Yes	No
Karlebo-1A	713561.15	6202618.50	45.0	2301.5	2489.0	Yes	No	No
Lavø-1	697842.67	6214450.62	28.0	2413.0	2441.0	No	No	Yes
Margretheholm-1	728385.90	6177614.24	9.2	2651.7	2661.5	No	No	No
Margretheholm-2	728457.21	6177677.09	9.5	2743.3	3280.3	No	No	Yes
Ringe-1	595668.85	6127284.65	76.8	1363.1	1439.9	No	Yes	No
Rødby-1	655006.88	6063484.40	5.5	1529.5	1535.0	Yes	Yes	No
Rødby-2	652938.85	6063166.50	7.9	2938.0	2945.9	Yes	Yes	No
Slagelse-1	650704.69	6138977.29	40.9	2934.1	2975.0	No	No	Yes
Stenlille-1	665211.91	6158572.44	41.6	1622.4	1664.0	No	Yes	No
Stenlille-2	664759.13	6157910.00	47.7	1614.4	1662.1	No	Yes	No
Stenlille-3	664388.41	6157885.39	47.7	1456.3	1504.0	No	Yes	No
Stenlille-4	663335.71	6155664.31	38.4	1647.6	1686.0	No	Yes	No
Stenlille-5	665716.56	6157663.08	55.9	1662.1	1718.0	No	Yes	No
Stenlille-6	667291.73	6160214.24	33.0	1689.0	1722.0	No	Yes	No
Stenlille-19	664008.79	6157377.01	49.3	2466.9	2570.0	Yes	No	No
Søllested-1	647758.13	6075244.78	11.0	2691.0	2702.0	Yes	Yes	No
Ullerslev-1	604242.34	6137387.08	25.3	1037.8	1063.1	No	Yes	No
Terne-1	654870.13	6247334.00	37.3	3264.3	3343.0	No	Yes	No
Ørslev-1	691889.10	6074742.12	22.9	2551.1	2574.0	Yes	Yes	No
C-1	418159.64	6275079.28	37.2	3168.7	3205.9	No	Yes	No
D-1	286076.35	6258910.23	37.2	3527.8	3564.9	No	Yes	No
F-1	373024.69	6322980.00	37.2	2382.0	2419.5	No	Yes	No
Felicia-1	458659.90	6366522.00	40.0	2473.4	2514.0	No	Yes	No
Ibenholt-1	313245.93	6253782.99	40.8	2558.5	2599.3	No	Yes	No
Inez-1	375646.37	6301705.04	35.1	1947.5	1982.7	No	Yes	No
J-1	473073.50	6365777.00	37.3	1949.3	1986.7	No	Yes	No
K-1	388726.94	6333178.91	37.2	2254.2	2291.5	No	Yes	No
L-1	267618.54	6240671.69	37.2	2671.0	2708.2	No	Yes	No
R-1	369515.51	6232243.64	26.2	2675.8	2702.1	No	Yes	No
S-1	368766.99	6154292.42	29.9	3783.2	3813.1	No	Yes	No
Felicia-1A	458659.90	6366522.00	40.0	3218.7	3260.0	No	No	No
A-1	250728.50	6147115.65	9.4	1801.7	1811.1	No	No	No
A-2	250554.44	6147466.38	36.0	3360.1	3396.1	No	No	No
Adda-1	241184.28	6192807.81	34.1	3015.4	3049.5	No	Yes	No
Adda-2	239619.01	6192380.84	34.7	2707.6	2742.3	No	Yes	No
Adda-3	242431.27	6191292.18	38.4	2439.6	2478.0	No	Yes	No
Amalie-1	212999.92	6243064.06	36.0	5320.0	5356.0	No	Yes	No
Anne-3	251738.32	6145763.30	37.2	3522.3	3559.5	No	No	No
B-1	188199.97	6184987.23	35.7	3617.3	3653.0	No	Yes	No
Bo-1	222506.53	6193086.49	33.2	2709.4	2742.6	No	Yes	No
Boje-1	229350.44	6196184.96	35.1	2743.8	2778.9	No	Yes	No
Cleo-1	217523.62	6259014.80	40.5	4820.7	4861.3	No	Yes	No
Deep Adda-1	247650.78	6191698.02	39.0	3198.0	3237.0	No	Yes	No
Diamant-1	181846.02	6218699.60	37.5	4209.3	4246.8	No	Yes	No
E-1	239523.98	6184100.94	37.2	4049.6	4086.8	No	Yes	No
E-2	232663.80	6182034.41	37.2	2164.7	2201.9	No	Yes	No
E-3	234761.38	6184655.66	30.5	2630.4	2660.9	No	Yes	No
E-4	236310.88	6182719.99	32.8	2260.2	2293.0	No	Yes	No
East Rosa-1	223424.13	6168191.15	41.8	1482.2	1524.0	No	Yes	No
East Rosa-2	221818.82	6169158.17	35.7	1589.3	1625.0	No	Yes	No
East Rosa-3	223335.73	6169734.65	39.9	1568.5	1608.4	No	Yes	No
E. Rosa Flank-1	224581.55	6166378.64	33.8	3044.7	3078.5	No	Yes	No
Edna-1	211895.23	6177136.42	36.6	4159.3	4195.9	No	Yes	No
Elin-1	211100.52	6210060.41	41.5	4677.4	4718.9	No	Yes	No
Elly-1	205024.14	6192591.40	35.4	3771.6	3807.0	No	Yes	No
Elly-2	206471.80	6192623.38	36.6	4106.0	4142.5	No	No	No
Elna-1	224466.59	6265058.07	37.5	3097.4	3134.9	No	Yes	No
Emma-1	269908.88	6155735.59	37.2	2698.4	2735.6	No	Yes	No
G-1	258179.53	6166678.14	37.2	3777.7	3814.9	No	Yes	No
Gert-1	173496.01	6243105.99	38.7	4967.3	5006.0	No	Yes	No
Gert-2	176307.65	6240401.49	36.0	5032.2	5068.2	No	Yes	No
Gert-3	175364.87	6242159.05	34.4	5021.3	5055.7	No	Yes	No
Gulnare-1	217245.61	6234517.37	36.0	4735.0	4771.0	No	Yes	No

Gwen-2	193533.91	6229899.74	36.6	4364.7	4401.3	No	Yes	No
H-1	227000.94	6189660.09	37.2	2126.9	2164.1	No	Yes	No
I-1	204261.21	6222270.03	37.2	3878.9	3916.1	No	Yes	No
Iris-1	208189.33	6228683.10	35.7	4609.5	4645.2	No	Yes	No
Jens-1	219758.20	6183352.54	36.3	4433.6	4469.9	No	Yes	No
Jeppe-1	184189.40	6238423.06	38.4	5046.6	5085.0	No	Yes	No
John-1	234967.94	6148889.42	35.4	781.8	817.2	No	Yes	No
John Flank-1	236410.51	6148185.88	36.3	2417.4	2453.6	No	Yes	No
Karl-1	193983.60	6250085.75	35.1	4783.9	4819.0	No	Yes	No
Kim-1	158107.93	6232963.29	35.4	4640.6	4676.0	No	Yes	No
Liva-1	176790.73	6210043.22	39.9	4581.5	4621.4	No	Yes	No
Lone-1	160455.65	6235605.70	34.8	3923.1	3957.8	No	Yes	No
Lulu-1	209140.29	6253346.29	29.9	3690.5	3720.4	No	Yes	No
Lulu-2	208896.35	6251622.58	36.6	3602.4	3639.0	No	Yes	No
M-1	255632.58	6153976.31	33.5	2275.1	2308.6	No	Yes	No
M-8	254330.61	6155056.03	29.6	3630.1	3659.7	No	Yes	No
M-9	254032.14	6151580.64	33.8	2054.1	2087.9	No	Yes	No
Middle Rosa-1	216593.05	6170229.11	36.9	2110.1	2147.0	No	Yes	No
Middle Rosa-2	215906.12	6171492.50	39.9	2028.8	2068.7	No	No	No
M. Rosa Flank-1	218107.22	6169774.48	35.7	3037.3	3073.0	No	Yes	No
Mona-1	190799.17	6248230.57	36.6	4205.3	4241.9	No	Yes	No
N-1	231910.77	6167575.37	32.3	2454.6	2486.9	No	Yes	No
N-2	233732.31	6167640.69	31.4	2257.7	2289.1	No	Yes	No
N-3	232527.27	6168523.39	31.1	2262.9	2294.0	No	Yes	No
Nils-1	261015.57	6144527.96	34.4	1998.9	2033.3	No	No	No
Nils-2	261085.48	6144353.77	36.9	2075.4	2112.3	No	Yes	No
North Jens-1	221978.37	6196556.18	46.9	3981.0	4027.9	No	No	No
North Jens-2	221975.09	6196559.49	38.1	2349.9	2388.0	No	No	No
Nora-1	213059.26	6212342.60	37.5	5300.5	5338.0	No	Yes	No
O-1	266925.86	6141943.56	28.3	3550.1	3578.4	No	Yes	No
Olaf-1	171554.62	6215664.56	32.6	4358.3	4391.0	No	Yes	No
Otto-1	201288.77	6233555.61	34.1	2745.9	2780.1	No	Yes	No
P-1	174227.16	6222409.45	37.8	3456.1	3493.9	No	Yes	No
Per-1	254485.88	6189972.94	35.4	2745.6	2781.0	No	Yes	No
Q-1	195503.06	6227236.35	37.3	4457.0	4494.3	No	Yes	No
Ravn-1	201742.80	6202768.35	40.6	4972.4	5013.0	No	Yes	No
Ravn-2	201277.91	6199018.64	35.8	4471.2	4507.0	No	Yes	No
Roar-2	228034.11	6187210.92	35.4	2683.5	2718.8	No	Yes	No
Ruth-1	242250.84	6162477.75	35.1	1674.8	1709.9	No	Yes	No
S. E. Igor-1	264639.10	6164169.25	36.0	3261.0	3297.0	No	Yes	No
Sten-1	166148.97	6233691.22	39.0	4076.1	4115.1	No	Yes	No
T-1	200501.56	6238354.90	25.0	2631.0	2656.0	No	Yes	No
T-3	200897.73	6236601.96	37.8	2781.0	2818.8	No	Yes	No
Tordenskjold-1	159234.81	6212849.68	35.4	3703.6	3739.0	No	Yes	No
Tove-1	256136.11	6129994.72	33.2	1844.7	1877.9	No	Yes	No
U-1	234897.72	6158695.04	28.3	4862.2	4890.5	No	Yes	No
Ugle-1	261526.89	6181679.09	35.9	3021.1	3057.0	No	Yes	No
V-1	257202.04	6182999.85	33.5	3823.4	3856.9	No	Yes	No
Vagn-1	256236.78	6137044.03	34.1	1187.8	1221.9	No	No	No
Vagn-2	256521.23	6137524.06	32.9	1897.1	1930.0	No	Yes	No
W-1	196622.70	6206578.42	34.1	4347.4	4381.5	No	Yes	No
West Lulu-1	204892.26	6254368.61	39.9	4187.0	4227.0	No	Yes	No
West Lulu-2	203532.25	6253278.14	37.2	4016.7	4053.8	No	Yes	No
West Lulu-3	204038.33	6255417.85	35.1	3821.6	3856.6	No	Yes	No
West Lulu-4	201450.56	6252086.68	34.8	3814.9	3849.6	No	Yes	No
Pernille-1	839537.31	6109489.10	36.0	3588.0	3624.0	No	Yes	No
Stina-1	861773.32	6085966.65	36.2	2481.8	2518.0	No	Yes	No
ESKILSTORP-1	754979.63	6155094.85	30.1	2462.9	2493.0	No	No	No
BARSEBAEK-1	746539.51	6185059.26	9.9	2180.1	2190.0	No	No	No
HASLOV-1	756360.80	6149031.00	18.2	2553.8	2572.0	No	No	No
KUNGSTORP-1	751948.62	6150864.50	3.8	2069.2	2073.0	No	No	No
FFC-1	752678.40	6172652.00	0.0	2103.1	2103.1	No	No	No
SMYGEHUK-1	757026.90	6136278.00	22.6	1659.4	1682.0	No	No	No
FALSTERBOREV-1	739627.44	6135860.02	28.1	1394.9	1423.0	No	No	No

Wells available for this study. Notice that only a few have original seismic check shot available. Formation top picks are primarily from consistent selections from Nielsen and Japsen (1991)

Seismic database

Sum of Length in 2D (km)	Quality (pr. Line km)							
Row Labels	Fair	Good	Good shallow	NA	Poor	Very Good	Very Poor	Grand Total
AM84K		742,8						742,8
AM85D		417,8						417,8
AO85I skan					114,6			114,6
AU-FLyvefisken-2000			92,3					92,3
Carter_48							193,3	193,3
Carter_52							510,8	510,8
Copy of GSI75B skan		328,8		278,0	89,7	278,0		974,5
Copy of PRKL74A				153,2	153,2	153,2		459,6
Dana2000			1048,2					1048,2
Dana98			1143,8					1143,8
Dana99			845,8					845,8
DCS81C		9097,3						9097,3
DCS81K		2385,0						2385,0
DK84K_dig		254,9						254,9
DN82D_digital		86,6						86,6
DN84D_skan					134,8			134,8
DN86D		63,0						63,0
DN87O		62,2						62,2
DN90D		51,0						51,0
DN91D		76,9						76,9
DN92T		19,1						19,1
DN94O		63,6						63,6
DN95N				35,3				35,3
DNJ8183D		1260,0						1260,0
DSB82		262,6						262,6
DX85D					60,6			60,6
Farum						50,0		50,0
GC85T		99,3			95,9			195,2
GECO83AK (K83)		299,0						299,0
GSI75B skan		303,8			89,7			393,4
GY82K (G82_DK)		316,1						316,1
hgs		164,2				80,3		244,5
HILG Hillerød						55,8		55,8
HJARBAEK_2010						21,1		21,1
HVG_2012_Confidential__PSDM						85,1		85,1
NP85N		3418,7						3418,7
NWJ-NWDR-confidential						214,5		214,5
PH84D					366,6			366,6
PHD86D_skan					218,3			218,3
PRKL69	202,7				398,9			601,6

PRKL7374A skan					1154,9			1154,9
PRKL74A					153,2			153,2
PRKL74B	134,7				167,8			302,5
PRKL75A					280,7			280,7
PRKL75B					29,3			29,3
PRKL79 (navigation problems)					197,8			197,8
PRKL80B		263,8			679,8			943,6
RTD81K		799,7						799,7
SBG2007_mig3200001						38,8		38,8
SEI75		98,8						98,8
SGU Scanned Seismic Lines					1171,2			1171,2
SKAG-86		647,7						647,7
SSL6267 (A, AE lines) skan							322,1	322,1
SSL6267 (B-lines) skan							227,3	227,3
SSL6267 (H-lines) skan							490,8	490,8
SSL6267 (L-lines) skan							572,8	572,8
SSL6267 (R-lines) skan							949,0	949,0
SSL6267 (S,V-lines) skan							949,2	949,2
SSL6267 (AA-lines) skan							626,4	626,4
SSL72		289,5			92,5			382,0
SSL73		292,5						292,5
ST87T		52,2						52,2
Stenlille_2D				62,4				62,4
TX84K skan (GY84K)					36,9			36,9
TX84T		704,4						704,4
TX85K skan (GY85K)					255,9			255,9
Tønder 3D						0,0		0,0
VAT2008 Confidential						217,5		217,5
WG85T		396,5						396,5
WGC64B_skan					389,9			389,9
WGC70					846,6			846,6
WGC78		174,4			346,9			521,3
WGC79A		91,9			649,0			740,8
WGC79B					81,0			81,0
WGC80		631,4						631,4
WGC81B		63,5			25,4			89,0
WGC81C					158,9			158,9
WGC82A					35,3			35,3
Aabenraa2011		12,8						12,8
Grand Total	**337,5**	**24291,5**	**3130,1**	**528,9**	**8475,2**	**1194,2**	**4841,7**	**42799,1**

Seismic surveys available for this study. The line-km length for each survey are listed by its subjectively evaluated quality and grand total km.

Appendix B: Geological structure catalogue

The following pages is a data catalogue of the structures evaluated in this study.

Hanstholm structure (Gassum Fm)

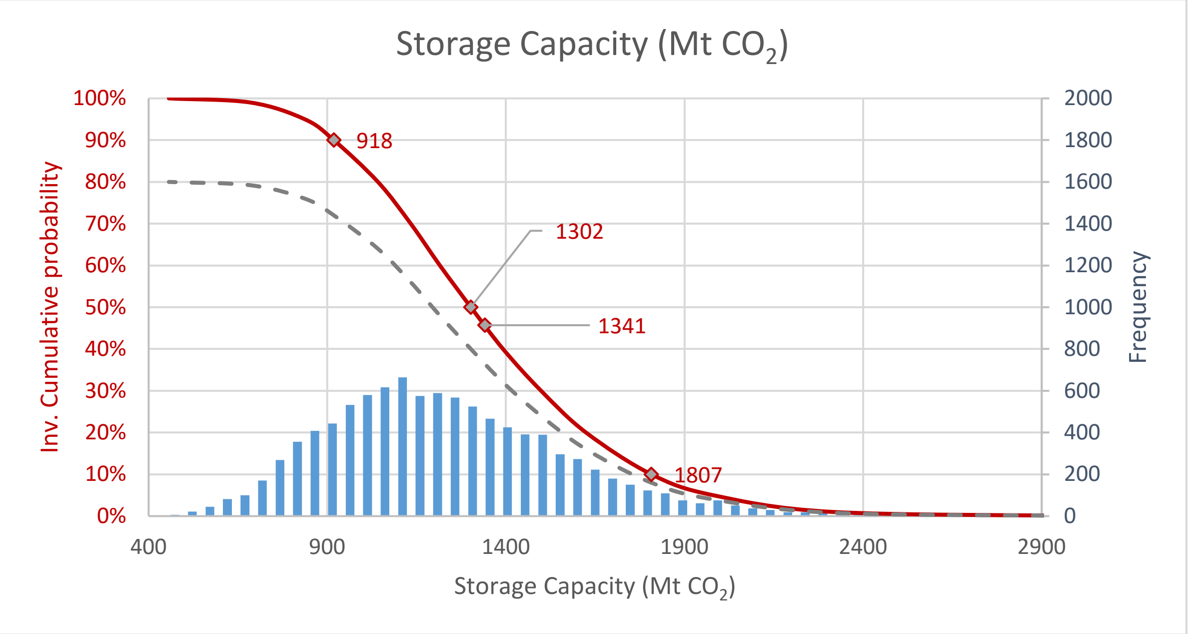
General	
Structure name	Hanstholm GF
Top Site Location	Onshore
Area potential (km^2)	364
Reservoir stratigraphy	U. Triassic - L. Jurassic
Reservoir Formation	Gassum
Reservoir lithology	Sandstone
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev
Top Seal lithology	Mudstone
Top seal integrity	No observed crestal faults, extensional regime on structure apex could have fractures
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	4-way closure domal structure
Max. areal Offshore Fraction (%)	100%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	60%	Unproven at structure. No major faults observed (open grid)? Minor seismic activity	3D seismic, pressure tests
Geological	Structure	100%	Compartmentalisation might occur!	3D seismic
Geological	Reservoir	100%	Drilled in Felicia-1	Drilling, Seismic inversion
Engineering	Injection feasi-bility	40%	Current depth conversion sug-gests a shallow apex where it is uncertain whether CO_2 will be in supercritical phase	Further work on depth conversion. Temperature modelling. Well control
Engineering	Seismicity	5%	Low, but near seismic zone	
Engineering	Groundwater contamination	2%	Low	
Cost	3D-seismic		Low	
Cost	Drilling		high	
Cost	Transport		Offshore	
QHSE	Environment		National and local authorities, Natura 2000 protection area,	
QHSE	Safety		Low	

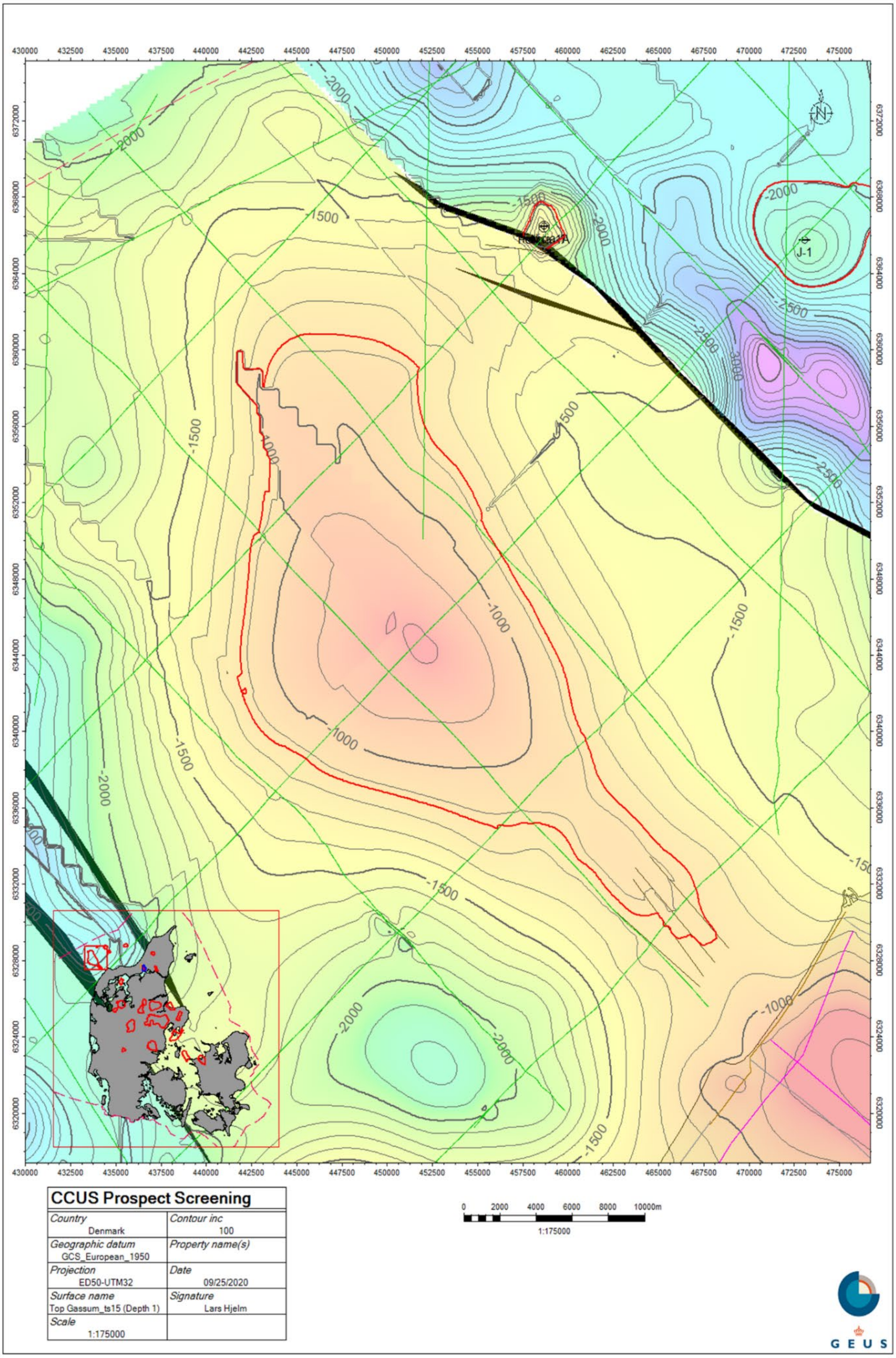
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain from current open grid. Spill towards SE and the Thisted N structure
Uncertainty	#_Line_Coverage	6-7 lines
Uncertainty	Apex def.	Fair control
Uncertainty	Top_Seal thickness	250 ms
Mapped	Apex depth (TVDSS, m)	-788
Mapped	Spill point depth (TVDSS, m)	-1130
Inferred	Structural relief (m)	342
Assumption	Permeability (Liquid, mD)	173
Assumption	Pressure (MPa)	11,1
Assumption	Temperature (>x, C)	40

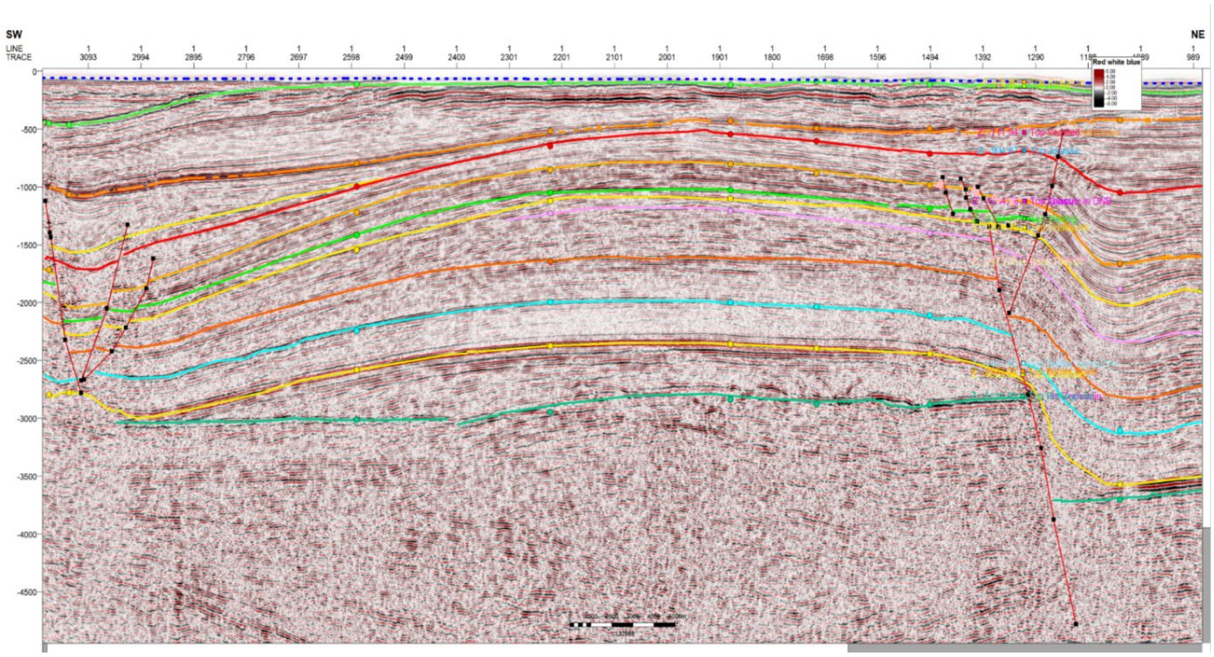
Volume Assumptions		Min.	Mode	Max.
Assumption	Area	181,75	363,5	472,55
Assumption	Geometric corr. Factor	0,55	0,64	0,8
Assumption	Gross Thickness (m)	200	250	300
Assumption	Net/Gross (%)	0,32	0,4	0,48
Assumption	Porosity (%)	0,16	0,2	0,35
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO_2 Density, kg/m^3	550	687	720

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	3,477	4,860	6,703	**5,006**
Calculation	Buoyant eff. storage volume (Km^3)	1,389	1,943	2,681	**2,002**
Calculation	Buoyant storage capacity (Mt)	923,3	1302,3	1804,1	**1341,0**



General geological setting	The structure is situated in the NW part of the Danish Basin bordering the Sorgenfrei-Tornquist zone. The reservoir has been defined at the level of the Gassum Formation. The formation of the elongated dome shaped structure is caused by post depositional halokenesis and formation of a underling salt pillow dynamics
Well database and seismic survey	The seal and reservoir are penetrated by the nearby Thisted, Felicia 1a and J-1 wells although seismic wells ties are not good. The seismic data include only few lines crossing the structure (see structure map). The lack of new high-quality seismic data increases the uncertainties in the interpretation of the storage site architecture and therefore also the capacity estimations and definition of the storage complex is uncertain. An important uncertainty is mapping of the overburden as the Chalk Gr and shallower section are very difficult to constrain, and large uncertainty percolate into depth conversion and further efforts are needed here (see artifacts in structure map)
Storage quality	Sandstones of the Gassum Formation is expected to constitute the primary reservoir unit in the Hanstholm structure with an expected porosity in 20% range. Permeability is estimated to c. 50-100 mD (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir in approx. 800 m below msl. with current depth conversion model (very uncertain) and a gross thickness of c. 250 m is expected with net/gross value of c. 0.40 which leads to a net sand thickness of c. 100 m. It is expected that the reservoir could be compartmentalised by layers of heteroliths and claystones and perhaps minor faults within the structure.
Subsurface storage capacity	The closure is defined by an elongated domal structure with a total relief of c. 340 m. The last closing contour is at 1130 m depth with spill towards the south east and defines a large area of up to 364 km^2. The pressure and temperature are expected to follow the normal Danish gradients, but it is uncertain how the underlying salt affects temperature gradient here. These input values lead to an estimated maximum storage capacity of 1300 Mt CO_2 for the Hanstholm structure.
Caprock (Seal)	The marine mudstones of the Fjerritslev Formation are expected to constitute the seal. Minor faults are observed, but larger might be present.


CCUS Prospect Screening
Country
Denmark
Contour inc
100
Geographic datum
GCS_European_1950
Property name(s)
Projection
ED50-UTM32
Date
09/25/2020
Surface name
Top Gassum_ts15 (Depth 1)
Signature
Lars Hjelm
Scale
1:175000
0 2000 4000 6000 8000 10000m
1:175000
J-1
GEUS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-2000
-2500
-3000
-3500
-4000
-4500

Hanstholm structure (Skagerrak Fm)

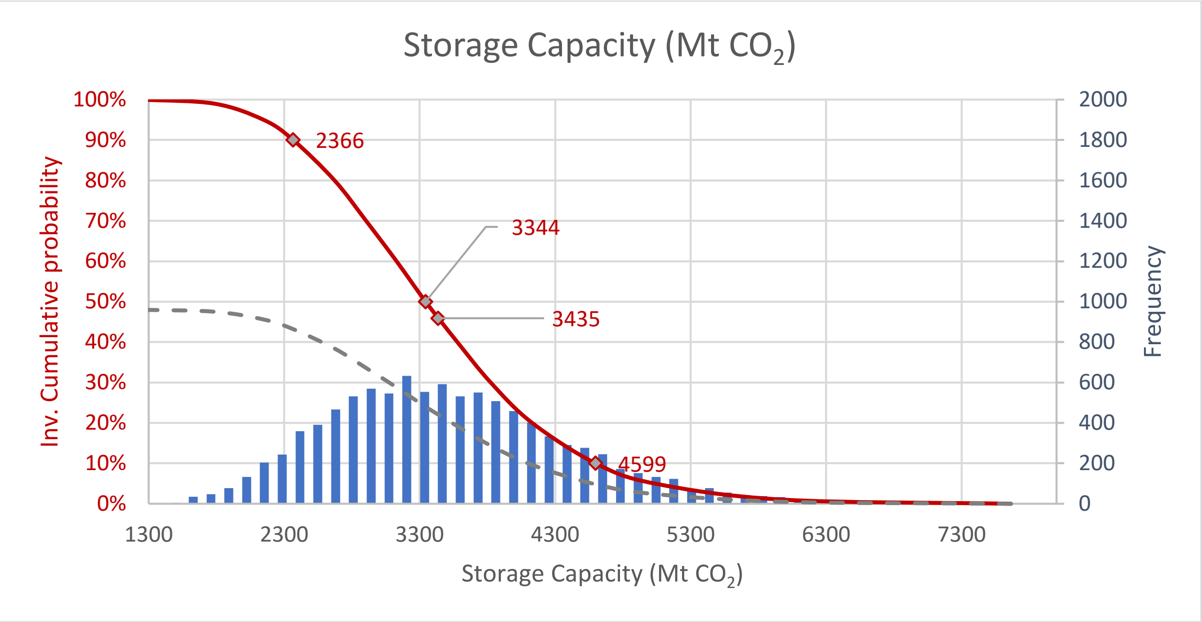
General	
Structure name	Hanstholm SF
Top Site Location	offshore
Area potential (km^2)	334,4
Reservoir stratigraphy	Triassic
Reservoir Formation	Skagerrak Fm
Reservoir lithology	Sandstone
Reservoir Facies	Fluvial
Top Seal Stratigraphy	Triassic
Top Seal Formation	Oddesund Fm
Top Seal lithology	Mudstone
Top seal integrity	Not yet investigated
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	4-way closure domal structure
Max. areal Offshore Fraction (%)	100%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	60%	Unknown seal capacity at structure. Some concern is the retention capacity the intra Triassic Oddesund and Vinding Fm between the Skagerrak and the Gassum Fm.	3D seismic, well core, pressure tests
Geological	Structure	100%	Compartmentalisation might occur!	3D seismic. More fault control needed
Geological	Reservoir	80%	Drilled by several wells (very thick)	Drilling, Seismic inversion
Engineering	Injection feasibility	100%		
Engineering	Seismicity	5%	Low	
Engineering	Groundwater contamination	2%	Low	
Cost	3D-seismic		Low	
Cost	Drilling		High	
Cost	Transport		Offshore	
QHSE	Environment		National and local authorities, Natura2000 area partly covers norther part of structure	
QHSE	Safety		Low	

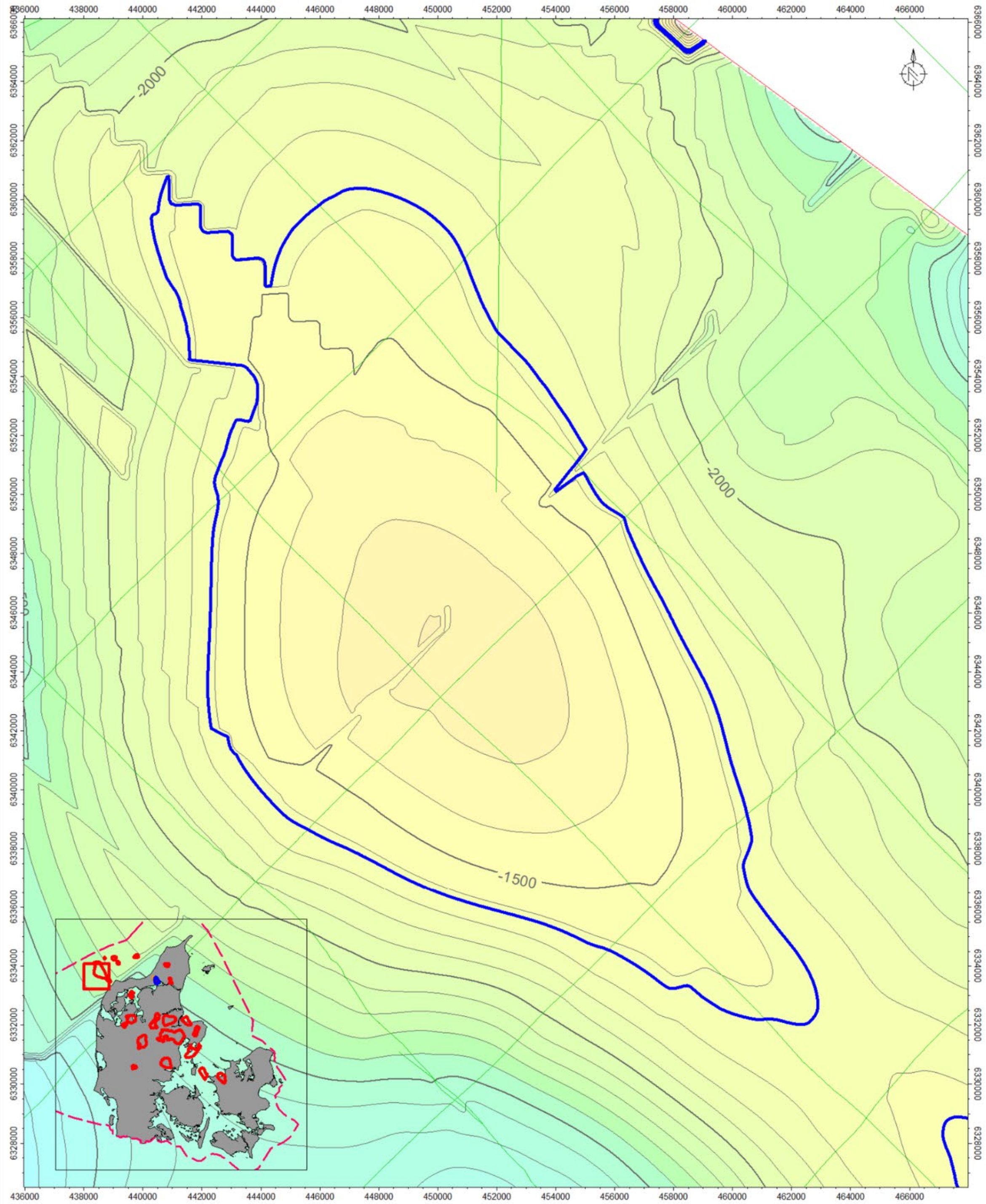
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain from current open grid. Spill towards SW and the Legin structure. Legin has a very shallow apex (-530m)
Uncertainty	#_Line_Coverage	5-6 lines
Uncertainty	Apex def.	From map algorithm - Fair control
Uncertainty	Top Seal thickness	250 ms
Mapped	Apex depth (TVDSS, m)	-1060
Mapped	Spill point depth (TVDSS, m)	-1625
Inferred	Structural relief (m)	565
Assumption	Permeability (Liquid, mD)	1000
Assumption	Pressure (MPa)	15,9
Assumption	Temperature (>x, C)	35

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	167,2	334,4	434,72
Assumption	Geometric corr. Factor	0,35	0,42	0,7
Assumption	Gross Thickness (m)	597,6	747	896,4
Assumption	Net/Gross (%)	0,416	0,52	0,676
Assumption	Porosity (%)	0,14	0,2	0,24
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO2 Density, kg/m^3	700	750	830

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	7,901	11,166	15,433	**11,471**
Calculation	Buoyant eff. storage volume (Km^3)	3,160	4,466	6,174	**4,588**
Calculation	Buoyant storage capacity (Mt)	2383,9	3373,3	4676,1	**3463,5**



General geological setting	The structure is situated in the northern most part of the Danish Basin bordering the Sorgenfrei-Tornquist fault zone reservoir level and has been defined at the Skagerrak Fm level of the Upper Triassic. The formation of the almost circular dome shaped structure is caused by post depositional halokenesis and formation of an underling salt pillow uplift.
Well database and seismic survey	The seal and reservoir are penetrated by the Thisted Wells. The seismic data include an only few lines crossing the structure considering the size (see structure map). The data is of fair quality, but depth conversion is made difficult due to difficult seismic well tie and difficult Chalk Gr interpretation (see map jacket contours cause by inconsistencies. Purposely left like this as further work is needed). The interpretation of the storage site architecture and therefore also the capacity estimations and definition of the storage complex is uncertain.
Storage quality	Sandstones of the Skagerrak Formation is expected to constitute the reservoir unit in the Hanstholm SF structure at Skagerrak level with an expected porosity in low end around 20%. Permeability is estimated to c. 50-100 mD (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir in approx. 1060 m below msl. and a gross thickness of >700 m is expected with net/gross value of 0.5 which leads to a net sand thickness of 300-400 m. It is expected that the reservoir could be compartmentalised by layers of heteroliths and claystones and crestal faulting.
Subsurface storage capacity	The closure is defined by a domal structure with a total relief of c. 500 m. The last closing contour is at 1625 m depth with spill towards the south east and defines an area of more than 330 km^2. The pressure is expected to be hydrostatic, but temperature could be very cold at the structure. These input values lead to an estimated storage capacity of 3450 Mt CO_2 for the very large structure.
Caprock (Seal)	The Oddesund and Vinding Fm are estimated to constitute c. 300-400 m thick seal in the Thisted wells. Minor faults are observed, but larger might be present.

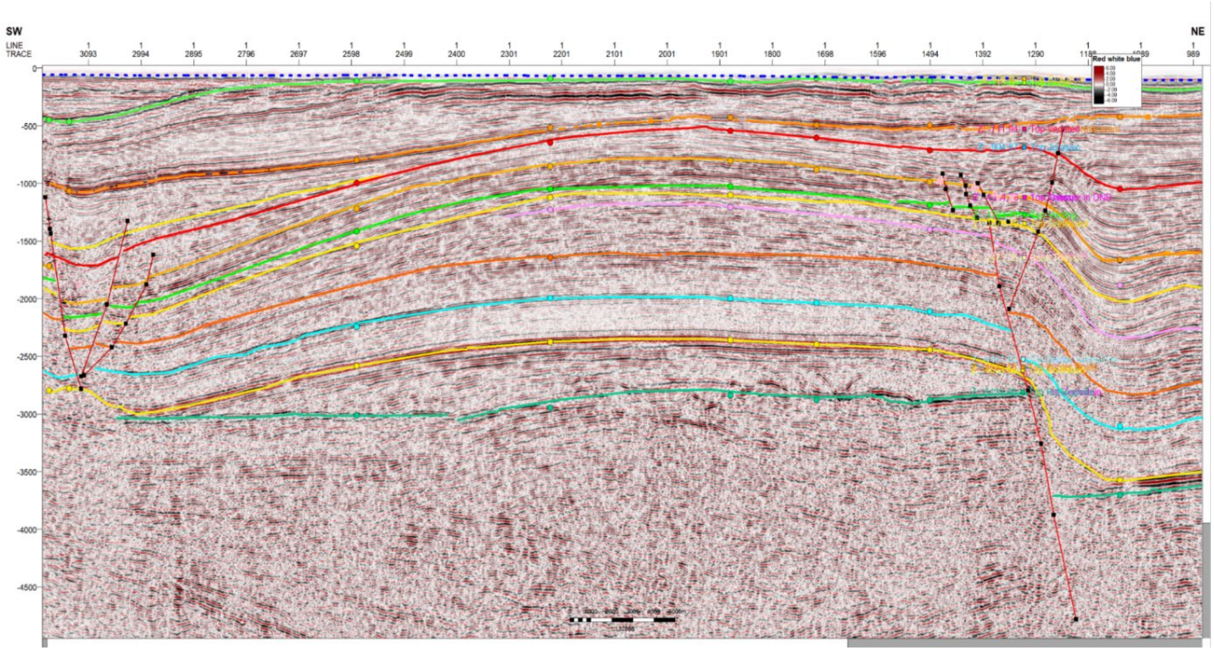


CCUS Prospect Screening	
Country Denmark	*Contour inc* 100
Geographic datum GCS_European_1950	*Property name(s)*
Projection ED50-UTM32	*Date* 10/22/2020
Surface name top Skagerak_lh (Depth 2: Z > Surface(x,y))	*Signature* Lars Hjelm
Scale 1:120000	

0 1000 2000 3000 4000 5000m

1:120000

GEUS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Thisted Structure

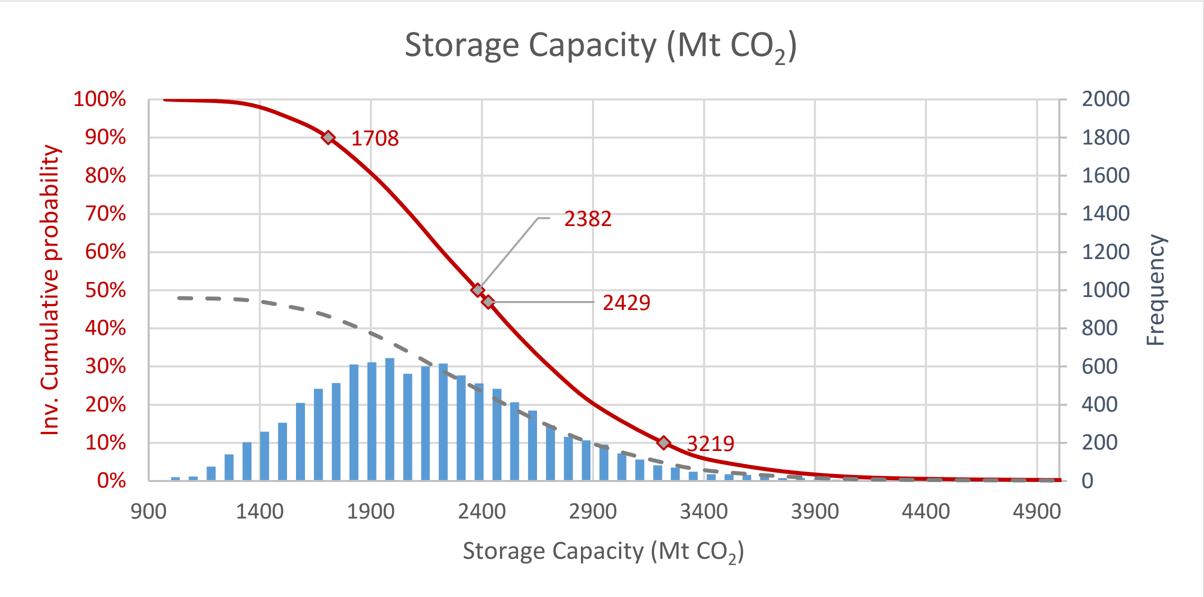
General	
Structure name	Thisted N
Top Site Location	Onshore
Area potential (km^2)	231
Reservoir stratigraphy	Triassic
Reservoir Formation	Skagerrak Fm
Reservoir lithology	Sandstone
Reservoir Facies	Fluvial
Top Seal Stratigraphy	Jurassic
Top Seal Formation	Fjerritslev
Top Seal lithology	Mudstone
Top seal integrity	Not yet investigated
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	4-way closure domal structure
Max. areal Offshore Fraction (%)	7%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	60%	Unknown capacity at structure. Some concern is the retention capacity the intra Triassic Oddesund and Vinding Fm between the Skagerrak and the Gassum Fm. Leakage to Gassum Fm will potentially cause CO_2 to fall out of Supercritical phase	3D seismic, pressure tests
Geological	Structure	100%	Compartmentalisation might occur!	3D seismic, more fault control needed
Geological	Reservoir	100%	Drilled by several wells (very thick)	Drilling, Seismic inversion
Engineering	Injection feasibility	60%	Shallow and low temp - Close to CO_2 not being in super critical phase	Temperature modelling, refine depth conversion
Engineering	Seismicity	2%	Low	
Engineering	Groundwater contamination	2%	Low	
Cost	3D-seismic		Low	
Cost	Drilling		High	
Cost	Transport		Offshore	
QHSE	Environment		National and local authorities,	
QHSE	Safety		Low	

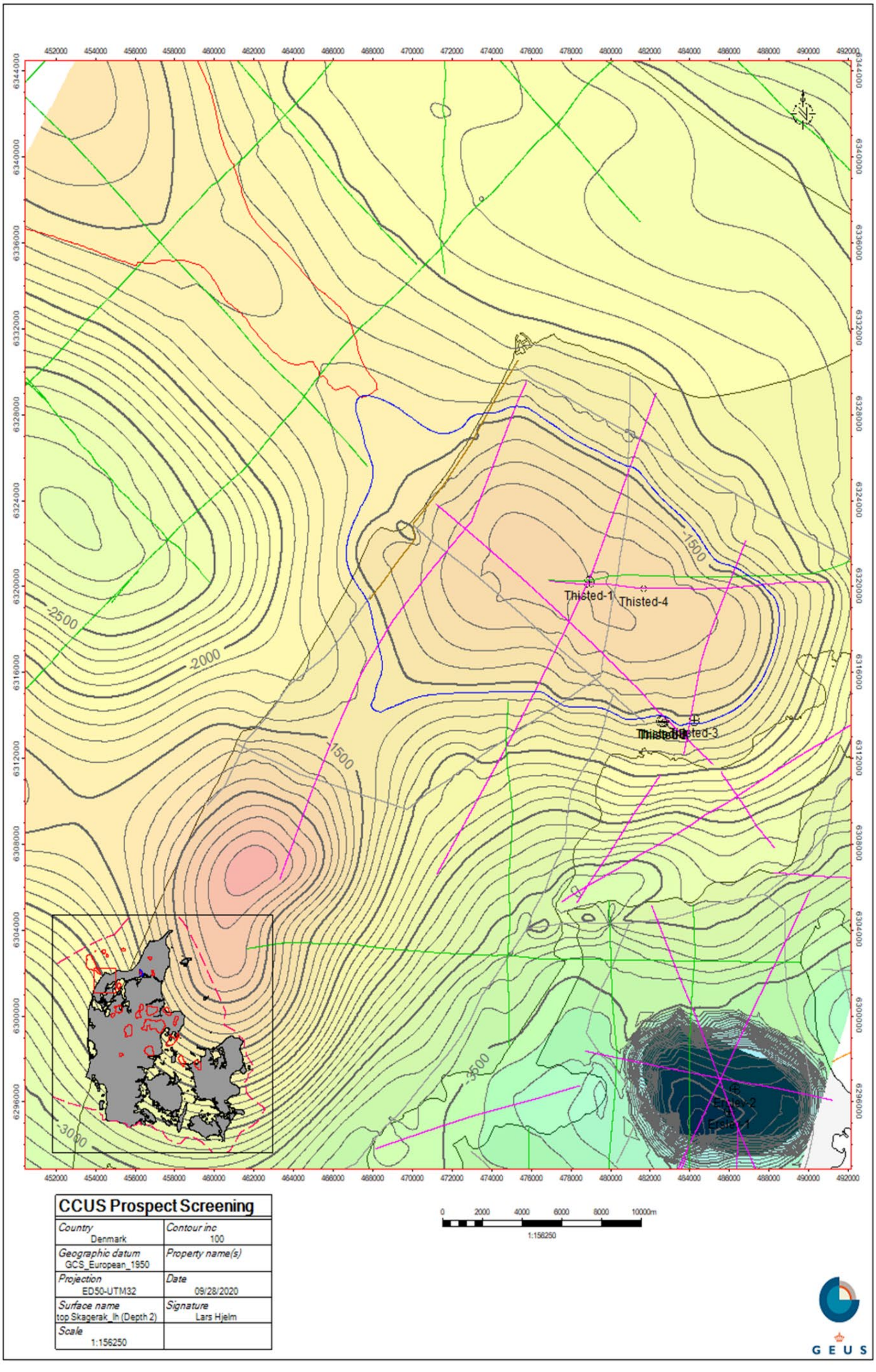
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain from current open grid. Spill towards SW and the Thisted S structure. Thisted S (previous Legin) has a very shallow apex (-530m)
Uncertainty	#_Line_Coverage	5-6 lines
Uncertainty	Apex def.	From map algorithm - Fair control
Uncertainty	Top_Seal thickness	250 ms
Mapped	Apex depth (TVDSS, m)	-1060
Mapped	Spill point depth (TVDSS, m)	-1550
Inferred	Structural relief (m)	490
Assumption	Permeability (Liquid, mD)	500?
Assumption	Pressure (MPa)	15,2
Assumption	Temperature (>x, C)	35

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	115,5	231	300,3
Assumption	Geometric corr. Factor	0,4	0,42	0,7
Assumption	Gross Thickness (m)	597,6	747	896,4
Assumption	Net/Gross (%)	0,416	0,52	0,676
Assumption	Porosity (%)	0,14	0,2	0,24
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO2 Density, kg/m^3	700	750	810

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	5,689	7,872	10,620	**8,034**
Calculation	Buoyant eff. storage volume (Km^3)	2,275	3,149	4,248	**3,214**
Calculation	Buoyant storage capacity (Mt)	1705,4	2360,7	3198,7	**2415,3**



General geological setting	The structure is situated in the northern most part of the Danish Basin bordering the Sorgenfrei-Tornquist fault zone Reservoir level and has been defined at the Skagerrak Fm level of the Upper Triassic. The formation of the almost circular dome shaped structure is caused by post depositional halokenesis and formation of an underling salt pillow uplift.
Well database and seismic survey	The seal and reservoir are penetrated by the Thisted Wells. The seismic data include an only few lines crossing the structure (see structure map). The lack of new high-quality seismic data increases the uncertainties in the interpretation of the storage site architecture and therefore also the capacity estimations and definition of the storage complex is uncertain.
Storage quality	Sandstones of the Skagerrak Formation is expected to constitute the reservoir unit in the Thisted N structure with an expected porosity in low end around 20%. Permeability is estimated to c. 50-100 mD (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir in approx. 1060 m below msl. and a gross thickness of >700 m is expected with net/gross value of 0.5 which leads to a net sand thickness of 300-400 m. It is expected that the reservoir could be compartmentalised by layers of heteroliths and claystones and crestal faulting.
Subsurface storage capacity	The closure is defined by a domal structure with a total relief of c. 500 m. The last closing contour is at 1550 m depth with spill towards the south west and defines an area of up to 230 km^2. The pressure is expected to be hydrostatic, but temperature could be very cold because of the underlying salt. These input values lead to an estimated storage capacity of 2425 Mt CO2 for the Thisted N structure.
Caprock (Seal)	The Oddesund and Vinding Fm are estimated to constitute c. 300-400 m thick seal in the Thisted wells. Minor faults are observed, but larger might be present.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Contour inc
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Projection
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Date
09/28/2020
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Signature
Lars Hjelm
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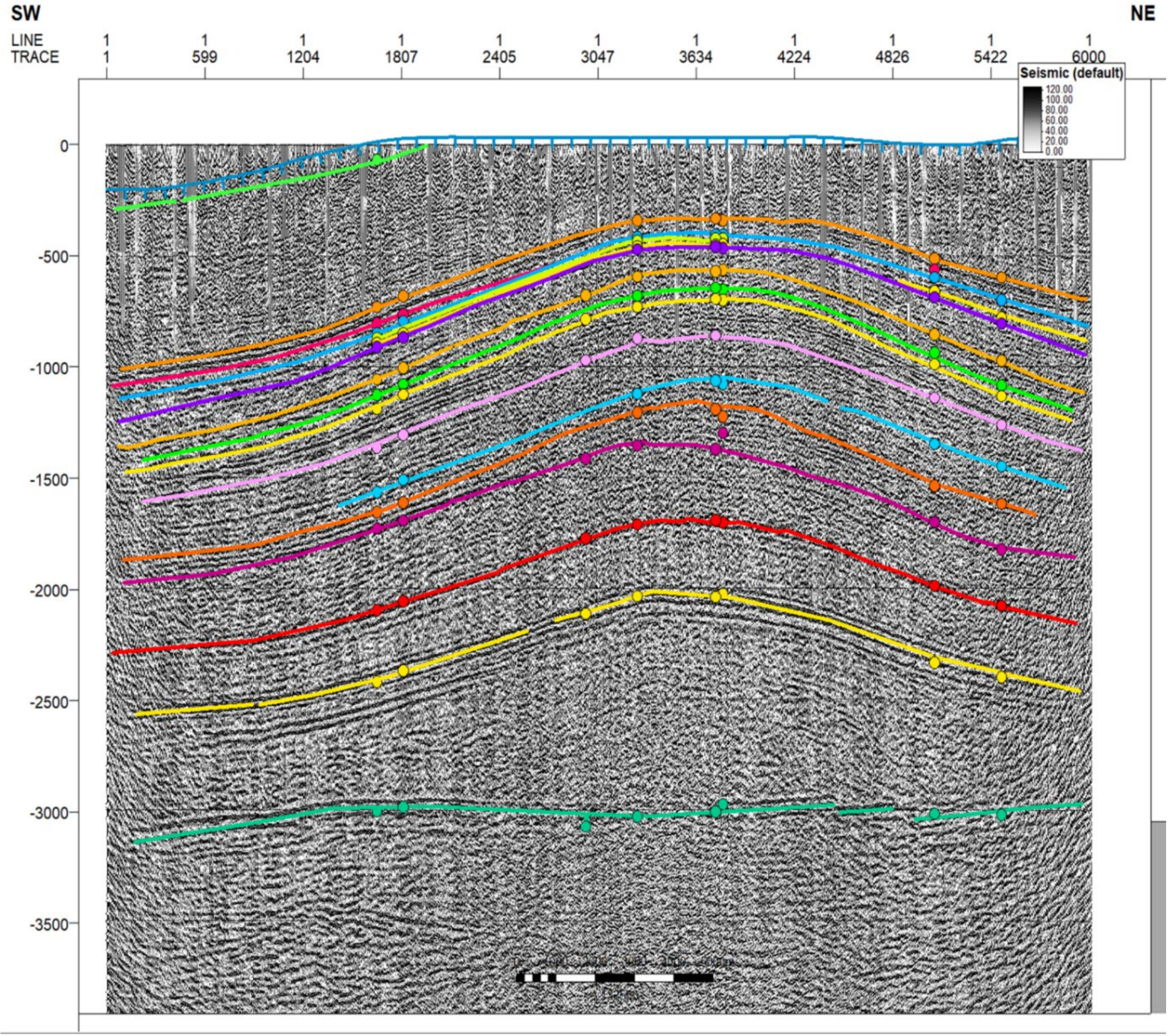
GEUS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80.00
60.00
40.00
20.00
0.00
0
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-1000
-1500
-2000
-2500
-3000
-3500

Legin structure

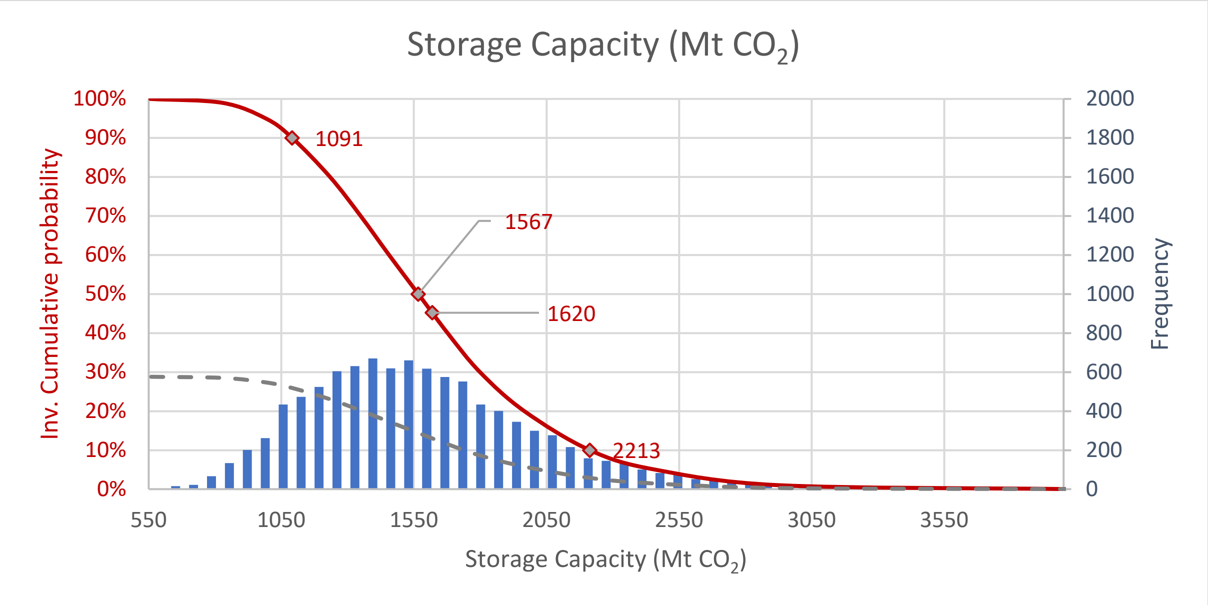
General	
Structure name	Legin SF
Top Site Location	Onshore
Area potential (km^2)	224,6
Reservoir stratigraphy	Triassic
Reservoir Formation	Skagerrak Fm
Reservoir lithology	Sandstone
Reservoir Facies	Fluvial
Top Seal Stratigraphy	Triassic
Top Seal Formation	Oddesund Fm
Top Seal lithology	Mudstone
Top seal integrity	Not yet investigated
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	Unknown, perhaps a 4-way closure domal structure (perhaps truncated)
Max. areal Offshore Fraction (%)	50%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	60%	Unknown capacity at structure. Some concern is the retention capacity the intra Triassic Oddesund and Vinding Fm between the Skagerrak and the Gassum Fm. Leakage to Gassum Fm will cause CO_2 to fall out of Supercritical phase	3D seismic, pressure tests
Geological	Structure	60%	Not seen on seismic, structure might be pierced by salt diapir. Apex depth unknown (very shallow)	More 2D lines for structural definition, 3D seismic.
Geological	Reservoir	80%	Drilled by several wells (very thick)	Drilling, Seismic inversion
Engineering	Injection feasibility	20%	Shallow - CO2 not believed to in super critical phase at 5 mpa	Temperature modelling, refine depth conversion
Engineering	Seismicity	5%	Low	
Engineering	Groundwater contamination	2%	Low	
Cost	3D-seismic		Low	
Cost	Drilling		Medium	
Cost	Transport		Onshore	
QHSE	Environment		National and local authorities	
QHSE	Safety		Low	

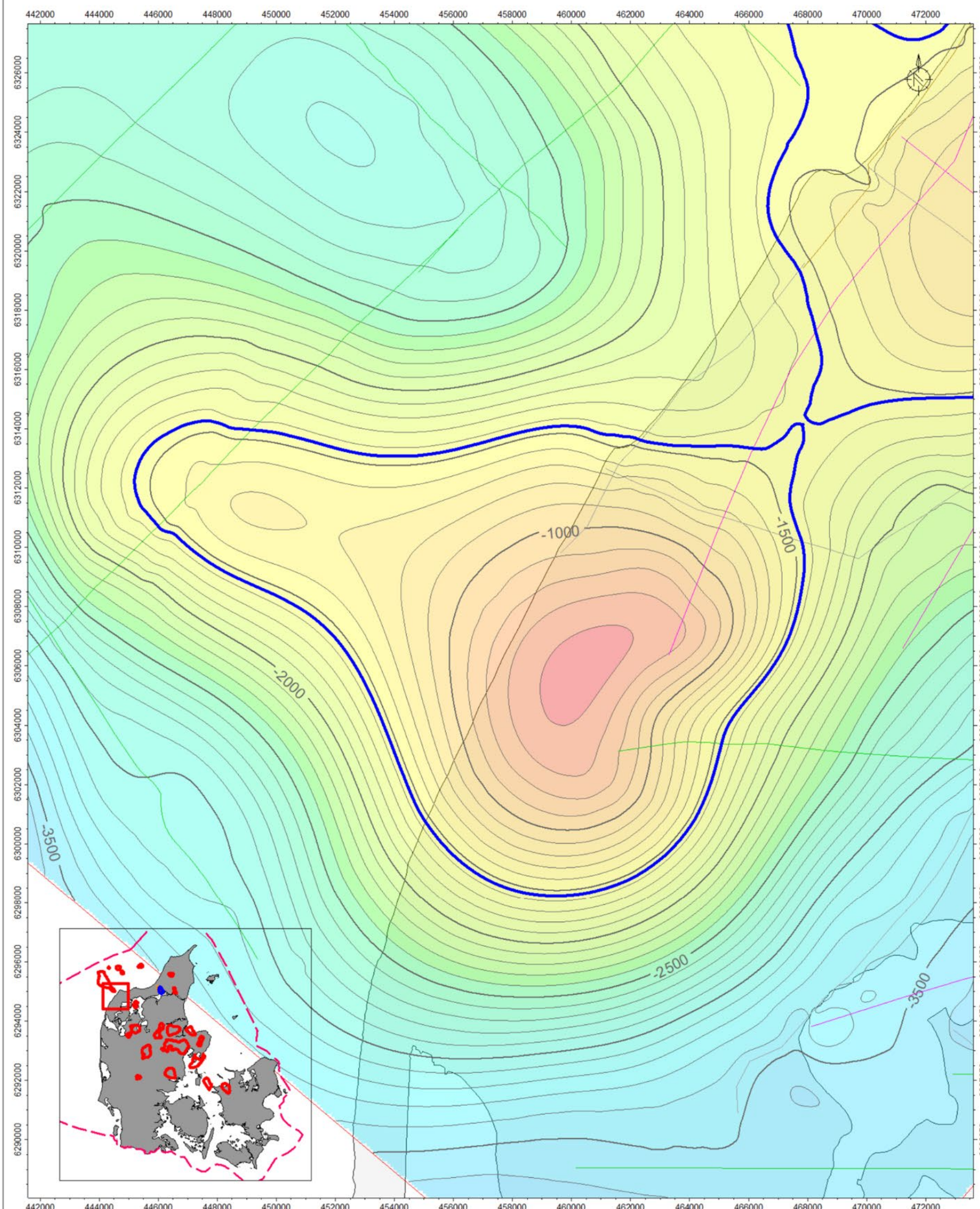
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain from current open grid. Spill towards N and the Thisted structure.
Uncertainty	#_Line_Coverage	2 half lines
Uncertainty	Apex def.	From map algorithm - poor control
Uncertainty	Top Seal thickness	250 ms
Mapped	Apex depth (TVDSS, m)	-550
Mapped	Spill point depth (TVDSS, m)	-1550
Inferred	Structural relief (m)	1000
Assumption	Permeability (Liquid, mD)	1000
Assumption	Pressure (MPa)	15,2
Assumption	Temperature (>x, C)	35

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	112,3	224,6	291,98
Assumption	Geometric corr. Factor	0,35	0,42	0,7
Assumption	Gross Thickness (m)	400	500	750
Assumption	Net/Gross (%)	0,416	0,52	0,676
Assumption	Porosity (%)	0,14	0,2	0,24
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO2 Density, kg/m^3	700	750	810

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	3,664	5,209	7,395	**5,395**
Calculation	Buoyant eff. storage volume (Km^3)	1,466	2,084	2,958	**2,158**
Calculation	Buoyant storage capacity (Mt)	1100,0	1565,4	2219,7	**1622,1**



General geological setting	The structure is situated in the northern most part of the Danish Basin close to the Sorgenfrei-Tornquist fault zone. Reservoir level and has been defined at the Skagerrak Fm level of the Upper Triassic. The formation of the structure is caused by post depositional halokenesis and formation of an underling salt pillow uplift.
Well database and seismic survey	The seal and reservoir are penetrated by the Thisted Wells. The seismic data include an only few lines on the crest of the structure (see structure map). The data is of poor to fair quality and no reach the apex of the structure. The interpretation of the storage site architecture and therefore also the capacity estimations and definition of the storage complex is uncertain.
Storage quality	Sandstones of the Skagerrak Formation is expected to constitute the reservoir unit in the Legin SF structure at Skagerrak level with an expected porosity in low end around 20%. Permeability is estimated to c. 1000 mD (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir in approx. 550 m below msl. and a gross thickness of >700 m is expected with net/gross value of 0.5 which leads to a net sand thickness of 300-400 m. It is expected that the reservoir could be compartmentalised by layers of heteroliths and claystones and crestal faulting.
Subsurface storage capacity	The closure is defined by a domal structure with a total relief of c. 1000 m. The last closing contour is at 1550 m depth with spill towards the North and defines an area of more than 220 km^2. The pressure is expected to be hydrostatic, and thus the pressure at the apex would be c. 5-6 MPa and not supporting supercritical phase for CO". These input values lead to an estimated storage capacity of 1600 Mt CO_2 for the very large structure given that storage could work successfully.
Caprock (Seal)	The Oddesund and Vinding Fm are estimated to constitute c. 300-400 m thick seal in the Thisted wells. It unknow whether faults at apex are present.



CCUS Prospect Screening	
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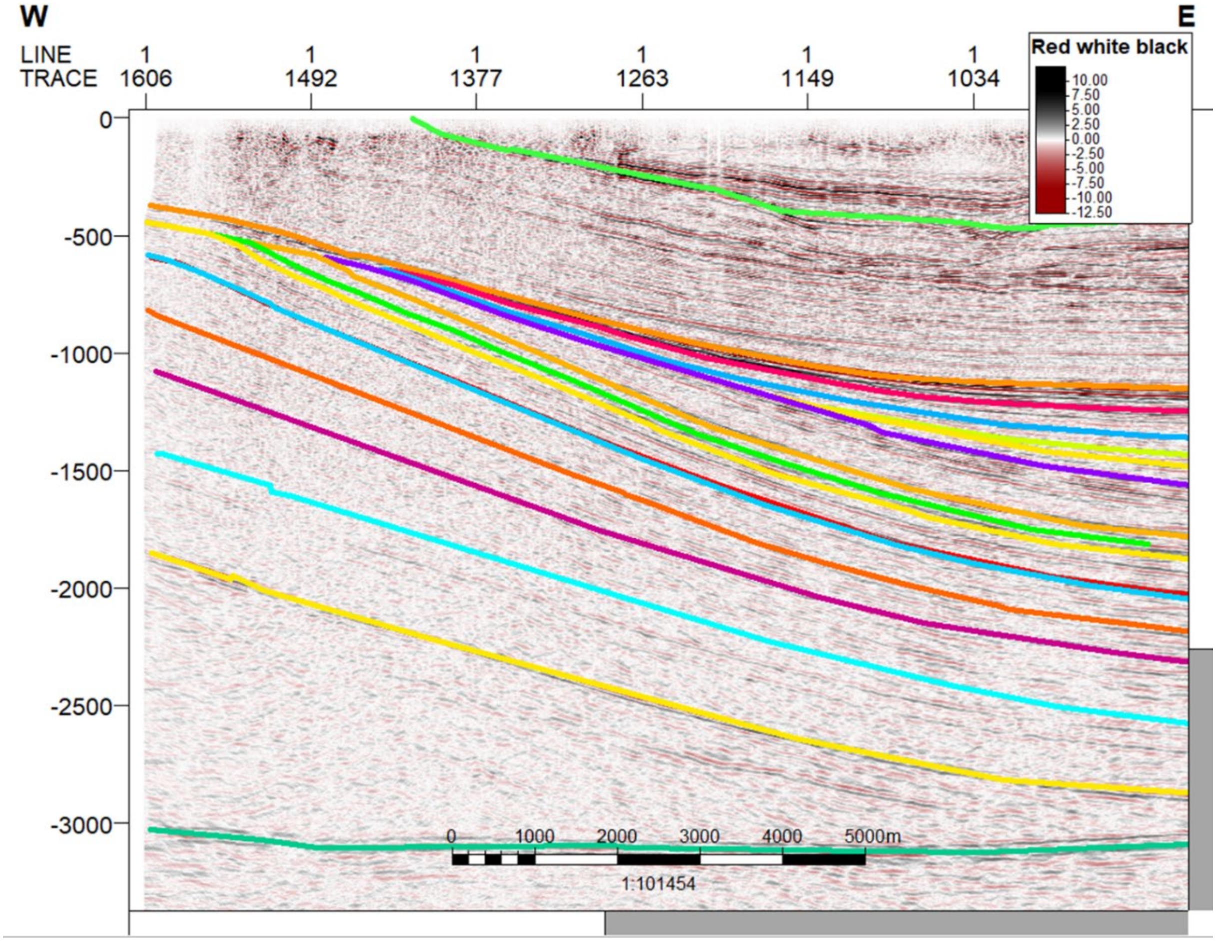
Projection ED50-UTM32	*Date* 10/22/2020
Surface name top Skagerak_lh (Depth 2: Z > Surface(x,y))	*Signature* Lars Hjelm
Scale 1:120000	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Vedsted Structure

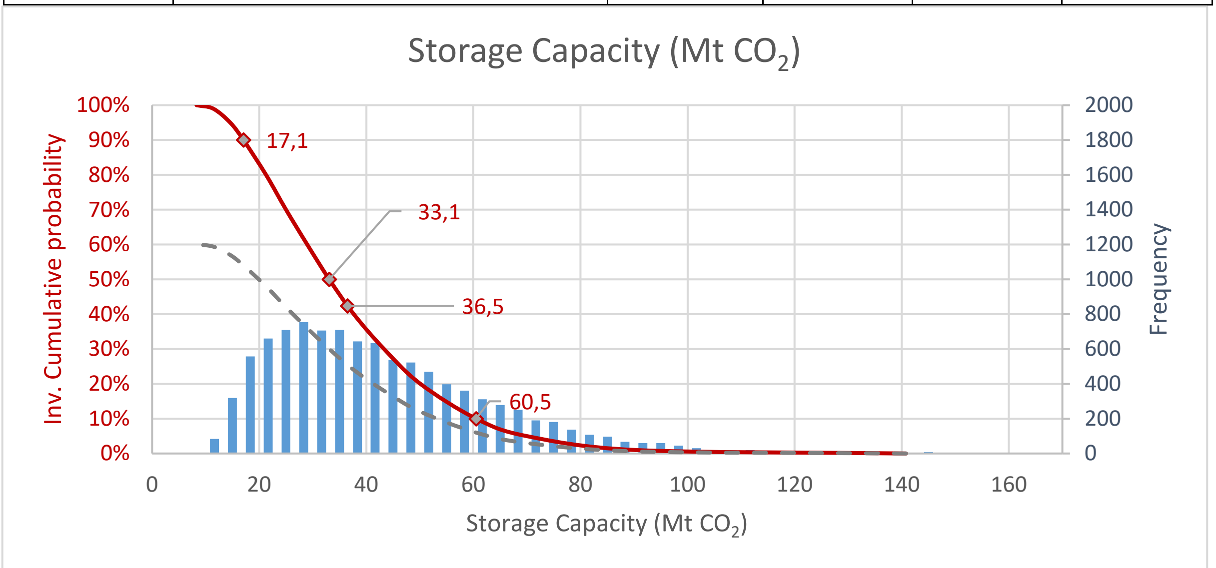
General	
Structure name	Vedsted
Top Site Location	Onshore
Area potential (km^2)	10,6
Reservoir stratigraphy	U. Triassic - L. Jurassic
Reservoir Formation	Gassum
Reservoir lithology	Sandstone
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev
Top Seal lithology	Mudstone
Top seal integrity	Several faults observed to cut the top seal and reservoir unit. Faults appear to reach surface. Trans-tensional regime on structure apex could have open fractures
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	Anticline associated wrench tectonics. 3 different trap geometries are possible depending on fault seal scenarios. 1. Open Faults defines a minor (10km^2) faulted 4-way closure resting within strike slip faults. 2. Given pressure communication across faults the structures extensive into a 37 km^2 large structure with structural spill towards NW. 3. Assuming completely sealing faults, the structure is spilling towards the N and extent into a 48km^2 area.
Offshore Fraction of max. areal (%)	0,1%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	60%	Unproven at structure. Several faults and a disturbed overburden are observed over structure. (unknown whether fault or fracture networks reach surface).	3D seismic, pressure tests
Geological	Structure	100%	Compartmentalisation might occur as several faults are expected in this trans-tensional/pressional setting	3D seismic
Geological	Reservoir	100%	Excellent, drilled. Compartments possible	
Engineering	Injection feasibility	100%		
Engineering	Seismicity	5%	Low	
Engineering	Groundwater contamination	2%	Low	
Cost	3D-seismic		High	
Cost	Drilling		Low	
Cost	Transport		Onshore	
QHSE	Environment		National and local authorities	
QHSE	Safety		Low	

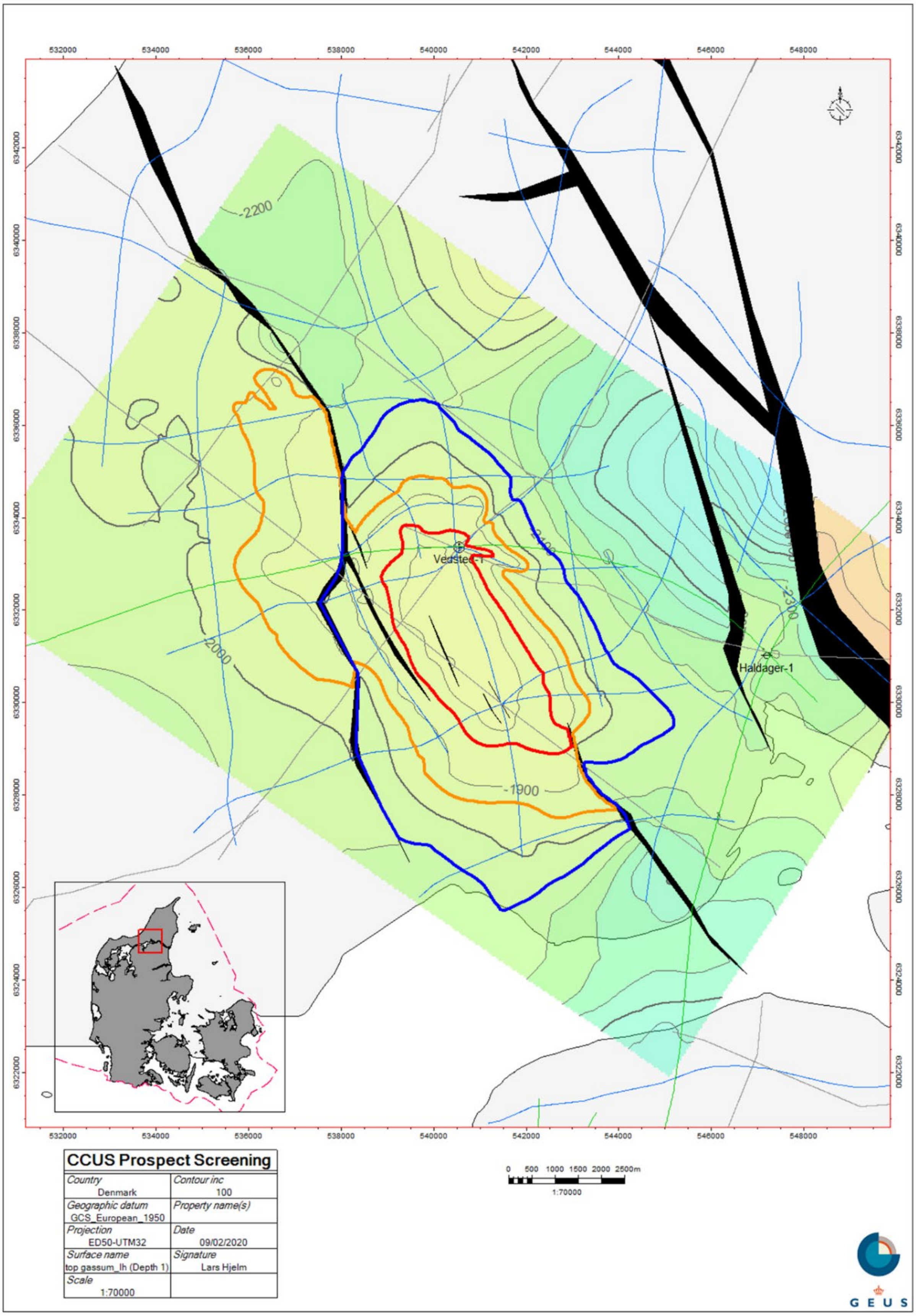
Volumetric			
Category	**Element**	**Comment**	**add. comm**
Uncertainty	Spill point def.	although relative fair seismic density, uncertain still resides in the mapping as three structural scenarios carries different spill definitions: 1. Open faults and 4way only scenario gives -1840m, 2. Cross fault pressure comm. scenario renders a -1940m spill and 3. Sealing faults scenario extents spill down to -2100m	
Uncertainty	#_Line_Coverage	11 lines	
Uncertainty	Apex def.	Close to offset well. Fair control	
Uncertainty	Top_Seal thickness	594m	
Mapped	Apex depth (TVDSS, m)	-1737	
Mapped	Spill point depth (TVDSS, m)	-1840	Structures involving fault renders spill at -1940m and -2100m.
Inferred	Structural relief(m)	103	
Assumption	Permeability (Liquid, mD)	173	
Assumption	Pressure (MPa)	18,1	
Assumption	Temperature (>x, C)	80	

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	5,28	10,56	48
Assumption	Geometric corr. Factor	0,4	0,42	0,8
Assumption	Gross Thickness (m)	156	195	234
Assumption	Net/Gross (%)	0,448	0,56	0,728
Assumption	Porosity (%)	0,16	0,2	0,24
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO_2 Density, kg/m^3	487,8	542	596,2

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	0,080	0,154	0,282	**0,170**
Calculation	Buoyant eff. storage volume (Km^3)	0,032	0,061	0,113	**0,068**
Calculation	Buoyant storage capacity (Mt)	17,2	33,3	61,6	**36,9**



General geological setting	The structure is situated in the southern flank of the Sorgenfrei-Tornquist zone and has been defined at the level of the Upper Triassic – Lower Jurassic Gassum Formation. The formation of the elongated anticline caused by trans-tension and subsequent trans-pression and later fault (and basin?) inversion.
Well database and seismic survey	The seal and reservoir are penetrated by the Vedsted-1 well situated close to the apex of the structure and form the primary input to the volumetric estimate. The seismic data include several lines crossing the structure (see structure map). Some good quality 2D seismic lines are available, but the structural definition of the structure is still challenged the lack of quality lines and the structural complexity of the potential site and therefore also the capacity estimations.
Storage quality	Sandstones of the Gassum Formation form the primary reservoir in the Vedsted structure with an expected porosity of 20 % and permeability estimated to be c. 50-100 mD (liquid permeability) on average. The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir in the Voldum-1 well is 1737 m below msl. In the Vedsted-1 well the Gassum Formation is c. 140 m thick and the net/gross value is 0.74 which leads to a net sand thickness of c. 100 m. It is expected that the reservoir could be compartmentalised by layers of heteroliths and claystones but also some a network of strike slip fault expected in tectonic setting.
Subsurface storage capacity	The min. closure is defined by an elongated 4-way anticline resting between two major strike-slip faults. The total min. relief is c. 100 m with the last closing contour at 1840 m depth. This form the assumption of the most likely structural setting. A potential upside to the storage capacity estimate involves an assumption that the faults are open for lateral flow only or completely sealing. these assumptions lead to deeper potential spill point that illustrated in the map. These input values lead to an estimated mean storage capacity of 39 Mt CO_2, but with at potential upside of up to potentially 100Mt CO_2 for the structure.
Caprock (Seal)	The marine mudstones of the Fjerritslev Formation are c. 600 m thick in the in Vedsted-1 well and form the primary seal of the aquifer, faults are seen penetrating the formation, but the thick mudstone unit may still seal



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Haldager-1
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CCUS Prospect Screening
Country
Denmark
Contour inc
100
Geographic datum
GCS_European_1950
Property name(s)
Projection
ED50-UTM32
Date
09/02/2020
Surface name
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Signature
Lars Hjelm
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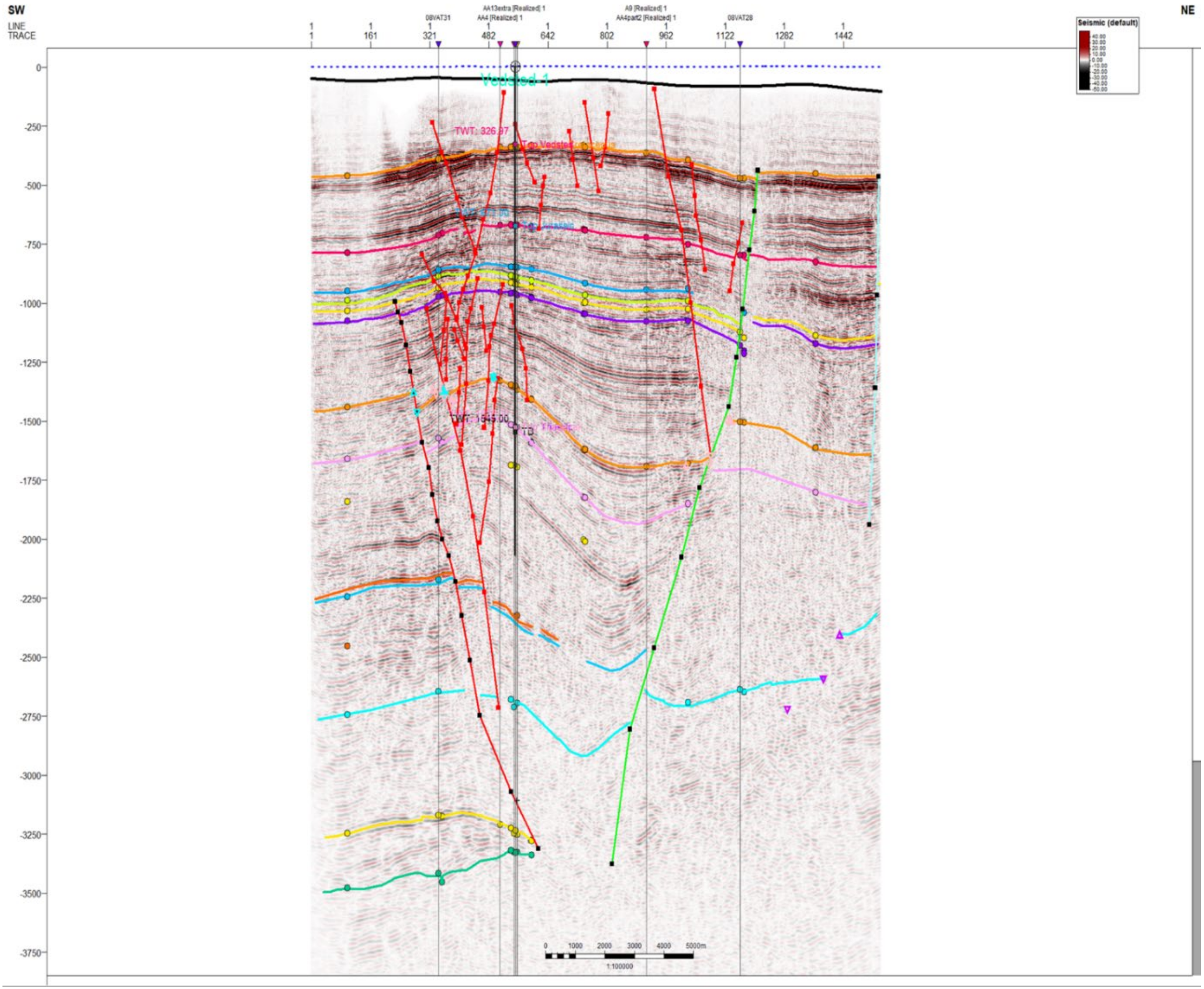
GEUS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Seismic (default)
Vedsted-1
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Skive structure

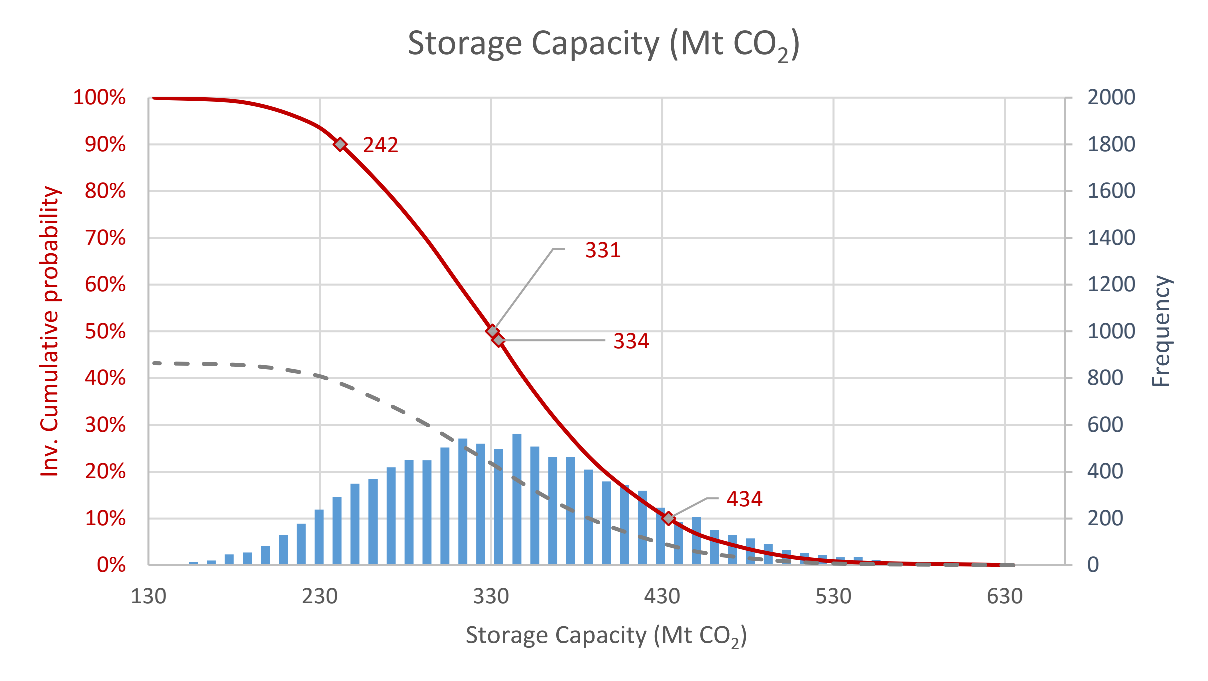
General	
Structure name	Skive
Top Site Location	Onshore
Area potential (km^2)	73,35
Reservoir stratigraphy	L. Triassic
Reservoir Formation	Bunter SS Fm
Reservoir lithology	Sandstone
Reservoir Facies	Arid, continental environment (playa facies)
Top Seal Stratigraphy	Triassic
Top Seal Formation	Ørslev Fm
Top Seal lithology	Mudstone
Top seal integrity	Indications of major collapse faults are observed. The dynamic haloki-netic rejuvenation could easily reactivate faulting
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	Trap geometry is created from det development of the Skive Salt pil-low/diapir?
Offshore Fraction of max. areal (%)	10%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	60%	Unproven at structure. Indication of several faults	3D seismic, pressure tests
Geological	Structure	80%	Apex not covered by seismic. Collapse feature potentially present	3D seismic
Geological	Reservoir	90%	Drilled by several wells	
Engineering	Injection feasi-bility	80%	Apex uncertain (current map indicates >800 m depth and questions whether supercritical phase is possible)?	3d seismic
Engineering	Seismicity	2%	Low	
Engineering	Groundwater contamination	2%	Low	
Cost	3D-seismic		High	
Cost	Drilling		Low	
Cost	Transport		Onshore	
QHSE	Environment		National and local authorities	
QHSE	Safety		Low	

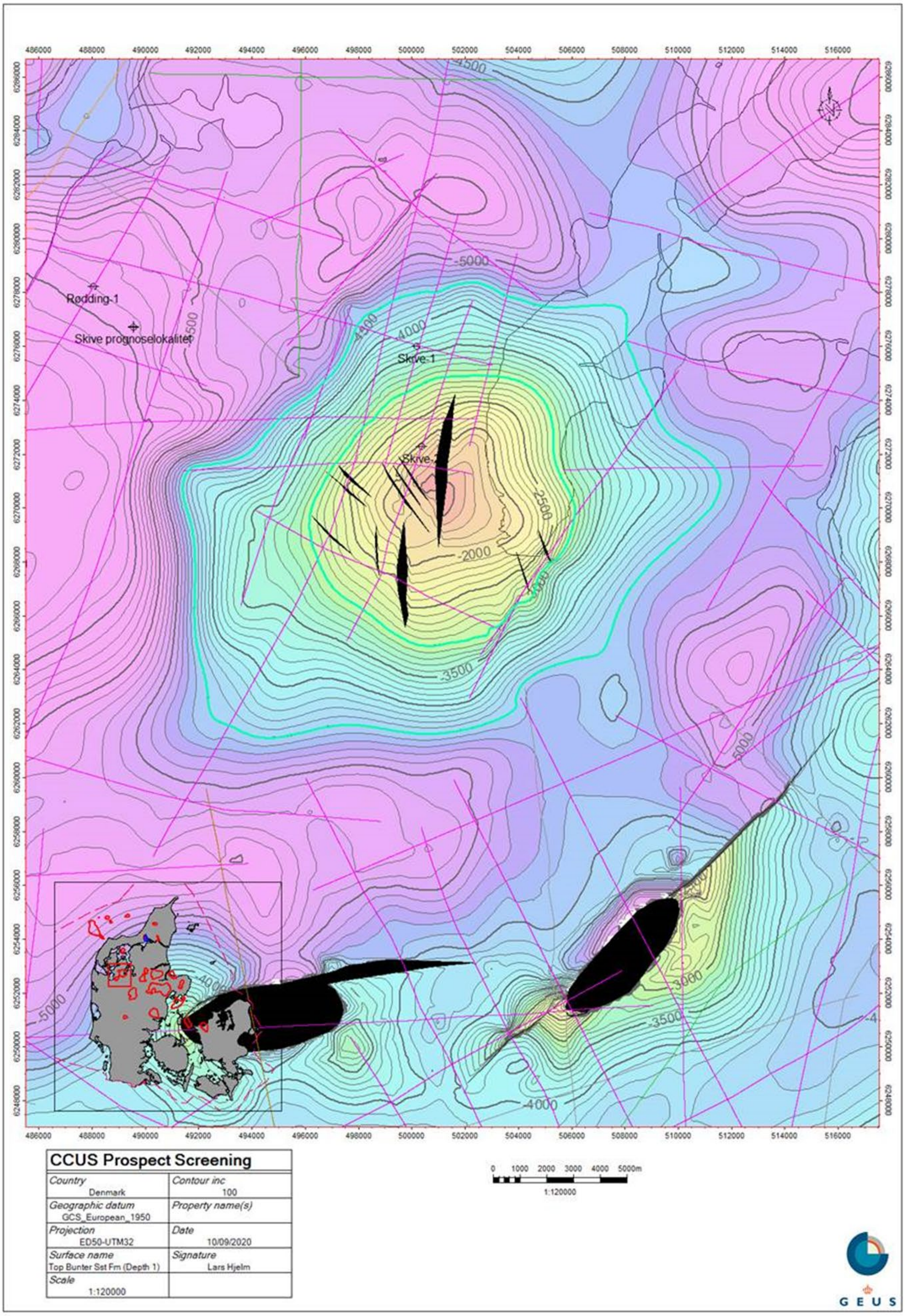
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Some uncertain still resides in the mapping and whether the structural spill towards the east is the shallowest spill point
Uncertainty	#_Line_Coverage	0.5 lines
Uncertainty	Apex def.	Drilled Fair control
Uncertainty	Top_Seal thickness	160-180 m
Mapped	Apex depth (TVDSS, m)	-1475
Mapped	Spill point depth (TVDSS, m)	-3000
Inferred	Structural relief (m)	1525
Assumption	Permeability (Liquid, mD)	18
Assumption	Pressure (MPa)	29,4
Assumption	Temperature (>x, C)	80

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	36,675	73,35	95,355
Assumption	Geometric corr. Factor	0,65	0,9	0,95
Assumption	Gross Thickness (m)	162,4	203	243,6
Assumption	Net/Gross (%)	0,592	0,74	0,9
Assumption	Porosity (%)	0,08	0,12	0,144
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO2 Density, kg/m^3	740	770	800

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	0,785	1,074	1,408	**1,088**
Calculation	Buoyant eff. storage volume (Km^3)	0,314	0,430	0,563	**0,435**
Calculation	Buoyant storage capacity (Mt)	241,680	330,447	433,997	**334,972**



General geological setting	The structure is situated in the northern part of the Danish German Basin, and has been defined at the level of the Lower Triassic Bunter SS Formation. The formation of the dome shaped structure is caused by post depositional halokenesis and formation of an underling salt pillow /diapir uplift.
Well database and seismic survey	The seal and reservoir are penetrated nearby wells. Only few 2D seismic delineated the structure but one line crosses the structure completely
Storage quality	Sandstones of the Bunter Formation is considered as the primary reservoir target in the Skive structure with an expected average porosity up to 12 % and permeability around 30 mD (liquid permeability). The permeability interpretation is uncertain. Depth to top reservoir in approximated to by c. 1475m below msl., and the Bunter Formation is believed to 200m thick on average across the structure with a net/gross value is 0.75 which leads to a net sand thickness of c. 150 m. It is expected that the reservoir could be compartmentalised by minor faults and/or divided into individual reservoir zones by heteroliths and claystones.
Subsurface storage capacity	The closure is defined by a semi-circular domal structure approximately with a potentially very large column of 2600 m. however the lower limit has been set to 3000m as it believed that permeability is small going deeper. The deepest contour is set at 3000 m depth and defines an area of approximately 75 km2. The temperature is expected to follow the Danish gradients (low end) with normal pressure gradient. These input values lead to an estimated maximum storage capacity of 334 Mt CO_2 for the Skive structure.
Caprock (Seal)	The 160-180m fine grained Ørslev Fm form the primary seal of the aquifer. Further investigation of the seals will be carried out on the available 3D survey



Rødding-1
Skive prognoselokalitet
Skive-1
Skive-2
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CCUS Prospect Screening
Country
Denmark
Contour inc
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Geographic datum
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Projection
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Date
10/09/2020
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Signature
Lars Hjelm
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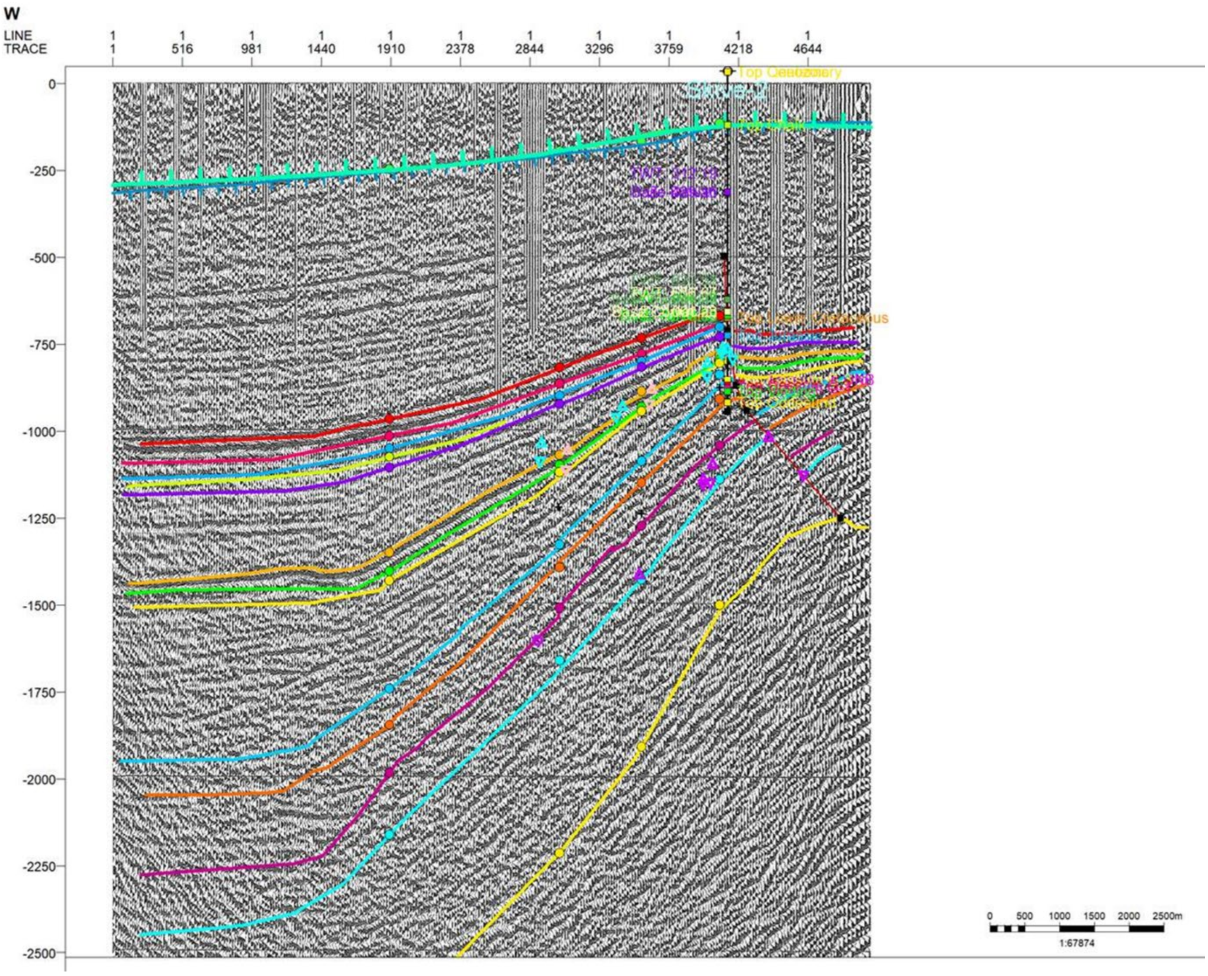
GEUS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Top Lower Cretaceous
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Gassum Structure

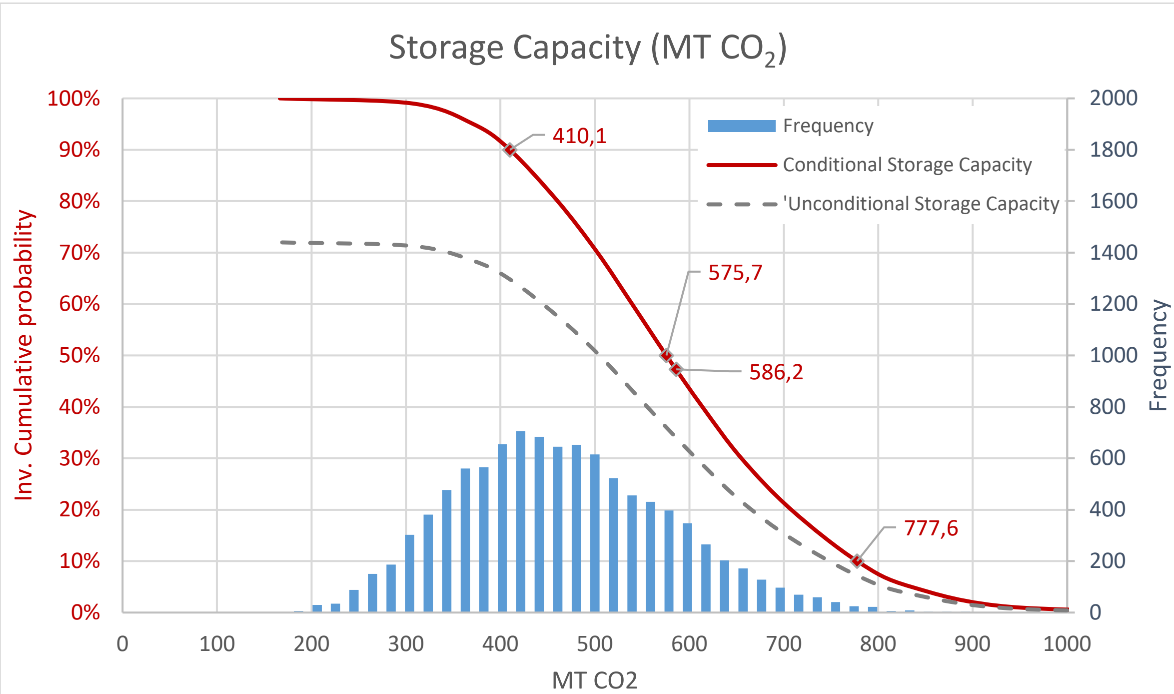
General	
Structure name	Gassum
Top Site Location	Onshore
Area potential (km^2)	233
Reservoir stratigraphy	U. Triassic - L. Jurassic
Reservoir Formation	Gassum
Reservoir lithology	Sandstones
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev
Top Seal lithology	Mudstone
Top seal integrity	Low fault intensity, extensional regime and low likelihood of fractures
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	4-way anticline above salt pillow. May spill into the Voldum structure at -2240m
Offshore Fraction of max. areal (%)	0%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	80%	Unproven across structure. Large faults (w. low offset) near apex and possible associated fracture systems should be considered	3D seismic may provide further knowledge, but a well and pressure tests are needed
Geological	Structure	100%	Collapse features observed on northern flank. Some compartmentalisation might occur! Spill point definition current very uncertain	3D seismic could better define structural setting and definition.
Geological	Reservoir	100%	Good knowledge from well. Believed to extent across most of structure	
Engineering	Injection feasibility	100%		
Engineering	Seismicity	Low		
Engineering	Groundwater contamination	Low		
Cost	3D-seismic	na	High	
Cost	Drilling	na	Low	
Cost	Transport	na	Onshore	
QHSE	Environment	na	National and local authorities	
QHSE	Safety	na	Low	

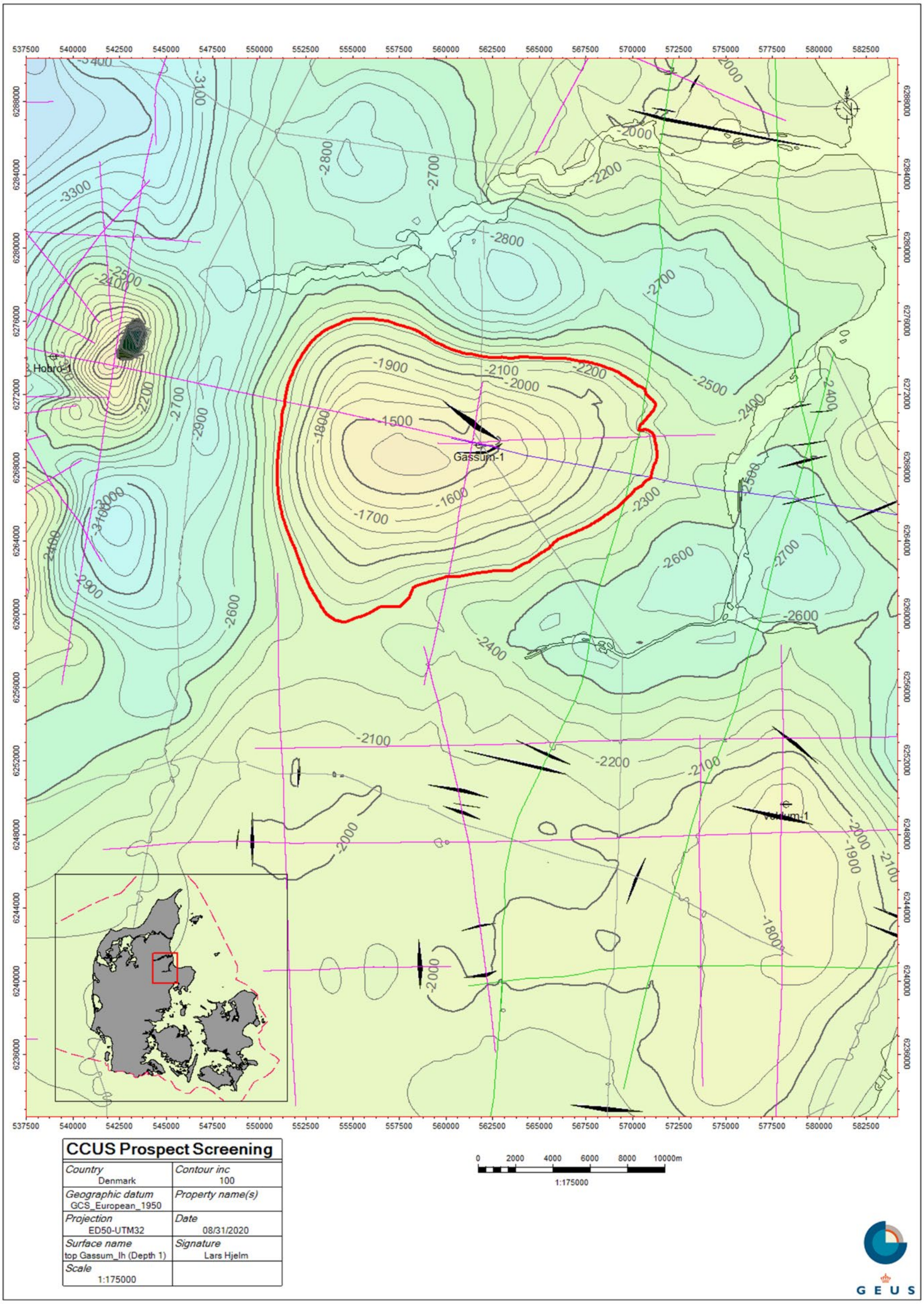
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain from gridding in very open Grid.
Uncertainty	#_Line_Coverage	no full lines. 6 half lines
Uncertainty	Apex def.	Offset from Well (uncertain)
Uncertainty	Top_Seal thickness	200 ms
Mapped	Apex depth (TVDSS, m)	-1364
Mapped	Spill point depth (TVDSS, m)	-2240
Inferred	Structural relief (m)	876
Assumption	Permeability (Liquid, mD)	461
Assumption	Pressure (MPa)	22,0
Assumption	Temperature (>x, C)	60

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	116,5	233	302,9
Assumption	Geometric corr. Factor	0,5	0,8	0,85
Assumption	Gross Thickness (m)	100	130	150
Assumption	Net/Gross (%)	0,27	0,37	0,45
Assumption	Porosity (%)	0,15	0,25	0,3
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	In-situ CO2 Density, kg/m^3	714,4	752	789,6

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	1,356	1,910	2,575	**1,943**
Calculation	Buoyant eff. storage volume (Km^3)	0,542	0,764	1,030	**0,777**
Calculation	Buoyant storage capacity (Mt CO_2)	407	574	774	**584**



General geological setting	The structure is situated in the central part of the Danish Basin and has been defined at the level of the Upper Triassic – Lower Jurassic Gassum Formation. The formation of the dome shaped structure is caused by post depositional halokenesis and formation of underling salt pillow uplift.
Well database and seismic survey	The seal and reservoir are penetrated by the Gassum-1 well situated close to the top point of the structure. Data for the Gassum structure are based on the three wells Gassum-1, Hobro-1 and Voldum-1. The seismic data include a few lines crossing the structure; SSL6267 from 1967, PRKL7374A from 1974 and DNJ8183D from 1983. The lack of new high-quality seismic data increases the uncertainties in the interpretation of the storage site architecture and therefore also the storage capacity estimations and definition of the storage complex is uncertain.
Storage quality	Sandstones of the Gassum Formation form the primary reservoir in the Gassum structure with an expected average porosity up to 25 %+ and permeability around 300 mD (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well 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 and the net/gross value is 0.32 which leads to a net sand thickness of 53 m. It is expected that the reservoir could be compartmentalised by faults and layers of heteroliths and claystones.
Subsurface storage capacity	The closure is defined by an almost circular domal structure approximately 800 m structural relief with steep flanks. The deepest closing contour is at -2240 m depth and defines an area of approximately 233 km^2. The spill point is situated towards the south. The pressure and temperature are expected to follow the normal Danish gradients although underlying salt could introduce higher heat gradients. These input values lead to an estimated maximum storage capacity of 443 Mt CO_2 for the Gassum structure.
Caprock (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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Contour inc
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Date
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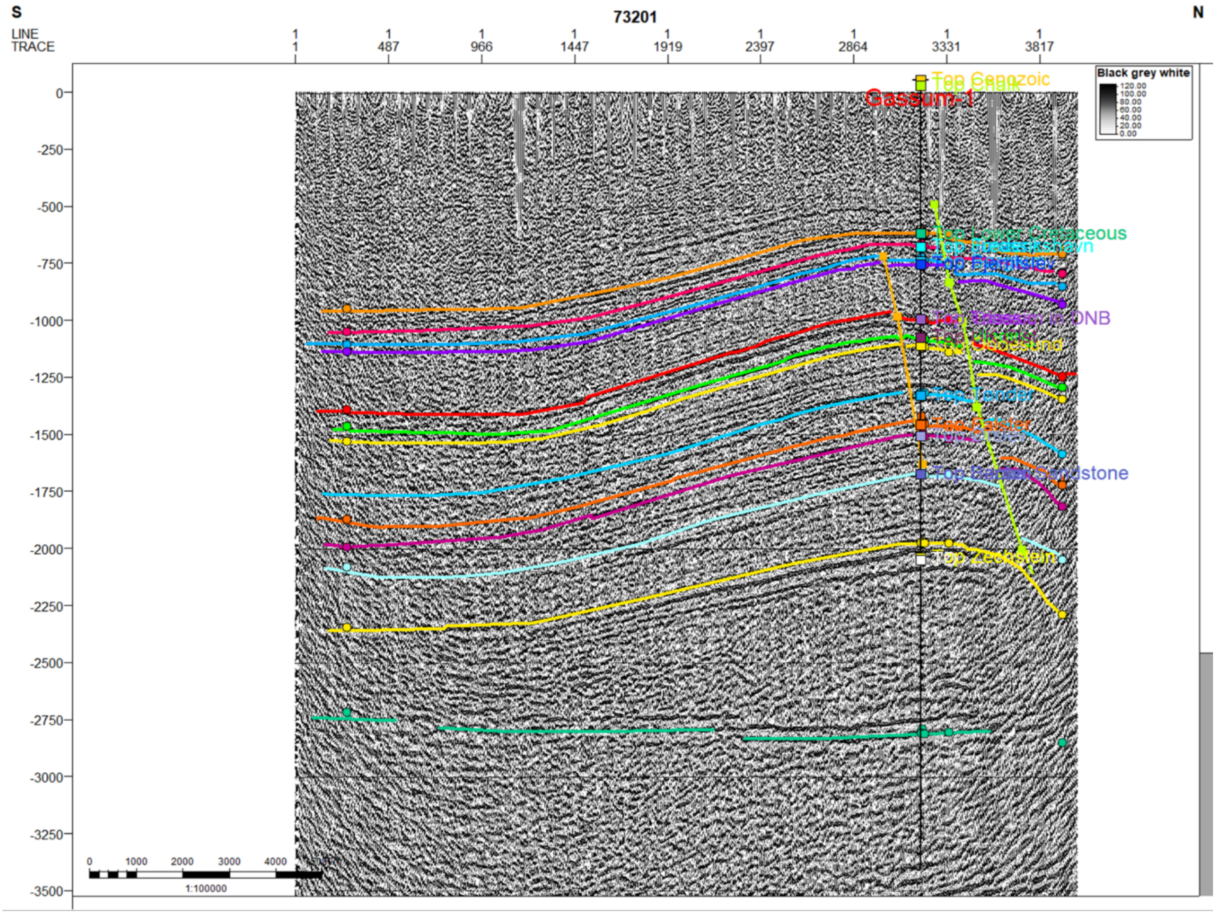
Voldum-1
GEUS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Gassum-1
Top Zechstein
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Voldum structure

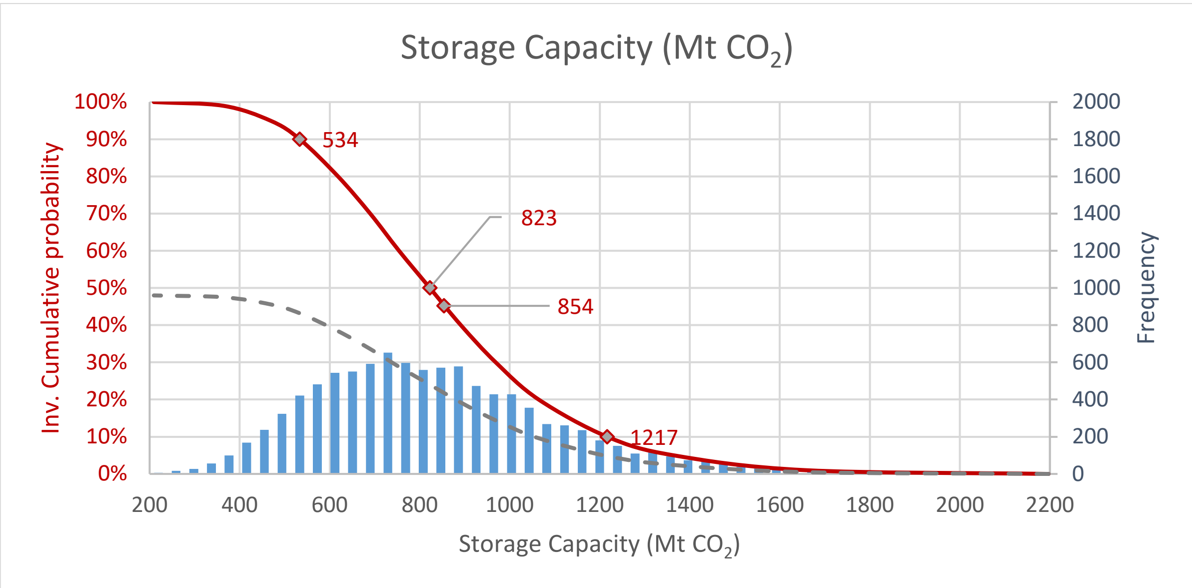
General	
Structure name	Voldum
Top Site Location	Onshore
Area potential (km^2)	560
Reservoir stratigraphy	U. Triassic - L. Jurassic
Reservoir Formation	Gassum
Reservoir lithology	Sandstones
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev Fm
Top Seal lithology	Mudstone
Top seal integrity	Low fault intensity, but faults are observed on structural crest. Extensional regime with an expected low likelihood of fractures
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	4-way anticline above salt pillow. May spill into the south at -2070m
Offshore Fraction of max. areal (%)	0%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	80%	Unproven across structure. Some faults (w. low offset) near apex and possible associated fracture systems should be considered	3D seismic may provide further knowledge, but a well and pressure tests are needed
Geological	Structure	100%	Normal faults penetrate the reservoir section and detached into the underlying salt. Some compartmentalisation might occur! Spill point definition currently very uncertain as the shallow overburden is difficult to map for depth conversion	3D seismic could better define structure setting and - definition.
Geological	Reservoir	60%	Good knowledge from well where the Gassum Fm show poor quality. The Fm may extent across most of structure and could have better quality	Extended flow tests needed
Engineering	Injection feasibility	80%	Poor reservoir	Reservoir performance needs to be invested further
Engineering	Seismicity	Low		
Engineering	Groundwater contamination	Low		
Cost	3D-seismic	na	High	
Cost	Drilling	na	Low	
Cost	Transport	na	Onshore	
QHSE	Environment	na	National and local authorities	
QHSE	Safety	na	Low	

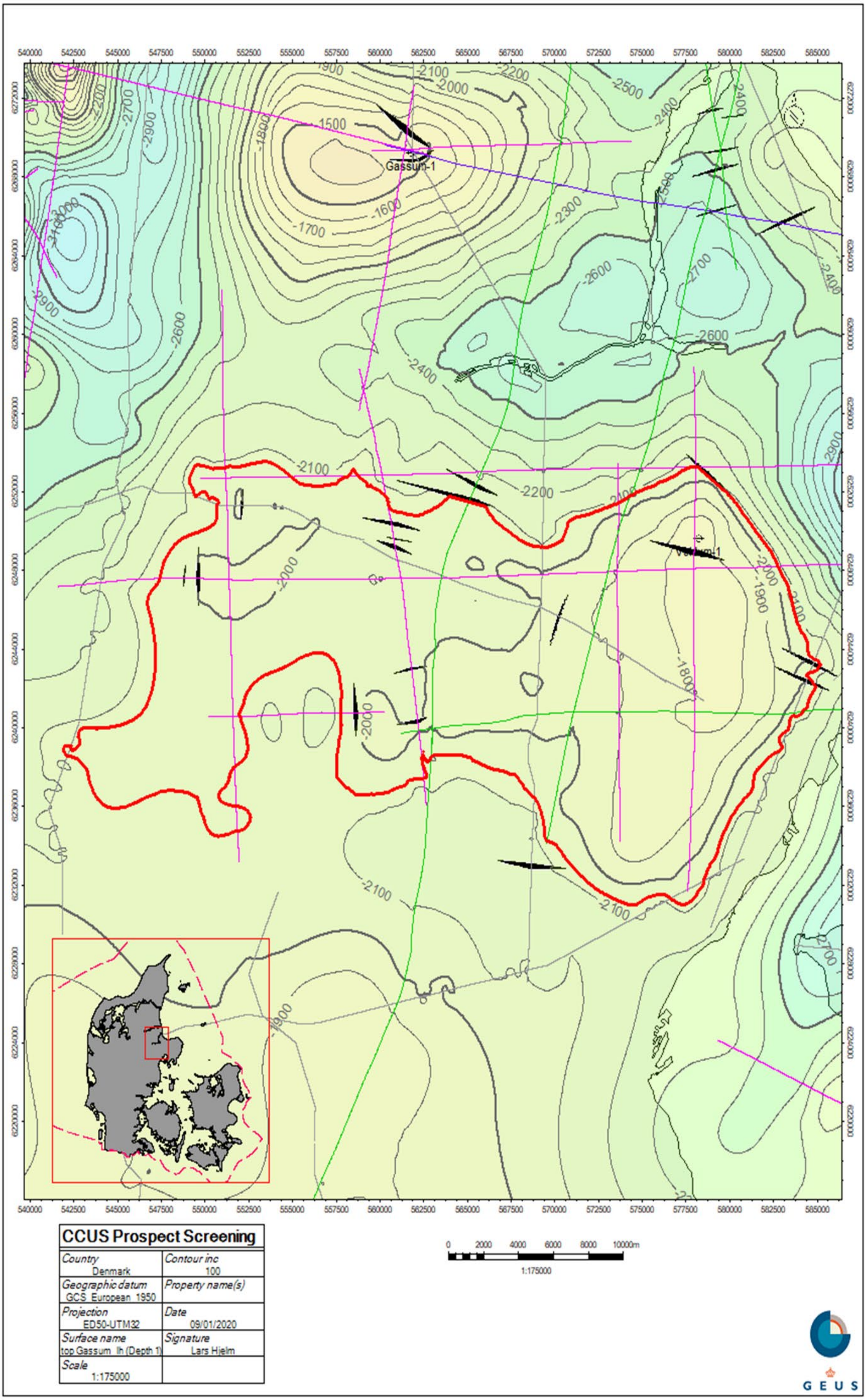
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain from gridding in very open Grid. The structure is very flat near spill and very sensitive to depth conversion
Uncertainty	#_Line_Coverage	8 widely space lines
Uncertainty	Apex def.	Close to offset well. Offset from seismic lines
Uncertainty	Top Seal thickness	200 ms
Mapped	Apex depth (TVDSS, m)	-1726
Mapped	Spill point depth (TVDSS, m)	-2070
Inferred	Structural relief (m)	344
Assumption	Permeability (Liquid, mD)	461
Assumption	Pressure (MPa)	20,3
Assumption	Temperature (>x, C)	60

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	280	560	728
Assumption	Geometric corr. Factor	0,7	0,78	0,9
Assumption	Gross Thickness (m)	102,4	128	153,6
Assumption	Net/Gross (%)	0,184	0,23	0,5
Assumption	Porosity (%)	0,08	0,25	0,3
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO_2 Density, kg/m^3	573,3	637	700,7

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	2,095	3,201	4,775	3,338
Calculation	Buoyant eff. storage volume (Km^3)	0,837	1,281	1,911	1,335
Calculation	Buoyant storage capacity (Mt)	532,2	816,3	1221,5	851,0



General geological setting	The structure is located within the Danish Basin and has been defined at the level of the Upper Triassic – Lower Jurassic Gassum Formation. The formation of the elongated dome shaped structure is caused by post depositional halokenesis and formation of an underling salt pillow. The Gassum Fm seen in the Voldum well is of poor quality, but may be better elsewhere on the very large structure
Well database and seismic survey	The seal and reservoir are penetrated by the Voldum-1 well situated just off the apex of the structure. Data for the structure are based on information from the three wells Gassum-1, Hobro-1 and Voldum-1. The seismic data include a few lines crossing the structure (see structure map). The lack of new high-quality seismic data increases the uncertainties in the interpretation of the structural definition and therefore also the capacity estimations and definition of the storage complex is uncertain.
Storage quality	Sandstones of the Gassum Formation form the primary reservoir in the Voldum structure with an expected porosity c. 25 % and unknown permeability perhaps in the 10-100 mD range (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir in the Voldum-1 well is 1722 m below msl. In the Voldum-1 well the Gassum Formation is 128 m thick and the net/gross value is 0.23 which leads to a net sand thickness of 29 m. It is expected that the reservoir could be compartmentalised by layers of heteroliths and claystones and the general reservoir quality is a challenge for the Voldum structure.
Subsurface storage capacity	The closure is defined by an elongated structure where most of the relief is situated in the eastern part and flattens out in a low relief and uncertain trap in the west. The total relief is c. 340 m. The last closing contour is at 2070 m depth and defines an area of up to 560 km2 with the spill point situated towards the south. The pressure and temperature are expected to follow the normal Danish gradients. These input values render an estimated maximum storage capacity of 850 Mt CO_2 for the Voldum structure. the gently dipping outer flanks of the structure might be problematic for injection
Caprock (Seal)	The marine mudstones of the Fjerritslev Formation are 334 m thick in the Voldum-1 well and form the primary seal of the aquifer



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Country
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Contour inc
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Projection
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Date
09/01/2020
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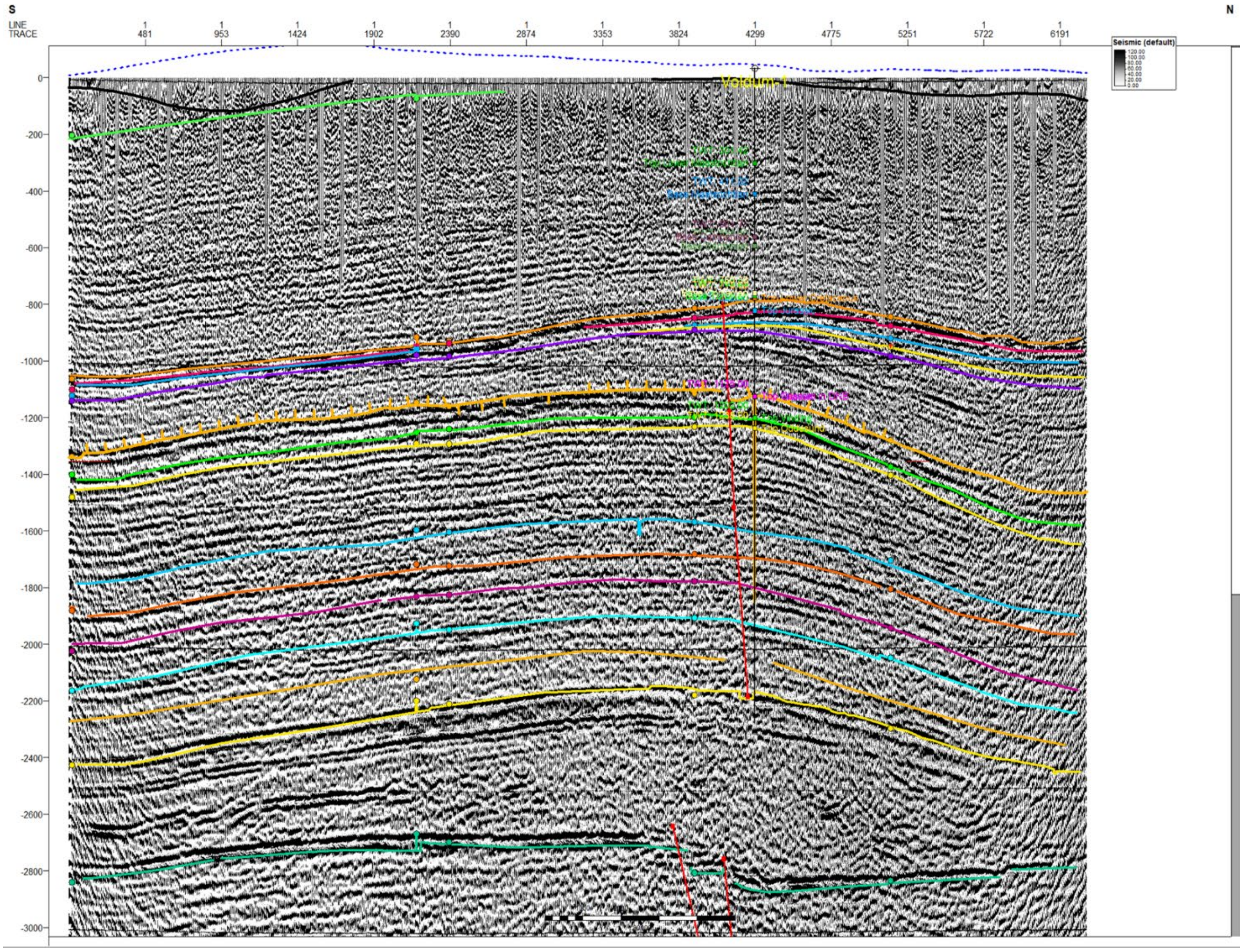
GEUS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Seismic (default)
Vovlum-1

Thorning Structure

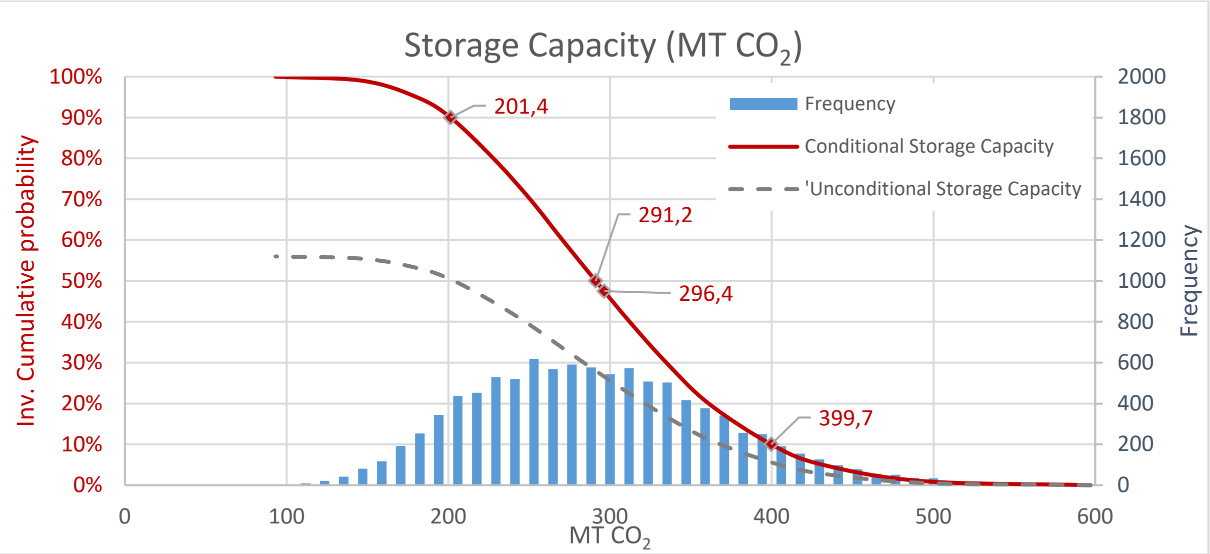
General	
Structure name	Thorning (prev. Pårup)
Top Site Location	Onshore
Area potential (km^2)	210
Reservoir stratigraphy	U. Triassic - L. Jurassic
Reservoir Formation	Gassum
Reservoir lithology	Sandstone
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev
Top Seal lithology	Mudstone
Top seal integrity	Some crestal faults, Extensional regime on structure apex could have fractures
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	4-way anticline above larger salt pillow. Structural setting toward the south is uncertain (line coverage), as the structural interaction with the southern salt diapir is poor imaged
Max. areal Offshore Fraction (%)	0%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	70%	Unproven at structure. Several faults cut the structure near apex.	3D seismic, pressure tests
Geological	Structure	100%	Compartmentalisation might occur!	3D seismic
Geological	Reservoir	80%	Gassum well is 40km away. Most likely present, but quality is unknow as in Voldum structure	Drilling, Seismic inversion
Engineering	Injection feasi-bility	100%		
Engineering	Seismicity	2%	Low	
Engineering	Groundwater contamination	2%	Low	
Cost	3D-seismic		High	
Cost	Drilling		Low	
Cost	Transport		Onshore	
QHSE	Environment		National and local authorities	
QHSE	Safety		Low	

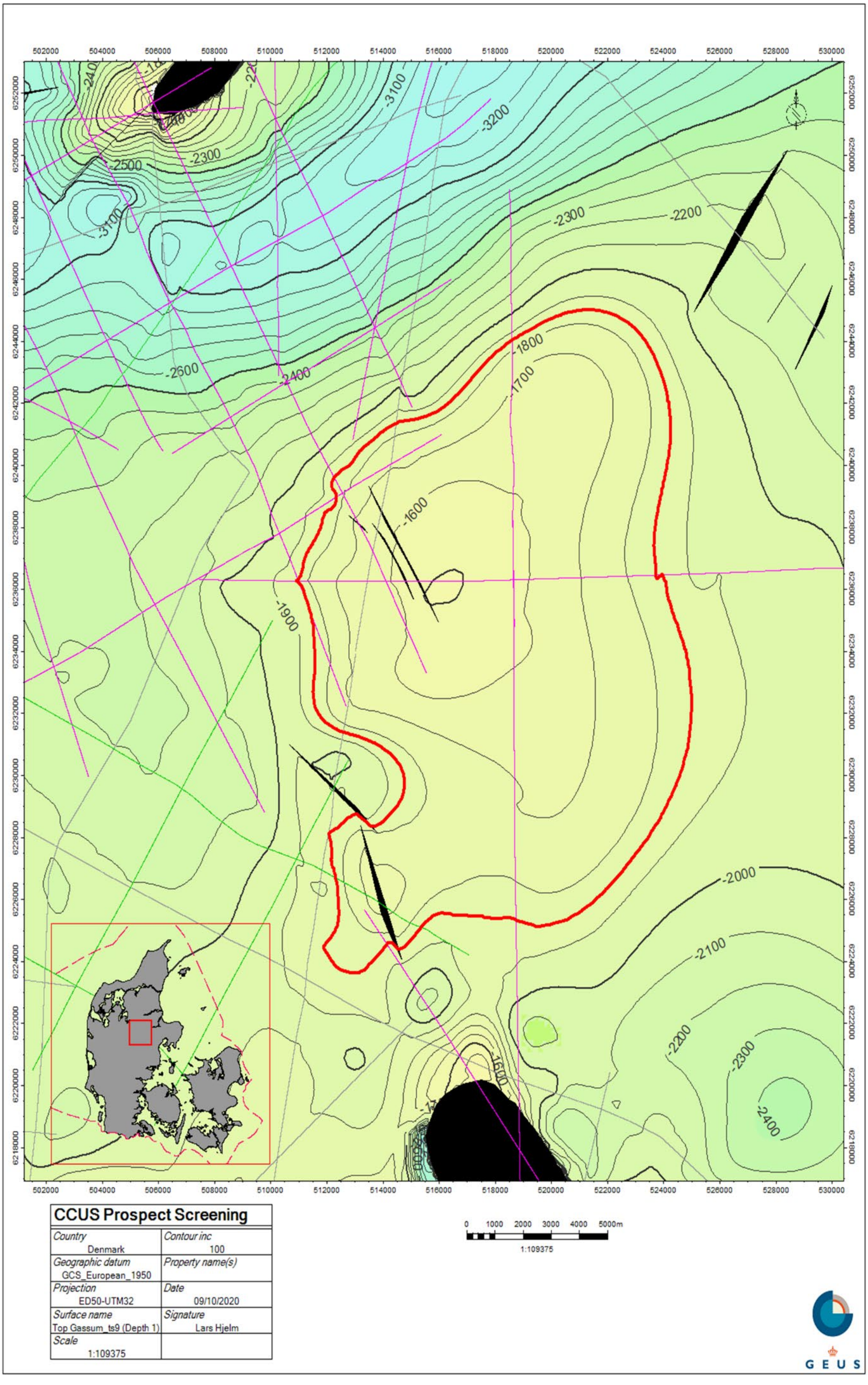
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain from current grid. 3 structural scenarios carry different spill definitions: 1) Open faults and 4-way only scenario gives -1840m, 2) Cross fault pressure comm. scenario renders a -1940m spill and 3) Sealing faults scenario extents spill down to -2100m
Uncertainty	#_Line_Coverage	3,5 lines
Uncertainty	Apex def.	Poor control
Uncertainty	Top_Seal thickness	200 ms
Mapped	Apex depth (TVDSS, m)	-1490
Mapped	Spill point depth (TVDSS, m)	-1850
Inferred	Structural relief (m)	360
Assumption	Permeability (Liquid, mD)	109
Assumption	Pressure (MPa)	18,1
Assumption	Temperature (>x, C)	70

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	105	210	273
Assumption	Geometric corr. Factor	0,6	0,68	0,85
Assumption	Gross Thickness (m)	100	130	150
Assumption	Net/Gross (%)	0,27	0,4	0,5
Assumption	Porosity (%)	0,08	0,18	0,21
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO2 Density, kg/m^3	584,25	615	645,75

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	0,821	1,184	1,623	**1,206**
Calculation	Buoyant eff. storage volume (Km^3)	0,328	0,473	0,649	**0,482**
Calculation	Buoyant storage capacity (Mt)	201,4	290,9	399,2	**296,6**



General geological setting	The structure is situated in the central part of the Danish Basin and has been defined at the level of the Upper Triassic – Lower Jurassic Gassum Formation. The formation of the almost kidney shaped structure is caused by post depositional halokenesis and formation of an underling salt pillow uplift.
Well database and seismic survey	The seal and reservoir are penetrated by the Voldum-1, Gassum-1 and other wells situated 30-40 km away. The seismic data include an only few lines crossing the structure (see structure map). The lack of new high-quality seismic data increases the uncertainties in the interpretation of the storage site architecture and therefore also the capacity estimations and definition of the storage complex is uncertain.
Storage quality	Sandstones of the Gassum Formation is expected to constitute the primary reservoir unit in the Thorning structure with an expected porosity in low end of 10 % due to the results in the Voldum-1 well. Permeability is estimated to c. 50-100 mD (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir in approx. 1500 m below msl. and a gross thickness of c. 130 m is expected with net/gross value of 0.4 which leads to a net sand thickness of 53 m. It is expected that the reservoir could be compartmentalised by layers of heteroliths and claystones and crestal faulting.
Subsurface storage capacity	The closure is defined by a domal structure with a total relief of c. 360 m. The last closing contour is at 1850 m depth with spill towards the south and defines an area of up to 210 km^2. The pressure and temperature are expected to follow the normal Danish gradients. These input values lead to an estimated maximum storage capacity of 300 Mt CO_2 for the Thorning structure.
Caprock (Seal)	The marine mudstones of the Fjerritslev Formation are estimated to c. 300-400 m thick in the crestal area and form the primary seal of the aquifer. Faults are observed to transect the top seal, but they are poorly imaged.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Contour inc
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Projection
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Date
09/10/2020
Surface name
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Signature
Lars Hjelm
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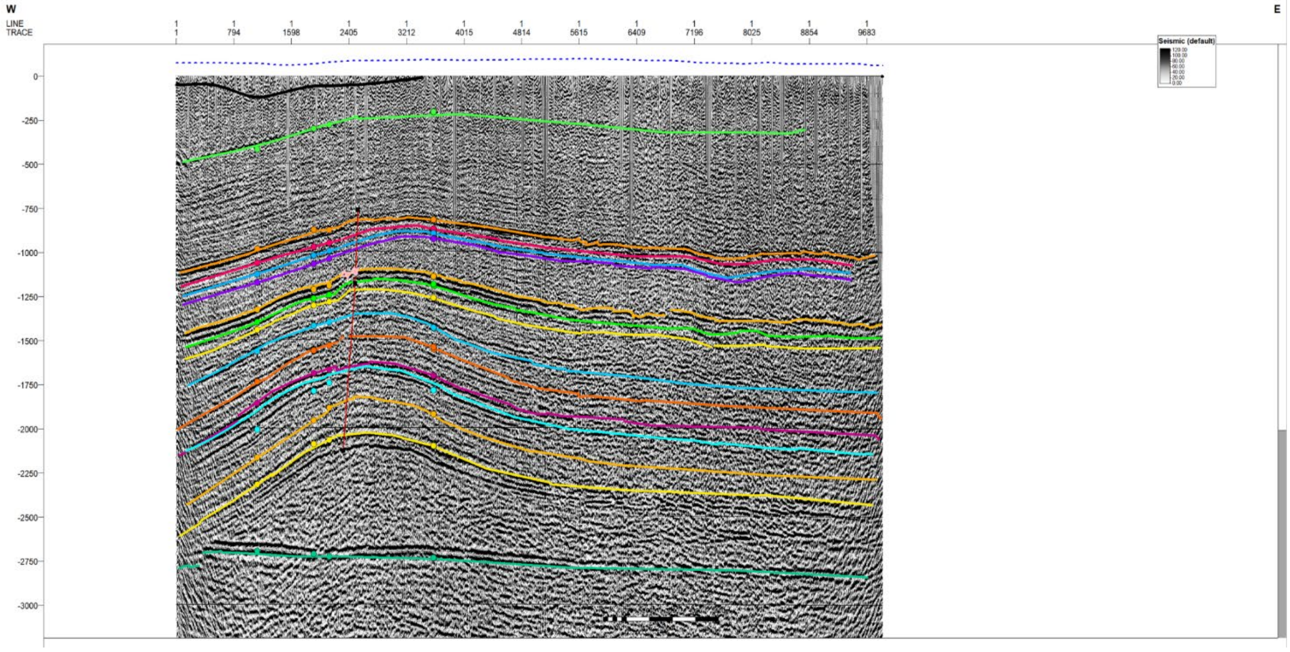
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4015
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5615
6409
7196
8025
8854
9683

Helgenæs structure

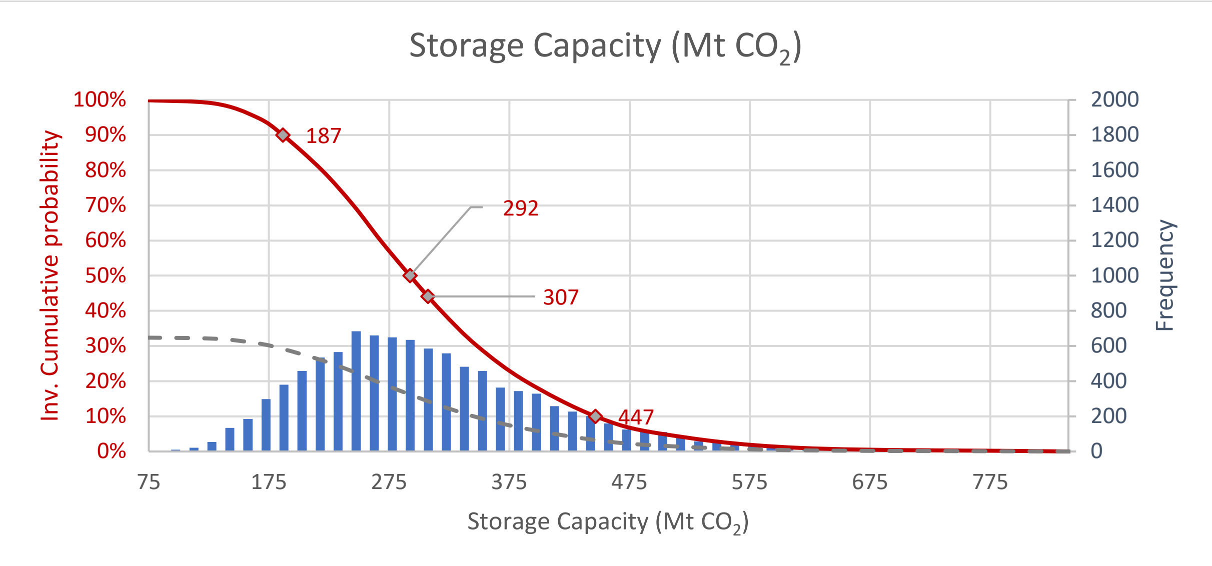
General	
Structure name	Helgenæs
Top Site Location	On/offshore
Area potential (km^2)	206,4
Reservoir stratigraphy	U. Triassic - L. Jurassic
Reservoir Formation	Gassum
Reservoir lithology	Sandstones
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev Fm
Top Seal lithology	Mudstone
Top seal integrity	Unknown due to very poor data
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	Uncertain due to lack of data. Perhaps 4-way anticline above salt pillow.
Offshore Fraction of max. areal (%)	85%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	60%	Unproven across structure. Some faults (w. low offset) should be considered as a possibility	3D seismic may provide further knowledge, but a well and pressure tests are needed
Geological	Structure	60%	Very poor data. Structure presence indicated but not easy to define	3D seismic could better define structure setting and - definition.
Geological	Reservoir	90%	Fair knowledge from wells like Voldum or Gassum, Rønde-1 ow poor quality. The Fm may have good quality	Extended flow tests needed
Engineering	Injection feasibility	100%		Reservoir performance needs to be invested further
Engineering	Seismicity	Low		
Engineering	Groundwater contamination	Low		
Cost	3D-seismic	na	High	
Cost	Drilling	na	Low	
Cost	Transport	na	Onshore	
QHSE	Environment	na	National and local authorities	
QHSE	Safety	na	Low	

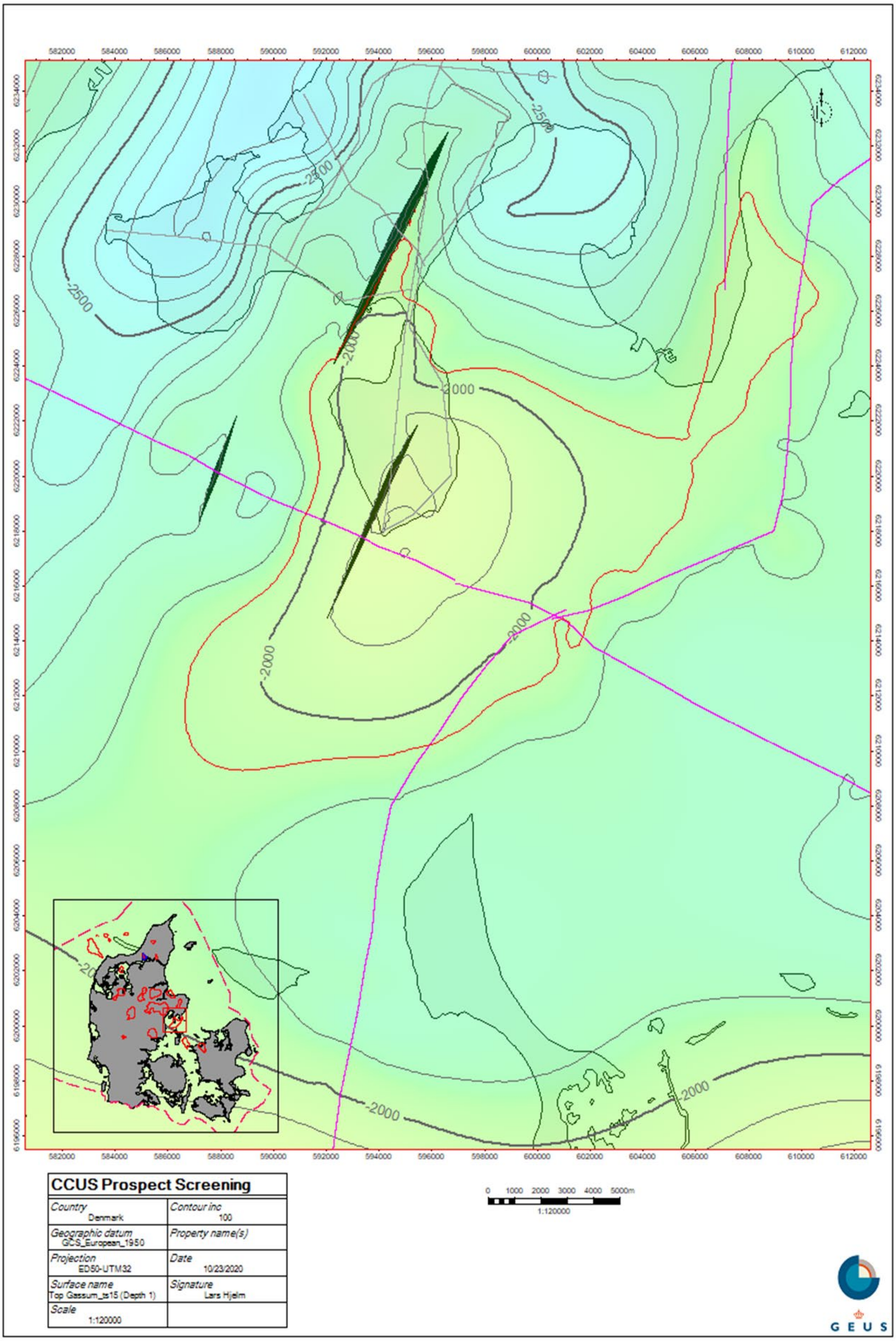
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain from gridding in very open Grid. The structure is very flat near spill and very sensitive to depth conversion
Uncertainty	#_Line_Coverage	1,5 widely space lines
Uncertainty	Apex def.	far from offset wells. Offset from seismic lines. Poor control on overburden
Uncertainty	Top Seal thickness	100 ms
Mapped	Apex depth (TVDSS, m)	-1748
Mapped	Spill point depth (TVDSS, m)	-2050
Inferred	Structural relief (m)	302
Assumption	Permeability (Liquid, mD)	461
Assumption	Pressure (MPa)	20,1
Assumption	Temperature (>x, C)	50

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	103,2	206,4	268,32
Assumption	Geometric corr. Factor	0,4	0,65	0,75
Assumption	Gross Thickness (m)	102,4	128	153,6
Assumption	Net/Gross (%)	18%	23%	50%
Assumption	Porosity (%)	8%	25%	30%
Assumption	Eff_Storage_Vol. Factor	40%	40%	40%
Assumption	in-situ CO2 Density, kg/m^3	720	785	840

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	0,594	0,934	1,429	**0,980**
Calculation	Buoyant eff. storage volume (Km^3)	0,238	0,374	0,571	**0,392**
Calculation	Buoyant storage capacity (Mt)	186,0	293,2	448,5	**307,1**



General geological setting	The structure is located within the Danish Basin and has been defined at the level of the Upper Triassic – Lower Jurassic Gassum Formation. The formation of an interpreted dome shaped structure is caused by post depositional halokenesis and formation of an underling salt pillow. The Gassum Fm seen in the Voldum well is of poor quality, but may be better on this structure
Well database and seismic survey	The seal and reservoir are penetrated by the Voldum-1 well some distance from of the structure. Data for the structure are based on information from the three wells Gas-sum-1 and Voldum-1. The seismic data include an only few lines crossing parts of the structure (see structure map). The lack of data increases the risk and uncertainties in the interpretation of the structural definition.
Storage quality	Sandstones of the Gassum Formation is believed to form the primary reservoir in the Helgenæs structure with an expected porosity c. 25 % and unknown permeability per-haps in the 10-100 mD range (liquid permeability). Depth to top reservoir in the Voldum-1 well is 1748 m below msl. The Gassum Fm is believed to be similar to the Voldum-1 well where the Gassum Formation is 128 m thick and the net/gross value is 0.23 which leads to a net sand thickness of 29 m. It is expected that the reservoir could be compartmentalised by layers of heteroliths and claystones and the general reservoir quality.
Subsurface storage capacity	The closure is very poorly defined by the available data. The total relief is indicated to be c. 300 m. The last closing contour is at 2050 m depth and poorly defines an area of up to 200 km2 with the spill point situated towards the south but this again very uncer-tain. The pressure and temperature are expected to follow the normal Danish gradi-ents. These input values render an estimated storage capacity of 300 Mt CO_2 for the Helgenæs structure.
Caprock (Seal)	The marine mudstones of the Fjerritslev Formation are 334 m thick in the Voldum-1 well and form the primary seal of the aquifer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Contour inc
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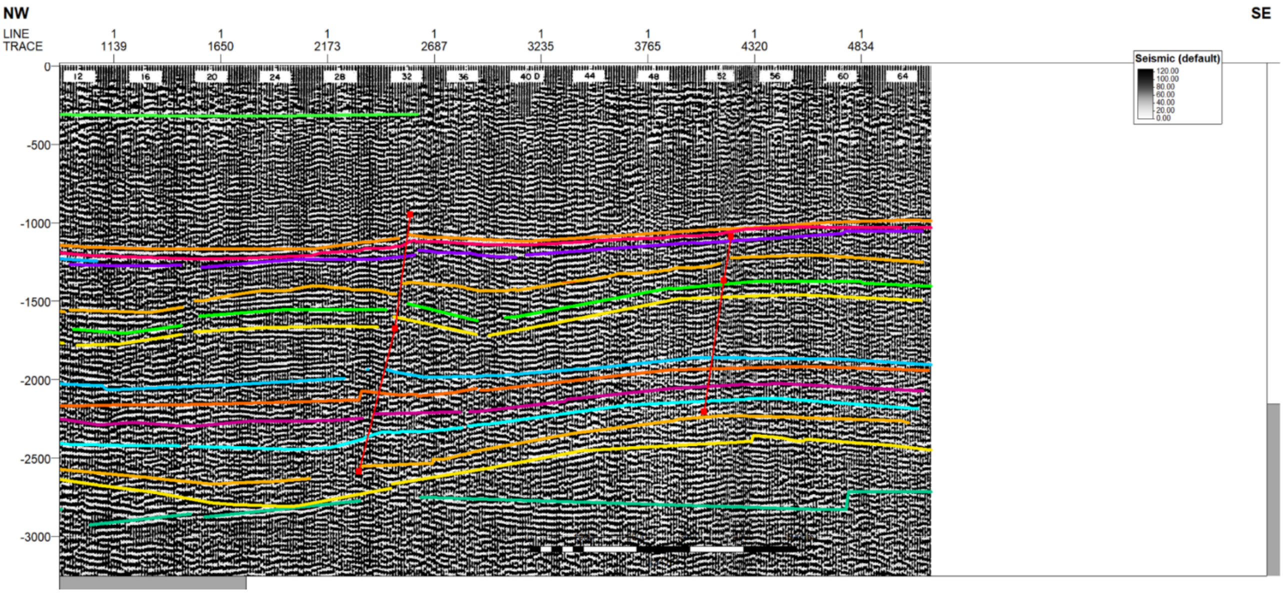
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Røsnæs Structure

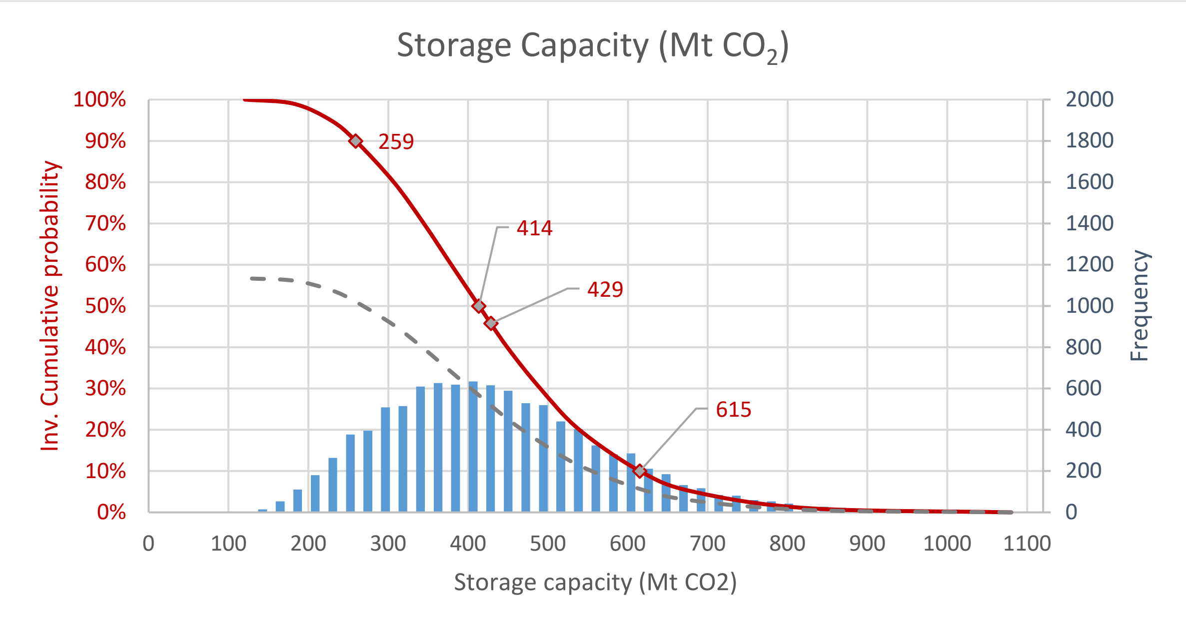
General	
Structure name	Røsnæs
Top Site Location	Offshore
Area potential (km^2)	118,9
Reservoir stratigraphy	U. Triassic - L. Jurassic
Reservoir Formation	Gassum
Reservoir lithology	Sandstones
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev
Top Seal lithology	Mudstone
Top seal integrity	Low fault intensity, extensional regime and low likelihood of fracture should be considered
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	Possible 4-way and associate fault supported 3-way anticline above salt pillow. Very uncertain 4-way part
Offshore Fraction of max. areal (%)	95%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	70%	Minor faults (w. very low offset) - possible associated fracture systems should be considered. Proven at Stenlille	3D seismic may provide further knowledge, but a well and pressure tests are needed
Geological	Structure	90%	4-way part uncertainty (might only be 3way.) Spill point definition currently very uncertain. Chalk gr poorly defined (depth conv. Uncertain).	3D seismic could better define structural setting and definition.
Geological	Reservoir	90%	Good knowledge from Stenlille wells. Believed to extent across most of structure. Data suggest more distal facies than in Stenlille area. 200m thick (150 @Stenlille)	Better Seismic data may give better confidence in seismic from Stenlille to Havnsø area
Engineering	Injection feasibility	100%		
Engineering	Seismicity	Low		
Engineering	Groundwater contamination	Low		
Cost	3D-seismic	na	Medium	
Cost	Drilling	na	Low or Medium / High	
Cost	Transport	na	perhaps onshore from Røsnæs peninsula	
QHSE	Environment	na	National and local authorities	
QHSE	Safety	na	Low	

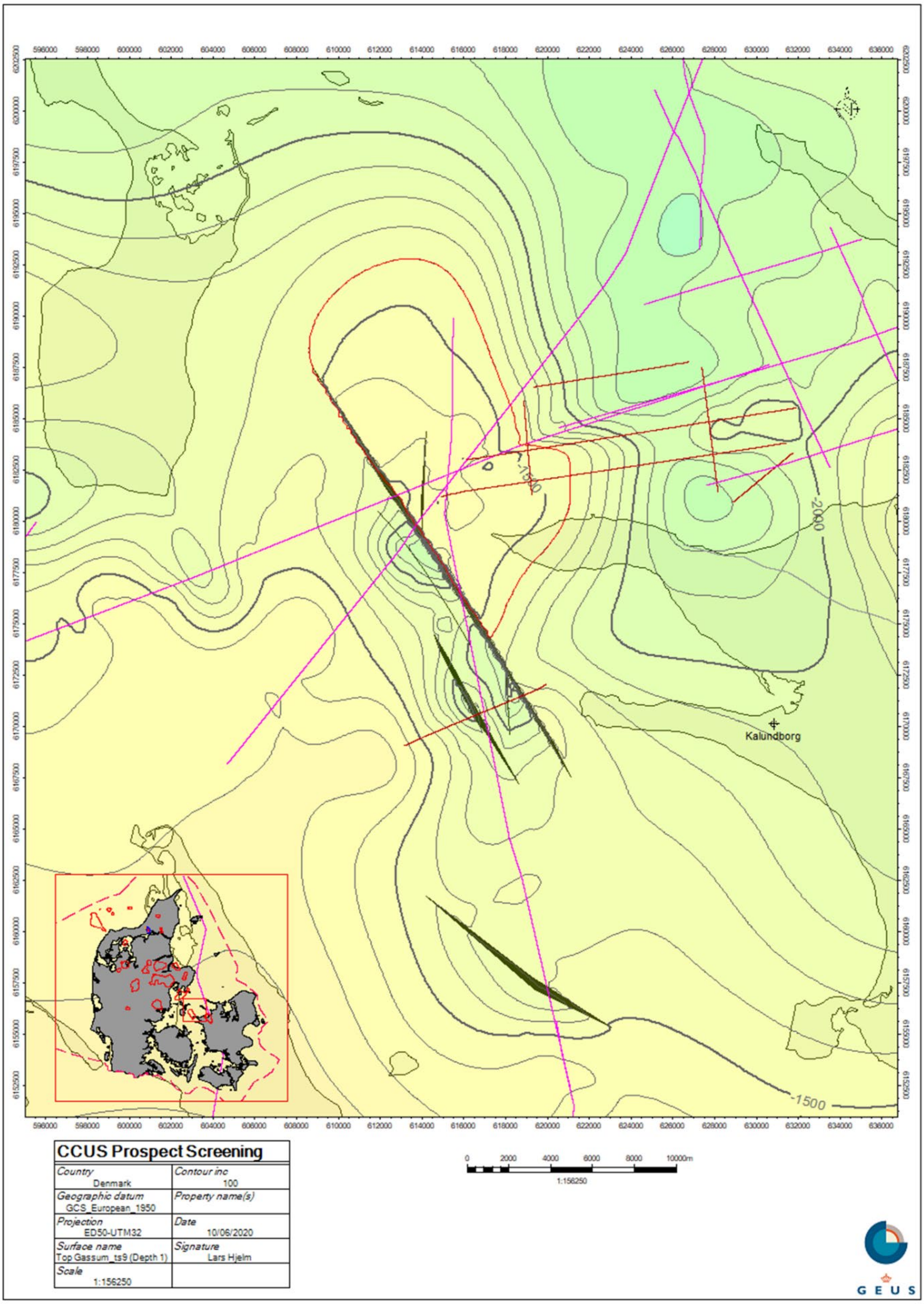
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain spill zone from gridding in open Grid (con-strain not seen from data cover). Data is uncertain and of low quality
Uncertainty	#_Line_Coverage	3 lines, 4 half lines
Uncertainty	Apex def.	Poor (low coverage)
Uncertainty	Top_Seal thickness	150-200ms
Mapped	Apex depth (TVDSS, m)	-1325
Mapped	Spill point depth (TVDSS, m)	-1600
Inferred	Structural relief (m)	275
Assumption	Permeability (Liquid, mD)	461
Assumption	Pressure (MPa)	15,7
Assumption	Temperature (>x, C)	50

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	59,45	118,9	154,57
Assumption	Geometric corr. Factor	0,45	0,58	0,8
Assumption	Gross Thickness (m)	100	200	250
Assumption	Net/Gross (%)	0,225	0,45	0,7
Assumption	Porosity (%)	0,2	0,25	0,3
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	In-situ CO_2 Density, kg/m^3	670	715	790

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	0,912	1,434	2,131	**1,488**
Calculation	Buoyant eff. storage volume (Km^3)	0,365	0,574	0,852	**0,595**
Calculation	Buoyant storage capacity (Mt CO_2)	262,863	412,0	615,4	**428,6**



General geological setting	The structure is situated in the southern part of the Danish Basin and has been defined at the level of the Upper Triassic – Lower Jurassic Gassum Formation. The formation of the dome shaped structure is caused by post depositional halokenesis and formation of underling salt pillow uplift. Major fault is believed to associated collapse of the SW flank. How much of Gassum is fault need further investigation
Well database and seismic survey	The seal and reservoir are penetrated by the Stenlille wells situated 60 km from the structure. Data for the Røsnæs structure is based on the Stenlille wells. The seismic data include a few lines crossing the structure. The lack of new high-quality seismic data increases the uncertainties in the interpretation of the storage site architecture and therefore also the storage capacity estimations and definition of the storage complex is uncertain.
Storage quality	Sandstones of the Gassum Formation form the primary reservoir in the Røsnæs structure with an expected average porosity up to 22 %+ and permeability around 1-300 mD (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir is 1375 m below msl. Gassum is believed to be c. 200m thick and the net/gross value is 50% which leads to a net sand thickness of 100 m. It is expected that the reservoir could be compartmentalised by faults and layers of heteroliths and claystones and perhaps additional faulting.
Subsurface storage capacity	The closure is defined by a semi-circular 4-way and 3-way combined structure approximately with potentially 275 m structural relief with generally uncertain geometry. The last closing contour is suggested to be at 1600 m depth (very uncertain) and defines an area of approximately 118 km2. The spill point is suggested to be associated a fault but is speculative. The temperature is expected to follow the low Danish gradients but with normal pressure gradient. These input values lead to an estimated maximum storage capacity of 430 Mt CO_2 for the Røsnæs structure.
Caprock (Seal)	The marine mudstones of the Fjerritslev Formation are fairly thick across the Røsnæs structure and form the primary seal of the aquifer.



Kalundborg
-1500
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CCUS Prospect Screening
Country
Denmark
Contour inc
100
Geographic datum
GCS_European_1950
Property name(s)
Projection
ED50-UTM32
Date
10/06/2020
Surface name
Top Gassum_ts9 (Depth 1)
Signature
Lars Hjelm
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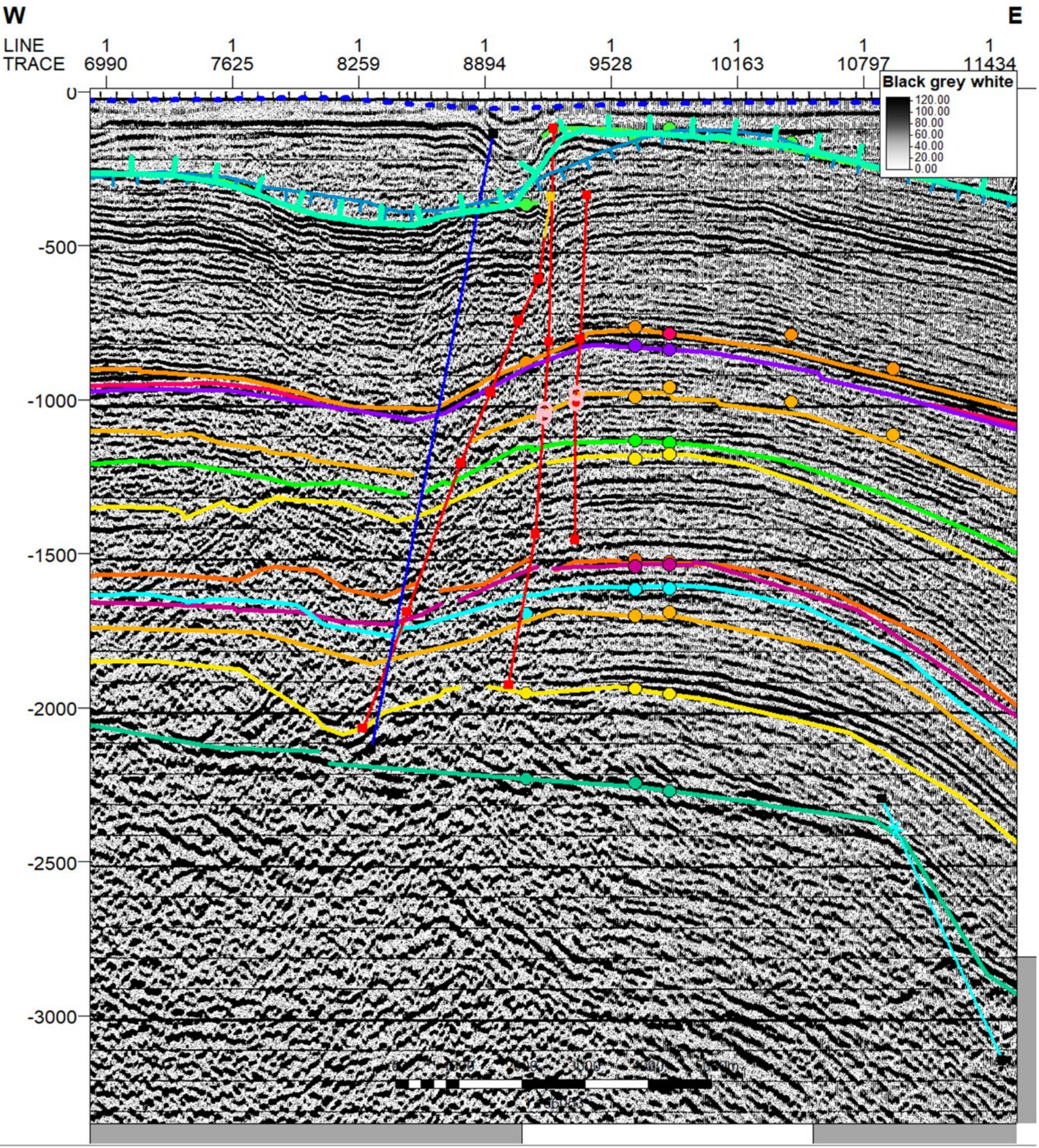
GEUS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80.00
60.00
40.00
20.00
0.00
0
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-1000
-1500
-2000
-2500
-3000

Havnsø Structure

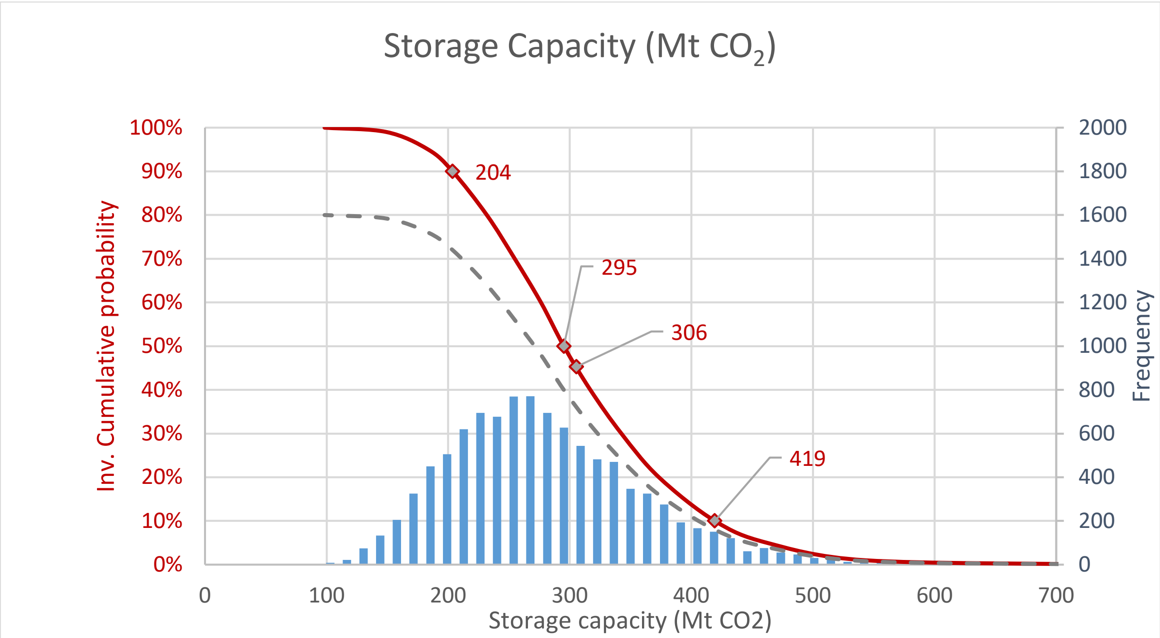
General	
Structure name	Havnsø
Top Site Location	Onshore
Area potential (km^2)	118,54
Reservoir stratigraphy	U. Triassic - L. Jurassic
Reservoir Formation	Gassum
Reservoir lithology	Sandstones
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev
Top Seal lithology	Mudstone
Top seal integrity	Low fault intensity, extensional regime and low likelihood of fracture should be considered
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	4-way anticline above salt pillow. May spill forwards the Stenlille structure at -1625m (uncertain)
Offshore Fraction of max. areal (%)	30%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	80%	Unproven at structure. Minor faults (w. very low offset) - possible associated fracture systems should be considered, Proven in Stenlille	3D seismic may provide further knowledge, but a well and pressure tests are needed
Geological	Structure	100%	Spill point definition currently very uncertain, broad zone on poor data. Chalk gr poorly defined (depth conv. Uncertain). Northern flank is offshore, data gap in transition zone	3D seismic could better define structural setting and definition.
Geological	Reservoir	100%	Good knowledge from Stenlille wells. Believed to extent across most of structure. Data suggest more distal facies than in Stenlille area. 200m thick (150 @Stenlille)	Better Seismic data may give better confidence in seismic from Stenlille to Havnsø area
Engineering	Injection feasibility	100%		
Engineering	Seismicity	Low		
Engineering	Groundwater contamination	Low		
Cost	3D-seismic	na	Very High (on/offshore)	
Cost	Drilling	na	Low	
Cost	Transport	na	Onshore	
QHSE	Environment	na	National and local authorities	
QHSE	Safety	na	Low	

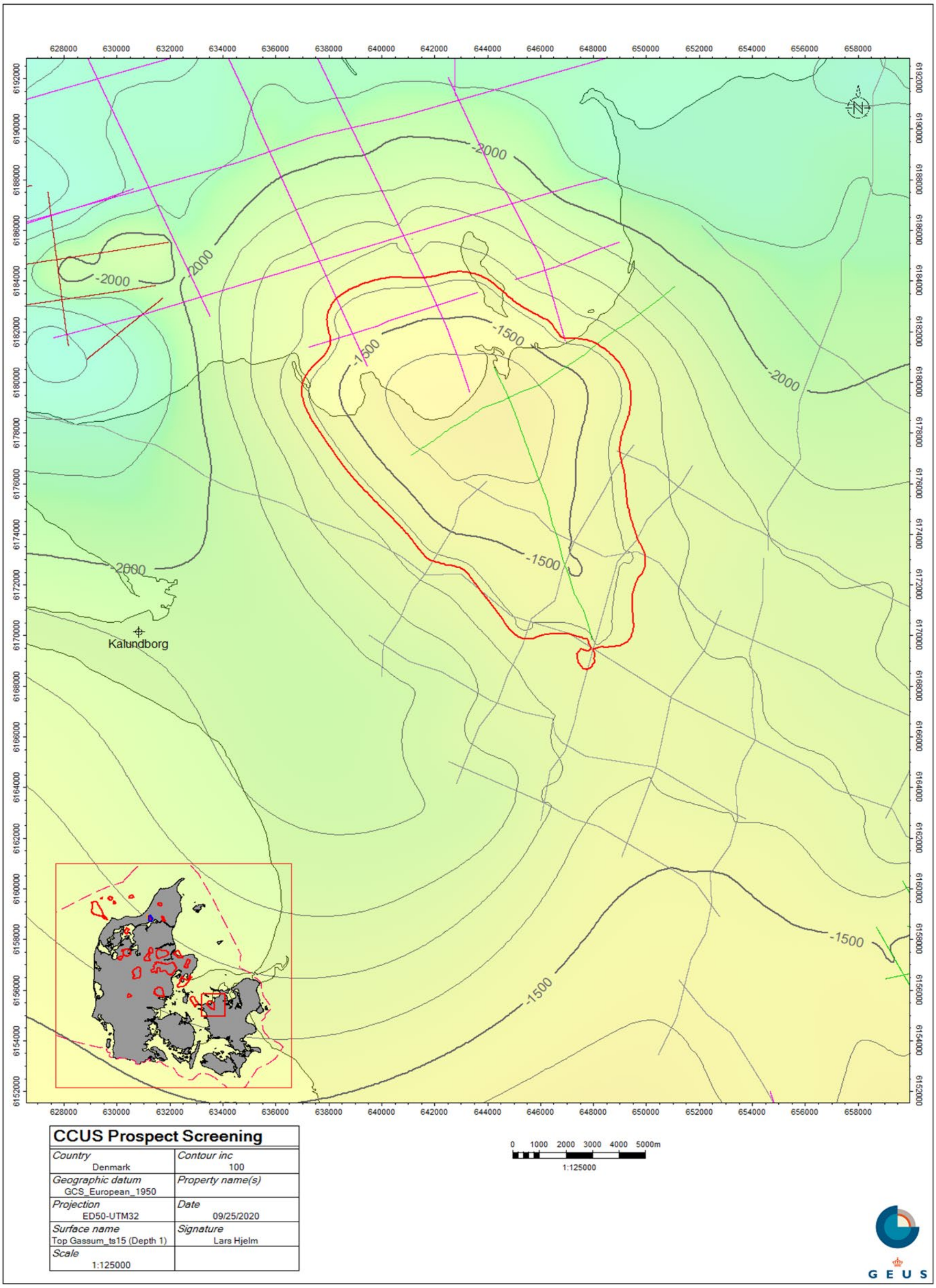
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Uncertain spill zone from gridding in open Grid. Data is uncertain and of low quality
Uncertainty	#_Line_Coverage	11 half lines
Uncertainty	Apex def.	Fair (low coverage)
Uncertainty	Top_Seal thickness	200ms
Mapped	Apex depth (TVDSS, m)	-1375
Mapped	Spill point depth (TVDSS, m)	-1625
Inferred	Structural relief (m)	250
Assumption	Permeability (Liquid, mD)	263
Assumption	Pressure (MPa)	15,9
Assumption	Temperature (>x, C)	40

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	59,27	118,54	154,102
Assumption	Geometric corr. Factor	0,4	0,46	0,75
Assumption	Gross Thickness (m)	140	200	240
Assumption	Net/Gross (%)	0,35	0,46	0,73
Assumption	Porosity (%)	0,15	0,22	0,25
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	In-situ CO_2 Density, kg/m^3	610	629	793

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	0,786	1,124	1,597	**1,165**
Calculation	Buoyant eff. storage volume (Km^3)	0,314	0,450	0,639	**0,466**
Calculation	Buoyant storage capacity (Mt CO_2)	203,7	294,0	417,6	**304,6**



General geological setting	The structure is situated in the southern part of the Danish Basin and has been defined at the level of the Upper Triassic – Lower Jurassic Gassum Formation. The formation of the dome shaped structure is caused by post depositional halokenesis and formation of underling salt pillow uplift.
Well database and seismic survey	The seal and reservoir are penetrated by the Stenlille wells situated less than 29km of the structure. Data for the Havnsø structure is based on the Stenlille well. The seismic data include a few lines crossing the structure. The lack of new high-quality seismic data increases the uncertainties in the interpretation of the storage site architecture and therefore also the storage capacity estimations and definition of the storage complex is uncertain.
Storage quality	Sandstones of the Gassum Formation form the primary reservoir in the Havnsø structure with an expected average porosity up to 22 %+ and permeability around 1-300 mD (liquid permeability). The permeability interpretation is uncertain as it is based on petrophysical log interpretations from old and low quality well logs (Michelsen 1981). Depth to top reservoir is 1375 m below msl. Gassum is believed to be c. 200m thick and the net/gross value is 50% which leads to a net sand thickness of 100 m. It is expected that the reservoir could be compartmentalised by faults and layers of heteroliths and claystones and perhaps additional faulting.
Subsurface storage capacity	The closure is defined by a semi-circular domal structure approximately with potentially 300 m structural relief with gently dipping flanks. The last closing contour is at 1625 m depth and defines an area of approximately 118 km2. The spill point is situated towards the south towards the Stenlille structure. The temperature is expected to follow the low Danish gradients but with normal pressure gradient. These input values lead to an estimated maximum storage capacity of 450 Mt CO_2 for the Havnsø structure.
Caprock (Seal)	The marine mudstones of the Fjerritslev Formation are fairly thick across the Havnsø structure and form the primary seal of the aquifer.



-2000
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Kalundborg
CCUS Prospect Screening
Country
Denmark
Contour inc
100
Geographic datum
GCS_European_1950
Property name(s)
Projection
ED50-UTM32
Date
09/25/2020
Surface name
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Signature
Lars Hjelm
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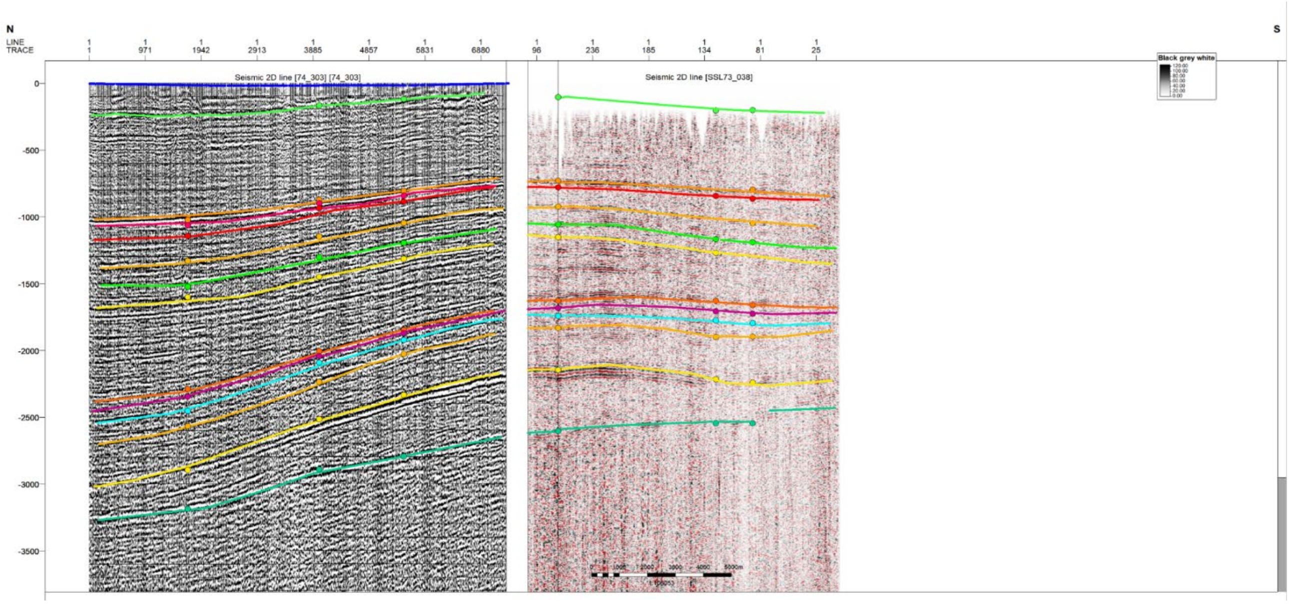
GEUS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Seismic 2D line [SSL73_038]
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-1500
-2000
-2500
-3000
-3500

Rødby Structure

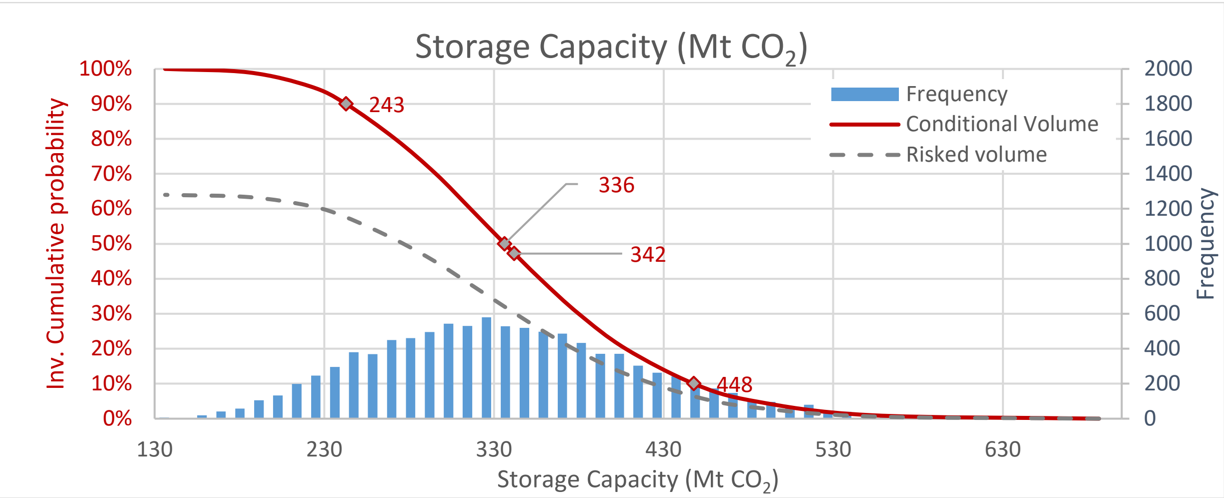
General	
Structure name	Rødby
Top Site Location	Onshore
Area potential (km^2)	137,5
Reservoir stratigraphy	L. Triassic
Reservoir Formation	Bunter SS Fm
Reservoir lithology	Sandstone
Reservoir Facies	Shore/Delta
Top Seal Stratigraphy	L. Jurassic
Top Seal Formation	Fjerritslev
Top Seal lithology	Mudstone
Top seal integrity	Several faults observed to cut the top seal and reservoir unit (no jet mapped). Faults might appear to reach surface, but poor seismic quality does not resolve this.
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	4-way anticline above salt pillow. May spill forwards the North East. Governed by halokinesis
Offshore Fraction of max. areal (%)	0,5%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	80%	Unproven at structure. Several faults indication and disturbed overburden (unknown whether fault networks reach surface).	3D seismic, pressure tests
Geological	Structure	100%	Compartmentalisation might occur as several faults could be present	3D seismic
Geological	Reservoir	80%	Good, drilled. Unknown connectiv-ity	
Engineer-ing	Injection feasi-bility	70%	Uncertain whether CO_2 will be at supercritical phase	
Engineer-ing	Seismicity	2%	Low	
Engineer-ing	Groundwater contamination	2%	Low	
Cost	3D-seismic		High	
Cost	Drilling		Low	
Cost	Transport		Onshore	
QHSE	Environment		National and local authorities	
QHSE	Safety		Low	

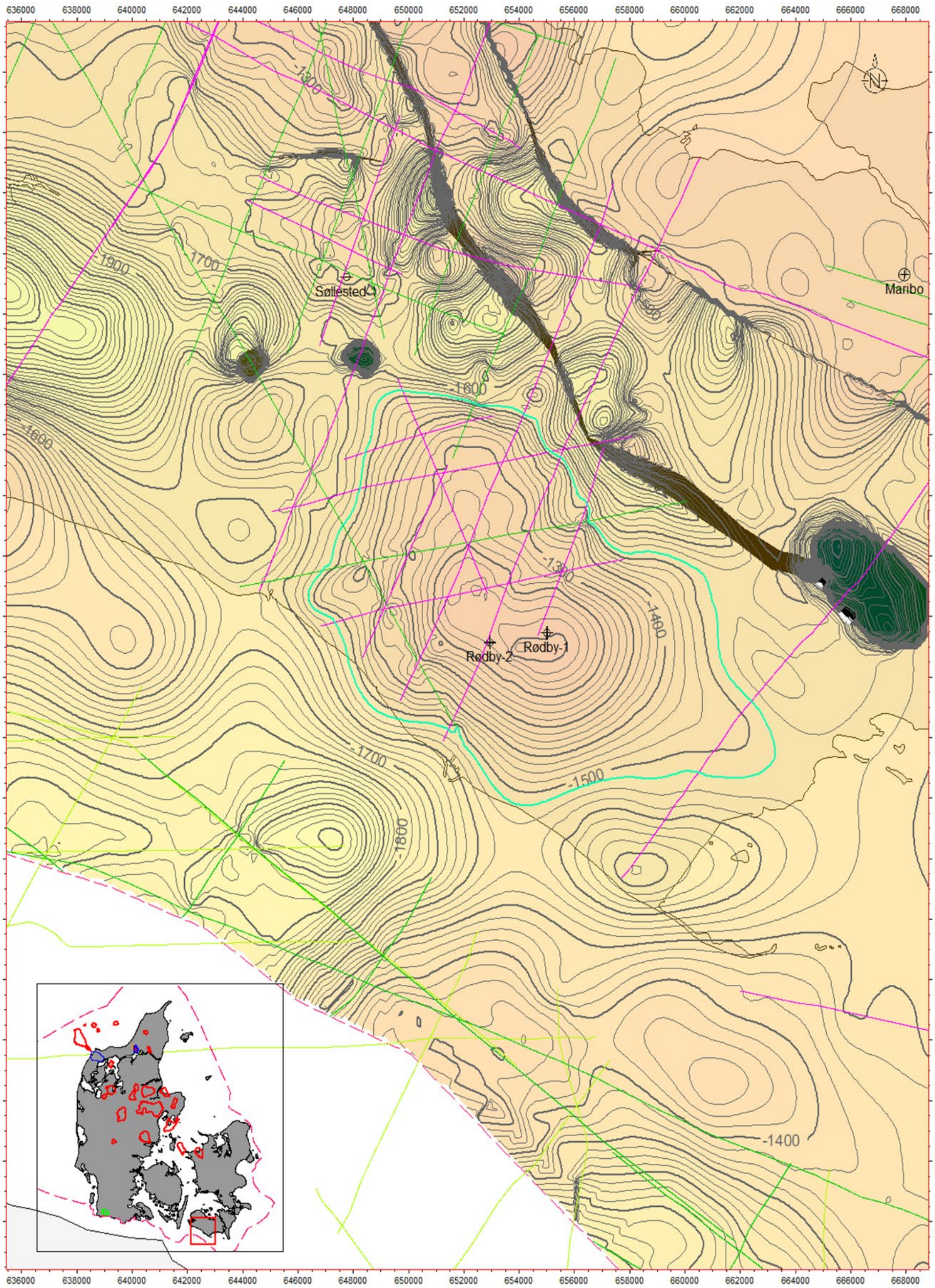
Volumetric			
Category	**Element**	**Comment**	
Uncer-tainty	Spill point def.	Structure is defined by one line towards the east and make spill point def. uncertain	
Uncer-tainty	#_Line_Coverage	11 lines	
Uncer-tainty	Apex def.	Wells near current apex definition	
Uncer-tainty	Top_Seal thickness	160m Ørslev Fm	
Mapped	Apex depth (TVDSS, m)	-1075	
Mapped	Spill point depth (TVDSS, m)	-1525	Structures involving fault renders spill at -1940m and -2100m.
Inferred	Structural relief (m)	450	
Assump-tion	Permeability (Liquid, mD)	385	
Assump-tion	Pressure (MPa)	15,0	
Assump-tion	Temperature (>x, C)	35	

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	68,75	137,5	178,75
Assumption	Geometric corr. Factor	0,55	0,6	0,8
Assumption	Gross Thickness (m)	204,8	256	307,2
Assumption	Net/Gross (%)	0,192	0,24	0,312
Assumption	Porosity (%)	0,168	0,24	0,288
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO2 Density, kg/m^3	630	700	770

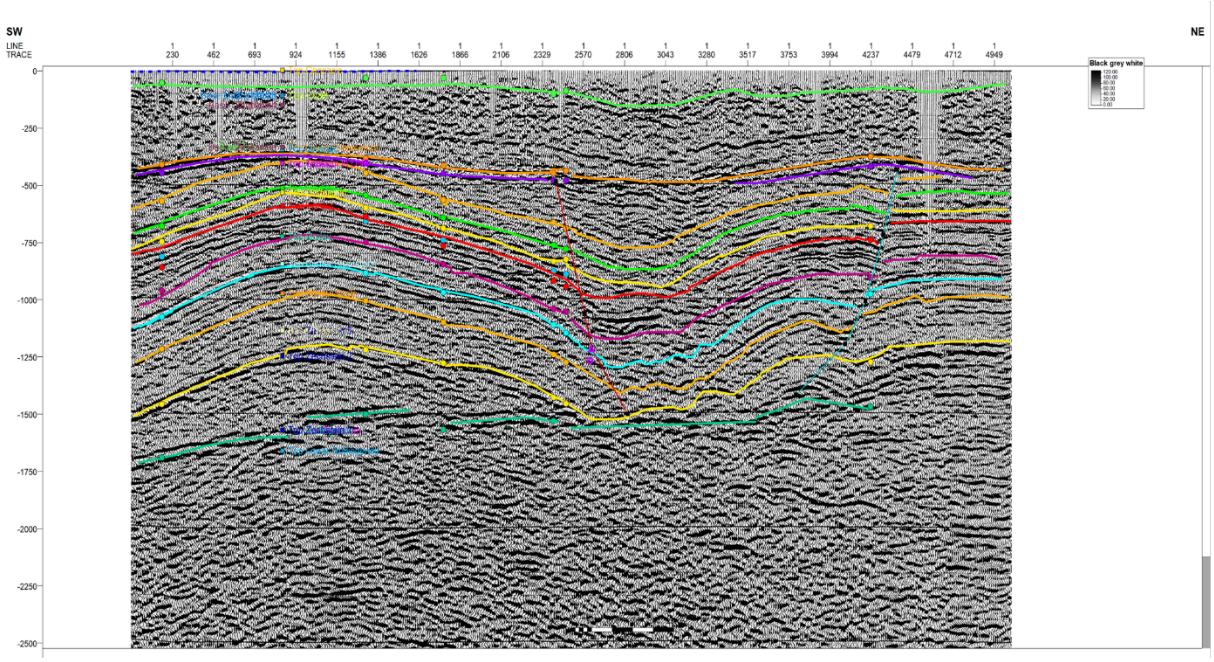
Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	0,876	1,201	1,596	**1,221**
Calculation	Buoyant eff. storage volume (Km^3)	0,351	0,480	0,638	**0,488**
Calculation	Buoyant storage capacity (Mt)	244,2	335,3	447,4	**341,7**



General geological setting	The structure is situated in the northern part of the North German Basin and has been defined at the level of the Lower Triassic Bunter SS Formation. The formation of the dome shaped structure is caused by post depositional halokenesis and formation of an underling salt pillow uplift.
Well database and seismic survey	The seal and reservoir are penetrated in the Rødby wells that are situated near apex of the structure. Some seismic data helps define the structure in the western part and only one line control spill towards the east which increases the uncertainties in the interpretation of this potential storage site. Poor quality seismic
Storage quality	Sandstones of the Bunter Formation is considered as the primary reservoir target in the Rødby structure with an expected average porosity up to 22 % and permeability around 300 mD (liquid permeability). The permeability interpretation is uncertain. Depth to top reservoir in approximated to by c. 1300m below msl., and the Bunter Formation is believed to 250m thick on average across the structure with a net/gross value is 0.46 which leads to a net sand thickness of c. 100-130 m. It is expected that the reservoir could be compartmentalised by minor faults and/or divided into individual reservoir zones by heteroliths and claystones.
Subsurface storage capacity	The closure is defined by a semi-circular domal structure approximately with potentially 450 m structural relief with fairly dipping flanks. The last closing contour is at 1525 m depth and defines an area of approximately 137 km^2. The spill point is situated towards the south towards the east but is uncertain. The temperature is expected to follow the Danish gradients (low end) with normal pressure gradient. These input values lead to an estimated maximum storage capacity of 365 Mt CO_2 for the Rødby structure.
Caprock (Seal)	The 160-170m fine grained Ørslev Fm were observed in the Rødby and Søllested wells and form the primary seal of the aquifer, fault that are reaching the surface might also penetrate the formation



CCUS Prospect Screening	
Country Denmark	*Contour inc* 25
Geographic datum GCS_European_1950	*Property name(s)*
Projection ED50-UTM32	*Date* 09/25/2020
Surface name Top Bunter Sst Fm (Depth 1)	*Signature* Lars Hjelm
Scale 1:125000	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LINE
TRACE
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693
924
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1866
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3517
3753
3994
4237
4479
4712
4949
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
Black grey white

Tønder Structure

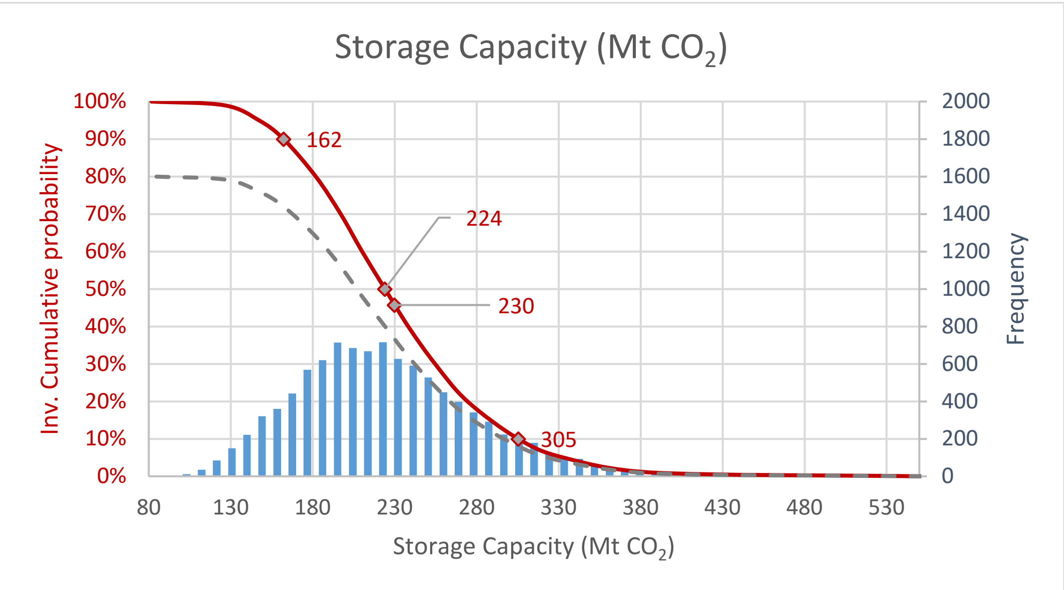
General	
Structure name	Tønder
Top Site Location	Onshore
Area potential (km^2)	58,97
Reservoir stratigraphy	L. Triassic
Reservoir Formation	Bunter SS Fm
Reservoir lithology	Sandstone
Reservoir Facies	Arid, continental environment (playa facies)
Top Seal Stratigraphy	Triassic
Top Seal Formation	Ørslev
Top Seal lithology	Mudstone
Top seal integrity	Several indications of faults are observed (not yet mapped). The dynamic halokinetic moving could easily force faulting
Top seal lateral extent	Believed to be continuous across structure
Trap configuration	Trap geometry is created from det development of the Tønder Salt pillow.
Offshore Fraction of max. areal (%)	0%

Risk assessment				
Category	**Element**	**Probability**	**Comments**	**Mitigation**
Geological	Seal	80%	Unproven at structure. Indication of several faults	3D seismic, pres-sure tests
Geological	Structure	100%	fairly well-defined geometry, Com-partmentalisation might occur as several faults are expected in this trans-tensional/pressional setting	3D seismic
Geological	Reservoir	100%	Drilled by several wells	
Engineering	Injection feasi-bility	100%		
Engineering	Seismicity	2%	Low	
Engineering	Groundwater contamination	2%	Low	
Cost	3D-seismic		High	
Cost	Drilling		Low	
Cost	Transport		Onshore	
QHSE	Environment		National and local authorities	
QHSE	Safety		Low	

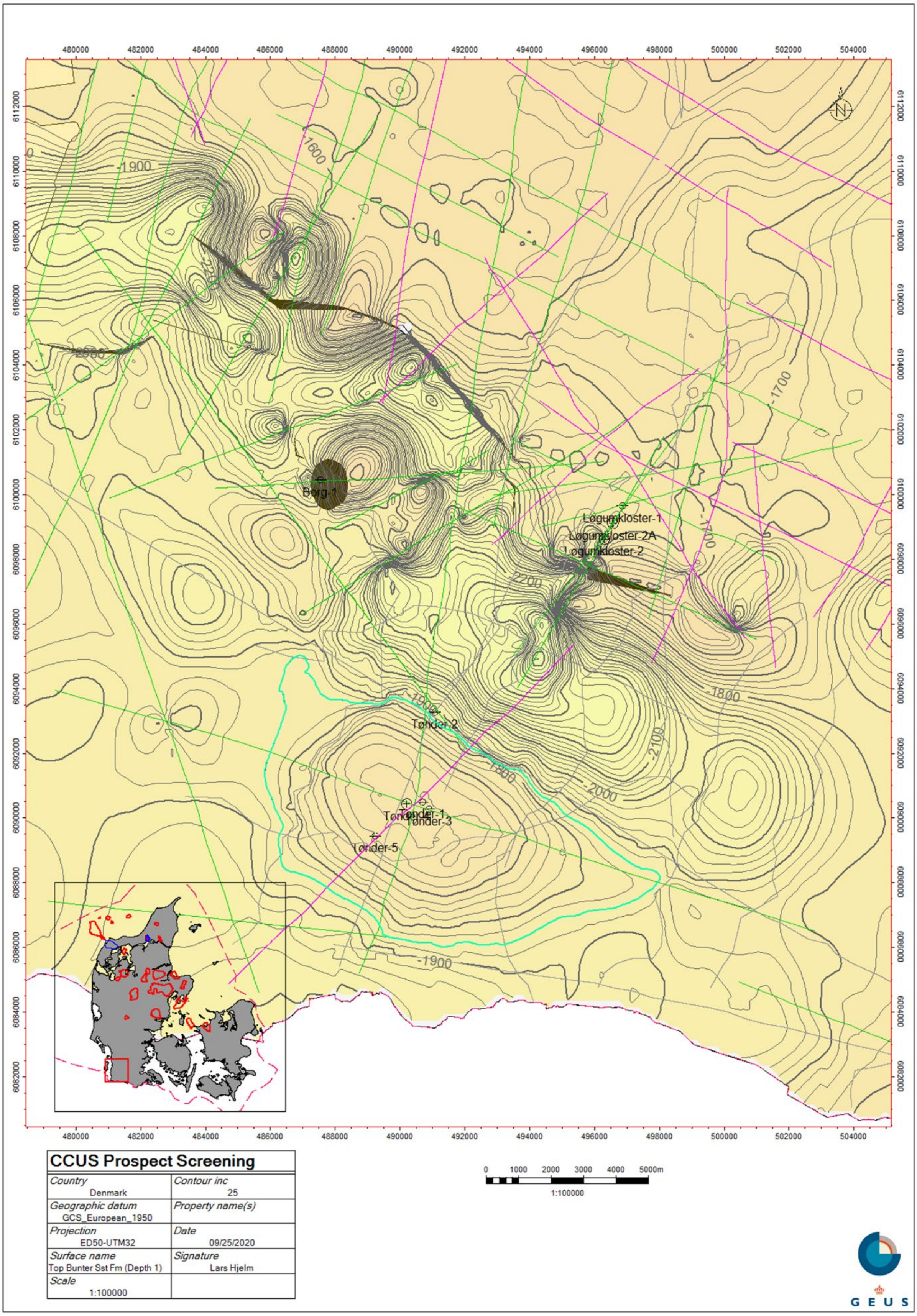
Volumetric		
Category	**Element**	**Comment**
Uncertainty	Spill point def.	Some uncertain still resides in the mapping and whether the structural spill towards the east is the shallowest spill point
Uncertainty	#_Line_Coverage	6 lines
Uncertainty	Apex def.	Drilled Fair control
Uncertainty	Top_Seal thickness	160-180 m
Mapped	Apex depth (TVDSS, m)	-1620
Mapped	Spill point depth (TVDSS, m)	-1850
Inferred	Structural relief (m)	230
Assumption	Permeability (Liquid, mD)	173
Assumption	Pressure (MPa)	18,1
Assumption	Temperature (>x, C)	70

Volume Assumptions		Min.	Mode	Max.
Assumption	Area	29,485	58,97	76,661
Assumption	Geometric corr. Factor	0,45	0,47	0,9
Assumption	Gross Thickness (m)	162,4	203	243,6
Assumption	Net/Gross (%)	0,592	0,74	0,9
Assumption	Porosity (%)	0,16	0,2	0,24
Assumption	Eff_Storage_Vol. Factor	0,399	0,4	0,401
Assumption	in-situ CO2 Density, kg/m^3	558	620	682

Storage Potential		P90	P50	P10	Mean
Calculation	Buoyant trapping pore volume (Km^3)	0,659	0,904	1,210	**0,925**
Calculation	Buoyant eff. storage volume (Km^3)	0,263	0,361	0,484	**0,370**
Calculation	Buoyant storage capacity (Mt)	163,0	224,5	301,2	**229,5**



General geological setting	The structure is situated in the northern part of the North German Basin and has been defined at the level of the Lower Triassic Bunter SS Formation. The formation of the dome shaped structure is caused by post depositional halokenesis and formation of an underling salt pillow uplift.
Well database and seismic survey	The seal and reservoir are penetrated in the Tønder wells that are situated across the structure. Only 2D seismic has been used to define the structure at this point. The structure is covered by a 3D seismic survey that will use moving forward.
Storage quality	Sandstones of the Bunter Formation is considered as the primary reservoir target in the Tønder structure with an expected average porosity up to 20 % and permeability around 300 mD (liquid permeability). The permeability interpretation is uncertain. Depth to top reservoir in approximated to by c. 1620m below msl., and the Bunter Formation is believed to 200m thick on average across the structure with a net/gross value is 0.75 which leads to a net sand thickness of c. 150 m. It is expected that the reservoir could be compartmentalised by minor faults and/or divided into individual reservoir zones by heteroliths and claystones.
Subsurface storage capacity	The closure is defined by a semi-circular domal structure approximately with potentially 230m structural relief with fairly dipping flanks. The last closing contour is at 1850 m depth and defines an area of approximately 60 km2. The spill point is situated towards the east or towards the west (uncertain). The temperature is expected to follow the Danish gradients (low end) with normal pressure gradient. These input values lead to an estimated maximum storage capacity of 230 Mt CO2 for the Tønder structure.
Caprock (Seal)	The 160-180m fine grained Ørslev Fm is observed in the Tønder wells and form the primary seal of the aquifer. Further investigation of the seals will be carried out on the available 3D survey


Borg-1
Løgumkloster-1
Løgumkloster-2A
Løgumkloster-2
Tønder-2
Tønder-1
Tønder-3
Tønder-5
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-1600
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CCUS Prospect Screening
Country
Denmark
Contour inc
25
Geographic datum
GCS_European_1950
Property name(s)
Projection
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Date
09/25/2020
Surface name
Top Bunter Sst Fm (Depth 1)
Signature
Lars Hjelm
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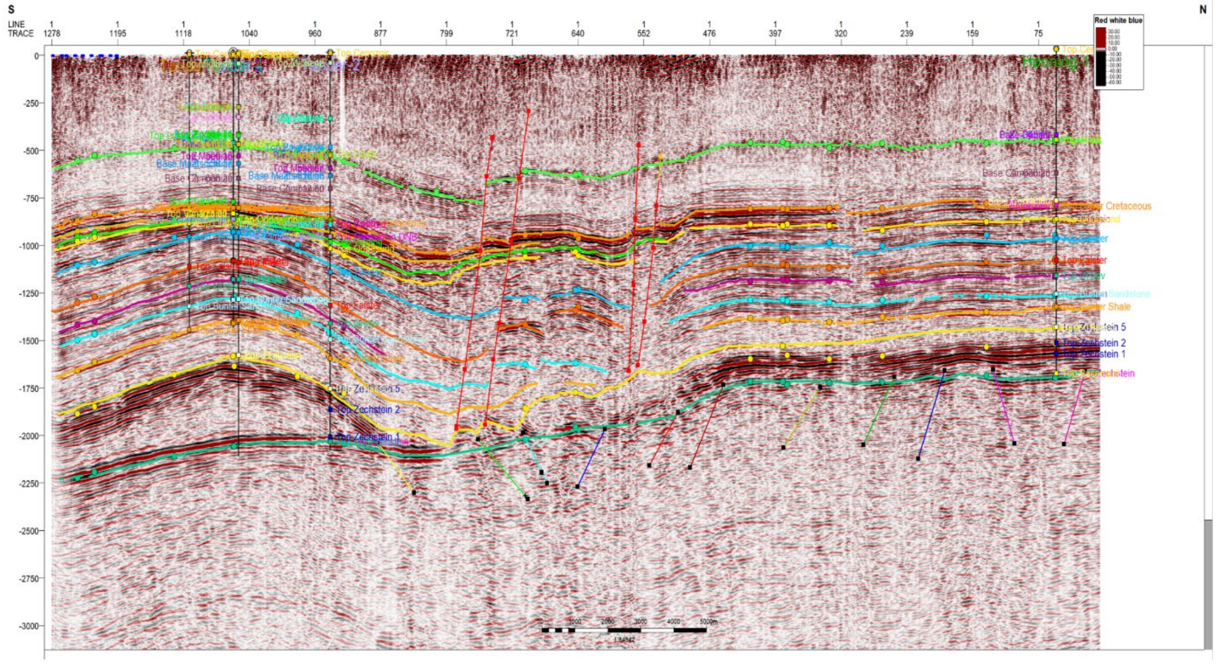

S
N
LINE
TRACE
Red white blue
Base Cretaceous
Top Zechstein 5
Top Zechstein 2
Top Zechstein 1
Top Zechstein
Base Campanian