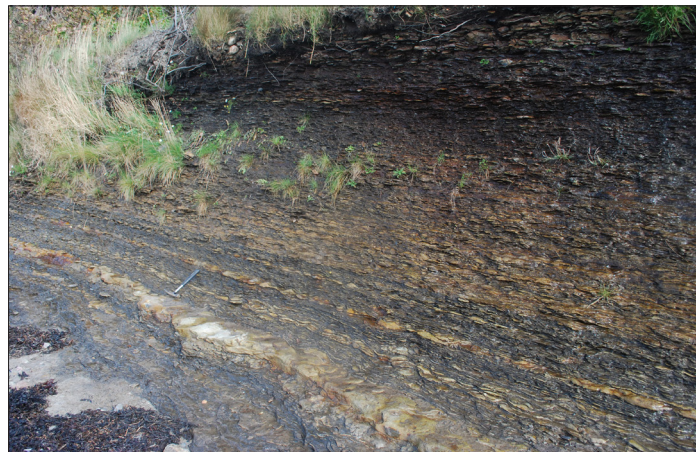


Subsurface geological setting in the Skagerrak area – suitability for storage of carbon dioxide

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Examensarbeten i geologi vid Lunds universitet,
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Bachelor's thesis
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Cover Picture: Sand and mudstones constituting a heterolite facies of Rhaetian, (Late Triassic), age in Kulla Gunnarstorp, Sweden (Calner 2011) .

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Abstract: As a part of a global attempt to mitigate impending climate change owing to increasing atmospheric CO₂ levels unconventional methods which may reduce CO₂ emissions are extensively researched. Carbon Capture and Storage (CCS) is considered to be a promising method for this purpose. As a consequence, worldwide prospection of geological sites in which CO₂ may be stored is currently underway. This thesis will be based on information from literature give a general introduction to CCS and thereafter present the geology in Skagerrak and thereafter evaluate the possibility for CO₂ storage in deep geological formations in the above mentioned area. A CCS infrastructure in the Skagerrak area could potentially be supplied with 14 MtCO₂, if storage of such volumes is possible it would greatly help the Scandinavian countries fulfill the climate goals regarding CO₂ emission reductions. The Skagerrak area is characterized by thick sedimentary sequences of Cambrian – Cretaceous age of which the Paleozoic sequences are severely faulted following Variscan orogeny related tectonism. Gently sloping undeformed sandstones and mudstones of Late Triassic – Middle Jurassic age inherit properties which are well suited for CO₂ storage. Results from models show that an injection of in total 250 MtCO₂ over 25 years is possible to attain without leakage in the Skagerrak Graben. Further studies are required to confirm that this area is suitable for storage of CO₂.

Keywords: CCS, Skagerrak, geology, CO₂.

Supervisors: Mikael Erlström, Mikael Calner.

Subject: Bedrock Geology

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Regionalgeologi i Skagerrakområdet – lämplighet för koldioxidlagring

DAVID WEIBULL

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Sammanfattning: Som en effekt av den globala strävan som syftar till att motverka klimatförändringar som tillskrivs ökande koldioxidnivåer i atmosfären försöker man hitta okonventionella sätt att minska koldioxidutsläpp. CCS anses vara en metod med stor potential för detta syfte vilket har föranlett en världsomspännande prospektering av platser som kan användas för geologisk lagring av koldioxid. Detta arbete baseras på en sammanfattning av tidigare publicerad litteratur som ska ge en översiktlig beskrivning CCSmetoden följt av en beskrivning av Skagerrakområdets geologi och dess förutsättningar för koldioxidlagring. Skagerrakområdet omgärdas av kustnära tung industri som årligen släpper ut fjorton miljoner ton koldioxid, en insamling och lagring av dessa utsläpp skulle hjälpa de skandinaviska länderna att uppnå de uppsatta klimatmålen gällande minskning av koldioxidutsläpp. Geologin i Skagerrakområdet är framförallt bestående av sedimentär berggrund avsatt under Kambrium fram till Krita. De Paleozoiska sekvenserna genomkorsas av förkastningar som uppkom efter den Variskiska Orogenesen och lämpar sig inte för lagring av koldioxid. Lätt lutande sand- och lerstenar avsatta från sen Trias till Krita verkar utifrån petrografiska egenskaper vara lovande för lagring av koldioxid. Resultat från simuleringar visar att en injektion av 250 miljoner ton koldioxid pågående under 25 år i sandstenar avsatta under Rät och Hettangium täckta av lerstenar från Sinemurium i Skagerrak kan ske utan risk för läckage i Skagerrakgravsänkan. Ytterligare undersökningar behövs för att ta reda på om området kan nyttjas för lagring av koldioxid.

Nyckelord: CCS, koldioxidlagring, Skagerrak, geologi.

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1 Introduction

As a result of the global approach to reduce atmospheric CO₂ in an attempt to reduce global warming, interest in the Carbon Capture and Storage, (CCS) technique has increased. A global search for finding sites which are suitable for CO₂ storage has initiated a re-evaluation of the geological feasibility for CO₂ storage in Sweden which was published by Erlström et al. (2011). In this publication the Skagerrak is mentioned as an area that has a potential to include suitable sites for geological storage of CO₂ in deep saline aquifers, however, more research is required in order to evaluate the area.

This bachelor thesis in Geology at Lund University corresponds to 15 points. The work presented here is the result of a literature study, which reviews numerous older and recent publications on the subject. A report from an EU Interreg IV project constitutes an important part of the presentation given below.

1.1 Aim and scope of this study

The main aim of this study is to gather, compile and evaluate the necessary conditions and thoughts concerning CO₂ storage in the Skagerrak area. Based on this information and the conclusions drawn from it I will try to determine if the CCS technique is feasible in the Skagerrak, primarily based on the geological premises. The scope of this study includes but is not limited to:

- What is CCS? Why is CCS necessary? Why is geology essential for CCS?
- What is the current status of CCS, in the World, in Scandinavia?
- The tectonic evolution of the Skagerrak, what geological features are interesting from a CCS point of view?
- Evaluating the potential for CCS in the Skagerrak.

2 Methods

2.1 Literature study

The list of publications that provide important details when writing this literature-based study was surprisingly quite large. Publications such as the IPCC special report on carbon dioxide capture and storage from 2007 and books by Shackley & Gough (2006) and Wilson & Gerard (2007) provided much of the core information about CCS.

Information about the more regional aspects of this paper was to a large extent based on different projects related to CCS. There are a number of ongoing and completed European projects which are often co-funded by governments, the EU and the industry. These projects have resulted in reports providing more elaborate information about all the aspects connected to CCS. A brief description of projects which have been significant for this study follows.

GESTCO, (European potential for Geological Storage of CO₂ from Fossil Fuel Combustion), lead by the GEUS, (Geological survey of Denmark and Greenland) and partially funded by the European Union have assessed the potential for CO₂ storage in Europe and its effectiveness in reducing CO₂ emissions from the industry until its completion in 2003.

EU GeoCapacity was a project which until 2008 investigated CO₂ emissions, infrastructure, potential storage sites and possible matching options of these parameters within the EU followed by economical evaluations.

CCS –Skagerrak/Kattegat was a Norwegian – Swedish project which published the Carbon Capture and Storage in the Skagerrak/Kattegat region Final report, marking the completion of this project in early 2012. This project was an Interreg IV project, which included partners of the Chalmers technical and Gothenburgh universities, the Energy Department of Västra Götaland in Sweden and some private companies and municipalities. The goal was to investigate the possibility of a multinational CCS infrastructure and collective solutions regarding capture transport and storage of CO₂ in the Kattegat/Skagerrak area. Much of the discussing and concluding chapters in this thesis are based on data from this project report.

3 Background

An extensive emission of carbon dioxide, which can be attributed primarily to the combustion of fossil fuels has induced a steady increase of CO₂ in the atmosphere during the past 100 years (Pachauri *et al.* 2008). Annual emissions of CO₂ during the period 1995 – 2004 were more than double the annual emissions between 1970 – 1994 (0,92 GtCO₂ compared to 0,42 GtCO₂ per year, respectively (Pachauri *et al.* 2008). Anthropogenic emission of CO₂ is responsible for an increase in atmospheric CO₂ concentrations of pre-industrial vales of 280 ppm to the 379 ppm of 2005 (IPCC, 2007). What effects this sudden change has on the climate, the ecology and many other parameters is currently widely debated; however, scientific consensus regarding the likelihood of substantial changes in climate has solidified as of late according to (Wilson & Gerard 2007).

Since the implementation of the Kyoto protocol a plethora of efforts to reduce global CO₂ emissions have been made. The EU and the UN climate panel, the Intergovernmental Panel on Climate Change (IPCC) have established climate goals which are intended to cause a “*Stabilization of greenhouse gas ... concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*” i.e. atmospheric CO₂ levels of 450 ppm by 2050 which would limit global warming to a maximum of 2°C compared to pre-industrial temperatures (IPCC, 2007a).

The climate goals have led to an agreement amongst the member states of the EU to reduce CO₂

emissions by at least 50% of 1990's levels by 2050; furthermore, 30% of the total energy production in the EU is scheduled to be renewable by 2020 (European commission, 2009).

The process of phasing over to using less carbon-intensive fuels, renewable energy sources and increasing efficiency in energy use are all core processes to reach climate goals. Moreover, the desire for this transition to take place is further catalyzed by steeper oil prices and the presence of an emission trading system (IPCC, 2007). Despite this, in order to reach the climate goals additional options to mitigate CO₂ emissions need to be researched and evaluated. The search for unconventional ways to reduce CO₂ emissions has resulted in the development of numerous different technologies which may be viable for this purpose, of which Carbon Capture and Storage is considered one of the most promising (IPCC, 2007).

4 CCS

4.1 Introduction

CCS is a fairly new technique developed in the 1990's which could possibly offer significant reductions in CO₂ emissions with viability regarding both technological and commercial aspects (Shackley & Gough, 2006; Wilson & Gerard, 2007). The method enables large point sources of CO₂ such as energy plants to be equipped with a system that allows chemical or physical absorption of CO₂ from combustion gases (Shackley & Gough, 2006). The captured CO₂ is then available for transport and subsequent storage. Out of several proposed storage options such as biological-, direct ocean- and geological storage, the latter is currently considered the most promising means of storage. In the case of geological storage, the captured CO₂ is transported in pipelines to a storage site where it is injected into a geological formation in which it is then locked up indefinitely (Shackley & Gough, 2006).

Geological storage of CO₂ is considered especially interesting due to the sheer storage capacity, which albeit previous overestimation and greatly varying figures depending on author is estimated by the IPCC to be on the order of 2000 GtCO₂. It is estimated that storage in geological formations initially would amount to a few GtCO₂/year which puts the former figure into context (Erlström, 2011; IPCC, 2007). Shackley & Gough (2006) state that the amount of point sources of CO₂ emissions which can be covered by CCS systems worldwide could equate to an estimated 20 – 40% reduction of CO₂ emissions from fossil fuel combustion.

Shackley & Gough (2006) mention that the transport and storage parts of CCS most likely has a cap regarding cost, which means that as soon as a transport and storage infrastructure, as in pipelines and injection wells, is established, there is little or no additional cost per volume of CO₂ that is stored. The capture part includes more maintenance and larger initial investments, such as large reconstructions and

an increased energy usage of 10 – 40%, and therefore accounts for the majority of the total cost of a CCS establishment. The safety of geological storage of CO₂ is not fully evaluated but assuming good site selection and evaluation and consistent monitoring it is most likely a very safe method (IPCC, 2007). Conclusively geological storage of CO₂ might, provided extensive further research, be a safe, relatively cheap and widely used means of reducing atmospheric CO₂ emissions.

4.2 Geological storage in deep saline aquifers

4.2.1 Applications

Currently there are only a few CCS operations in the world that inject >1 MtCO₂ per year, there are however many projects of varying size in the planning stage (Shackley & Gough, 2006). The purpose of many of the current and planned CCS operations is related to a process called Enhanced Hydrocarbon Recovery, (EHR) which allows extraction of otherwise unavailable gas or oil (IPCC, 2007). Another application of CCS is used in gas production on the Norwegian shelf, the extracted methane contains between 5 – 10% unwanted CO₂ which is separated from the methane and reinjected into the bedrock, in this case, this process prevents emission of approximately 1 MtCO₂ annually (IPCC, 2007).

4.2.2 Geological prerequisites

There are a number of different geological formations in which CO₂ can be stored, including deep saline aquifers, salt domes and depleted oil or gas fields (IPCC, 2007). Deep saline aquifers which occur in large sedimentary basins are thought to have a large potential for CO₂ storage. These sedimentary basins are filled with "fossilized groundwater" containing up to 20% dissolved salts which renders the water unsuitable for agricultural use and human consumption (IPCC, 2007). To efficiently store CO₂ it must be transformed into a supercritical state in which it inhibits properties similar to water. The transition takes place as gaseous CO₂ is subjected to 7.38 MPa of pressure combined with temperatures surpassing 31.1 °C (Erlström, 2011). A general rule of thumb is that the required pressure and temperature conditions are present at depths exceeding 800 m below the bedrock surface (Fang *et al.* 2010), hence the term geological storage in deep aquifers.

Geological storage of CO₂ in deep aquifer requires formations with structural features and physical properties that are more or less analogous to those in which hydrocarbon deposits are found. The necessary stratigraphic sequence has to be composed of two components, i.e. a trap and a seal, (Figure 1a).

The trap or reservoir rock is the formation in which supercritical CO₂ is injected, the CO₂ mixes with saline formation water and rises towards the top of the formation as in Figure 1. To allow storage of large amounts of supercritical CO₂ which quickly mi-

grates away from the injection well the trap should optimally possess the following properties according to Erlström (2011) and IPCC (2007):

- Large spatial distribution
- Thickness of >10 m
- High porosity and permeability
- Low level of diagenesis
- Homogenous lithology, e.g. mature sandstone.
- Located at 800 – 2500 m depth

The seal or cap rock which overlies the trap prevents vertical migration of CO₂ (Figure 1a and b). The trap is preferably composed of fine-grained clastic deposits such as claystone, mudstone or shale. The following properties are the most important for the seal cap rock unit (Erlström, 2011; Fang *et al.* 2010).

- Preferably >100 m thick
- No faults or fractures
- Low porosity and vertical permeability
- Homogenous lithology, e.g. a claystone without sand lenses
- Preferably semi-plastic which allows self-healing of faults or fractures

4.2.3 Geometry

Depending on the geometry of the formation the premises for CO₂ storage vary. The supercritical CO₂ is 30 – 50% lighter than the formation water and migrates towards the top of the formation. Similar to hydrocarbon deposits, anticlinal structural traps are excellent for holding the lighter CO₂ (Erlström, 2011). Apart from anticlinal traps, sloping open aquifers have recently been proposed as sites with large potential for CO₂ storage (Fang *et al.* 2010). In these aquifers the CO₂ will migrate primarily horizontally as opposed to vertically in anticlinal traps and as the horizontal permeability often exceeds the vertical permeability this

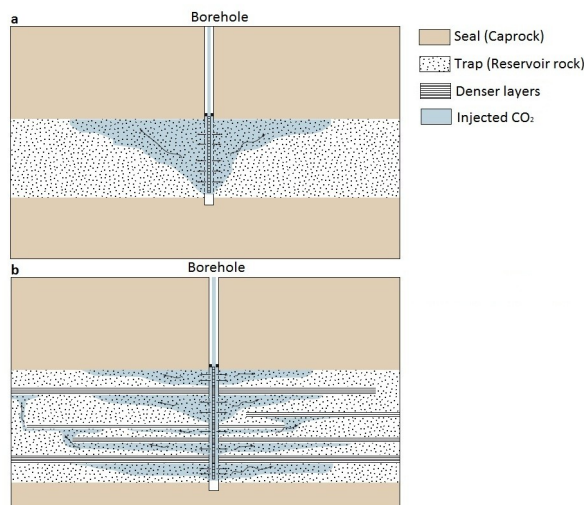


Figure 1: Generalized outline of homogenous (a) and heterogeneous (b) deep saline aquifers. Modified from (Erlström, 2011)

may allow storage of larger volumes of CO₂. Fault and stratigraphic traps are also often mentioned as potential candidates in the literature (Fang *et al.* 2010).

4.2.4 Trapping mechanisms

CO₂ is contained in the aquifer by four trapping mechanisms which operate on separate timescales (Fang *et al.* 2010). These are briefly described below and illustrated in Figure 2 (Fang *et al.* 2010).

4.2.4.1 Structural and stratigraphic trapping

The lighter CO₂ rises, displaces formation water and accumulates in the top of the aquifer just below the cap rock. This process is fairly rapid.

4.2.4.2 Residual trapping

As the CO₂ plume migrates upwards a large portion of the CO₂ is capillary trapped as the capillary forces exceed the rising capacity of the CO₂.

4.2.4.3 Solubility trapping

With time injected CO₂ will dissolve in the formation water. Predictions indicate that as much as 20 – 30% of the injected CO₂ is expected to be dissolved in the formation water after approximately 100 years. The CO₂ saturated formation water, holding up to 60 kg of CO₂ per m³ of H₂O, slowly sinks due to the increasing density.

4.2.4.4 Mineral trapping

The dissolution of CO₂ in formation water forms bicarbonate-, (CO₃²⁻), ions which may react with pre-existing minerals to form calcium-, ferrous- and magnesium carbonates. These reactions are slow and a noticeable effect is unlikely to be observed within 100's of years.

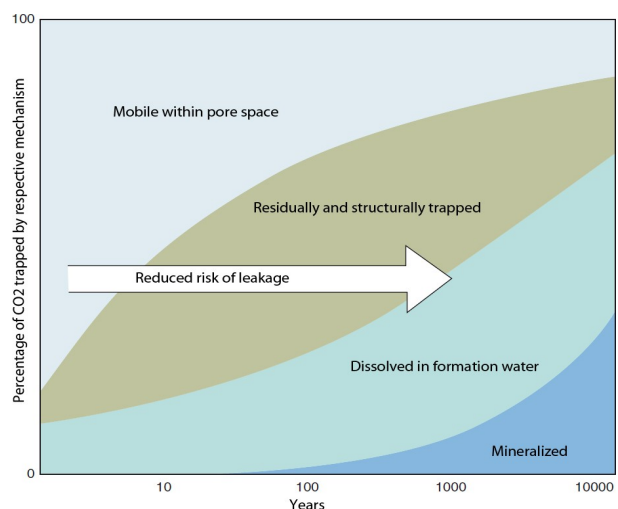


Figure 2: The figure shows what trapping mechanisms and how much influence each trapping mechanism has over 10 Ky. The larger portion of CO₂ trapped, the smaller is the risk of leakage. Modified after Erlström *et al.* (2011).

4.3 CO₂ storage in Scandinavia

The chapter below is based on Erlström (2011) and Bjørnsen *et al.* (2012). Despite the geological and industrial differences between Sweden and the rest of Europe there is a significant interest for CCS in Sweden. CCS is supported both by the abundant heavy industry and by the government in Sweden which considers CCS to be a technique that is required to fulfill the EU climate goals.

As a consequence of this endorsement, the Swedish geological survey (SGU) was assigned to update, re-evaluate and present the potential for geological storage of CO₂ in Sweden. The potential for geological storage in Sweden is quite limited and restricted to the Cambrian sandstones in the southern Baltic Sea and the Jurassic sandstones in Scania and southern Kattegat. It is concluded that the potential sites are often distributed across national boundaries and thus it is strongly suggested that cooperation with adjacent countries is established. The potential for CO₂ storage is much larger in Denmark due to the presence of thick sequences of sedimentary bedrock. In addition to the promising geological situation, Denmark has experience from extensive hydrocarbon exploration and consequently far better data coverage, qualifications and resources for evaluation and identification of potential storage sites. Furthermore Denmark has participated in numerous international research projects regarding CCS and the evaluation of geological storage of CO₂ in Denmark is very well on its way.

Possibly as a consequence of the above mentioned reasons the Interreg IVA CCS –Skagerrak/Kattegat project funded by EU, local industries and regional and national authorities started in June 2009. The goal of this project was to explore the feasibility of establishing a CCS infrastructure in the Skagerrak/Kattegat area, involving assessment of economical and technical parameters but especially focusing on identifying possible storage locations. The project was built around the three adjacent large clusters of industries located in Gothenburg, Aalborg and Southern Norway which combined with other large emission sources in the region annually emit 14 MtCO₂. A CCS infrastructure in the Skagerrak area could thus, prevent the emission of this of CO₂ which corresponds to roughly 25% of the reduction in CO₂ emissions that the Nordic countries have agreed on for 2020. The launch of a CCS operation would most likely promote future industry establishments in proximity to a CCS infrastructure in the Skagerrak area, the estimated area of interest is within the dotted circle in Figure 3 (Bjørnsen *et al.* 2012).

The presence of suitable formations for CO₂ storage has been studied and evaluated by the Geological Survey of Denmark and Greenland (GEUS). Their assessment in combination with results from the CO₂STORE project indicate relatively good possibilities for finding suitable storage sites in the Skagerrak area (Christiensen and Larsen, 2003). Based on the provided information, the Skagerrak area seems to be a

place which is well suited for a multinational CCS project. It is however of great importance that the geology of the area is carefully evaluated.

5 The Skagerrak

5.1 Geological setting of the Skagerrak area

The Skagerrak is a relatively deep sea located in between the North Sea and the Kattegat (Figure 3) (Larsson & Stevens 2008). The Skagerrak is situated upon the Skagerrak/Kattegat platform (SKP) which is bounded to the North and East by the Precambrian Fennoscandian Shield (Figure 4) (Bjørnsen *et al.* 2012). The gently westwards down sloping Fennoscandian Shield, (Figure 7), is overlapped by a sedimentary rock cover varying from very thick (Cambrian – Silurian) sequences to Triassic - Jurassic sand- and mudstones with thicknesses of 100's of meters. These formations are overlapped by thinner Jurassic, Cretaceous and Tertiary sequences, and ultimately by 50 – 100 meters of Quaternary deposits (Ro *et al.* 1990b; Lie *et al.* 1993; Rise *et al.* 2008a). The sedimentary outcrops become successively younger further away from the Swedish – Norwegian shoreline, (Figure 4) , additionally the average sediment thickness increases to the SW, with maximum sediment thickness of nearly 9 km at the Fjerristslev Fault (FF) (Ro *et al.* 1990b).

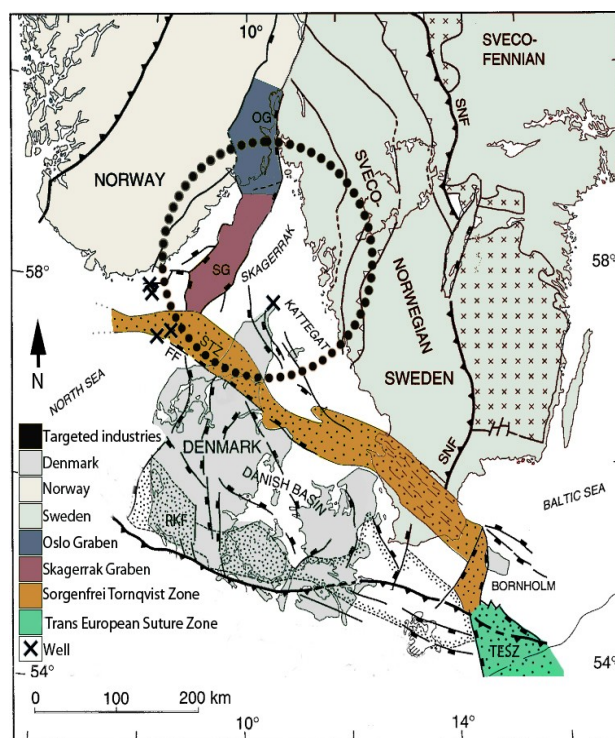


Figure 3: Tectonic map of southern Scandinavia. Several geological features are highlighted, including the Danish Basin, the Sorgenfrei-Tornquist Zone, the Skagerrak Graben and the Oslo Graben, noted with STZ, SG and OG respectively. The Fjerristslev Fault, (FF) delimits the Fjerristslev Fault Zone from the Danish Basin, the FFZ can be considered a continuation of the STZ). Modified from Thybo (1997).

Several large scale tectonic structures are present in the Skagerrak (Liboriussen *et al.* 1987). The Late Palaeozoic Oslo Rift constitutes two structural elements, the Oslo Graben, (OG) and further SW, the Skagerrak Graben (SG) of the same age (Figure 3 and 4). The Skagerrak Graben is demarcated by two parallel NW – SE trending faults, (A and B in Figure 4) (Ro *et al.* 1990b). The Sorgenfrei-Tornquist Zone (STZ) (Figure 3), a complex tectonic zone which began to form in Early Palaeozoic time is the continuation of the Trans-European Suture Zone (TESZ). The STZ trends in a NW – SE fashion and separates the stable Fennoscandian Shield from the less stable Danish basin (Liboriussen *et al.* 1987).

Despite rigorous exploration and studies of the adjacent North Sea, including thousands of boreholes and seismic lines produced during hydrocarbon exploration, the subsurface geology of Skagerrak has remained largely unexplored due to the lack of hydrocarbon deposits. Interpretations of seismic data from the Skagerrak are presented by several authors eg. (Ro *et al.* 1990a; Ro *et al.*; 1990b, Thybo, 1997). However, information from wells is limited to a single one in Skagen and a few in the western Skagerrak, marked as black crosses on Figure 3 (Thybo, 1997) and have been presented and interpreted by Nielsen (2003).

5.2 Geological history of the Skagerrak area

Knowledge about the tectonic evolution of an area which may be defined for storage of CO₂ is most essential. Fault patterns, fracturing, basin evolution and tectonic setting strongly affect the risk assessment regarding storage longevity and containment of the injected CO₂. A comprehensive geological setting and geological history of the southern margin of the

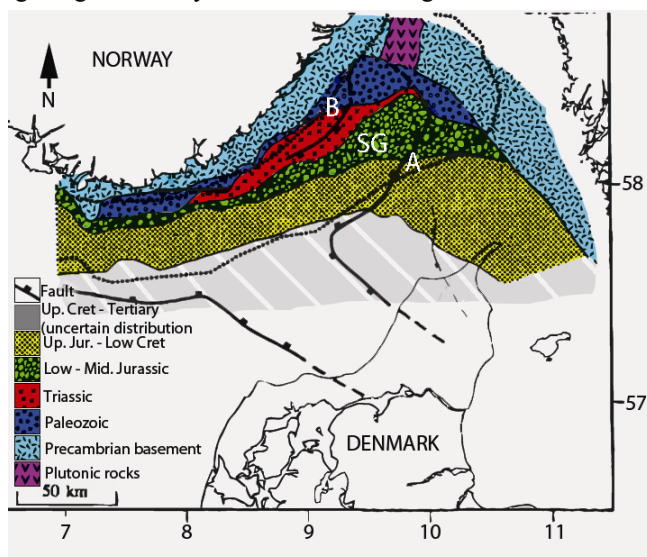


Figure 4: The distribution of sedimentary facies of varying ages in the Skagerrak area. Note how the relative age of the sediment decreases away from the Fennoscandian Shield. Note the faults marked A & B which delimitates the Skagerrak Graben. Modified from (Ro *et al.* 1990b)

Fennoscandian Shield is therefore presented in the appendix. This next chapter will however only briefly present the main tectonic events and the features which are significant for CO₂ storage in this area. During the Palaeozoic, thick sedimentary sequences of Cambrian, Ordovician and Silurian age accumulated in the Oslo rift, the Skagerrak and adjacent areas. Of these sequences, the majority is Silurian sediments, often several km thick, (Figure 7), which were deposited in more or less pronounced foreland basins which formed during the Caledonian orogeny (Ro *et al.* 1990a). Due to persisting tectonic activity following the Caledonian orogeny, the Skagerrak area was uplifted during the Late Silurian and much of the Palaeozoic sequences were removed by erosion, the erosive surface is clearly visible in Figure 6 (Liboriussen *et al.* 1987).

In Late Carboniferous time, (320-300 Ma), large parts of NW Europe was subject to a large scale tectonic event, the Variscan orogeny which as a consequence of the collision of Euramerica and Gondwana, formed the supercontinent Pangea (Thybo, 1997). This event reactivated the STZ by dextral wrench tectonics which furthermore induced SW – NE sinistral oblique or normal faulting which formed the Skagerrak Graben and further north the Oslo Graben. A simplified model of the tectonic regime in the Skagerrak area during Early – Middle Permian is presented in Figure 5.

The deep Skagerrak graben and the sediments which subsequently accumulated within it is depicted in Figure 6 and 7, it is one of the main structural elements which may allow CO₂ storage in this area (Bjørnsen *et al.* 2012). Following the Late Permian subsidence, sandstones belonging to the lithostrat-

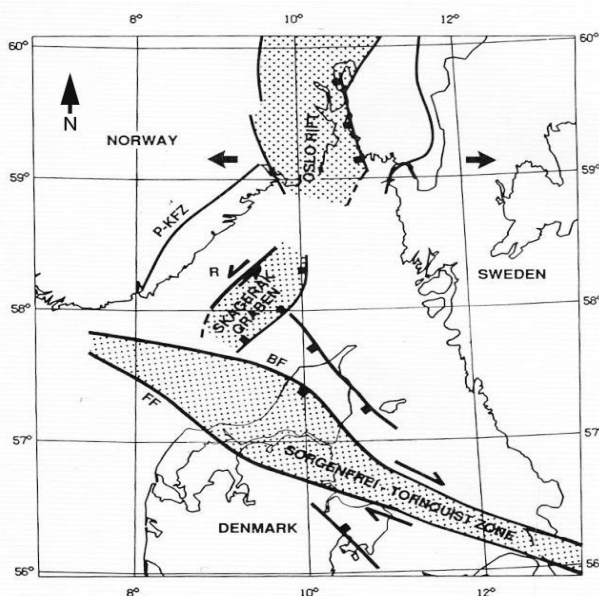


Figure 5: Early – Middle Permian tectonic regime in the Skagerrak area. Dextral strike slip fault along the STZ. Sinistral oblique- or normal faulting along the Skagerrak Graben, normal faulting due to relative extension demarcates the Oslo Graben. Modified from Fannavoll (1994).

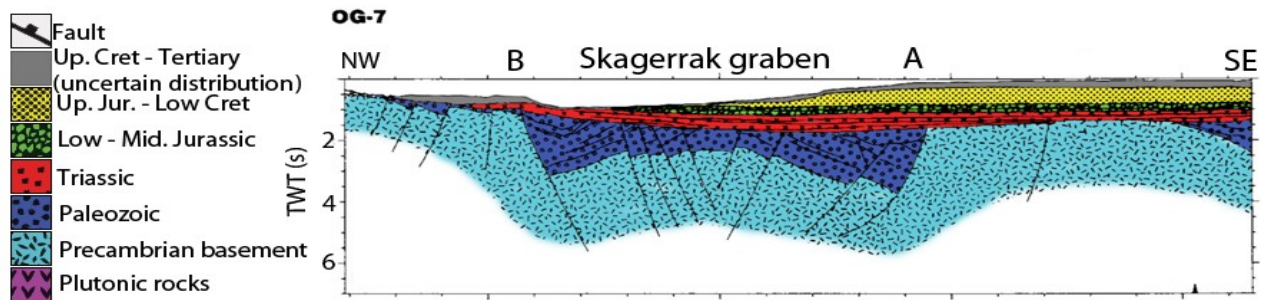


Figure 6: Vertical cross section through the Skagerrak Graben. Fault A and B which defined the Graben in Late Carboniferous – Early Permian times are clearly visible. The domal mid rift features is an effect of a conjugated movement of the two Skagerrak Graben boundary faults A and B. Modified from (Ro *et al.* 1990b).

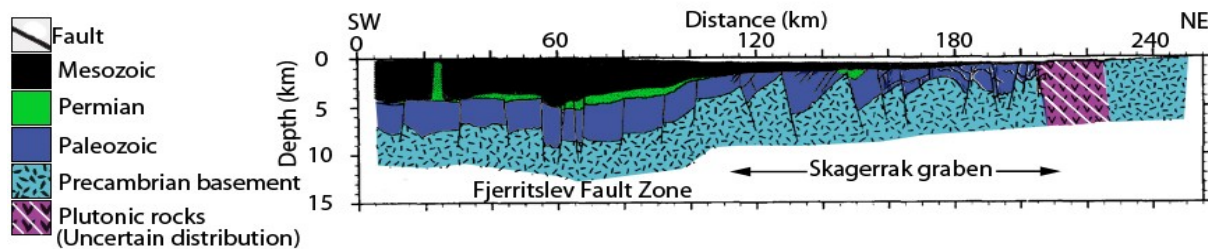


Figure 7: Cross section along the Skagerrak Graben. The exact distribution of plutonic rock in the NE is speculative and directly related to the plutonic rocks in the Oslo Graben. Note the large tilted blocks in the Skagerrak Graben, related to oblique sinistral strike slip movements (Figure 5). Also noteworthy is the large difference in Mesozoic sediment thickness in the Skagerrak Graben and the FFZ. The Permian Zechstein salt diapir formations in the SW correlates with the erosional infill in the Skagerrak Graben. Additionally the sloping Precambrian basement is apparent in this figure. Modified from (Ro *et al.* 1990a).

tigraphic unit Rotliegend accumulated over large parts of northern Europe. The Rotliegend sandstones are partly composed of erosional volcanoclastic material derived from Variscan orogeny related massive plutonic rock extrusions and might also be suitable for CO₂ storage (Heeremans, 2004; Michelsen & Nielsen, 1993).

During the Mesozoic, primarily Early Triassic until Early Cretaceous, thick sedimentary sequences dominated by sandstones and mudstones were deposited in the Skagerrak area. Sandstones belonging to the Skagerrak, Gassum and Haldager Sand formations were deposited and interlayered by very thick mudstones of the Fjerritslev and the Flyvbjerg & Børglum formations, effectively forming a trap and seal type of sequence which might be suitable for CO₂ storage (Heeremans, 2004). These sequences and their approximate distribution are described by the red, green and yellow areas in Figure 4 and 6. The Mesozoic sequences are deformed due to salt tectonics in the SW parts of Skagerrak (Figure 7 and 9). Movements of the thick Zechstein halite deposits of Late Permian age have formed anticlinal structural traps which may be used for CO₂ storage (Bjørnsen *et al.* 2012). Cenozoic sequences are more or less absent in the Skagerrak area due to Late Mesozoic uplift of the Fennoscandian Shield (Nielsen, 2003). Quaternary muds mainly of Weichselian age cover the Mesozoic sedimentary sequences, (Figure 12) (Longva *et al.* 2008; Rise *et al.* 2008b).

6 Results and discussion

6.1 Storage potential in the Skagerrak

Since this thesis mainly focuses on the geological issues related to the multi-disciplinary CO₂ storage research area, it will suffice to say that the other aspects regarding capture, transport, legal issues and so on concerning CO₂ storage in the Skagerrak are only briefly discussed or not discussed at all in this thesis. In depth information about the mentioned areas as well as other significant matters are presented in their full extent in (Bjørnsen *et al.* 2012).

Of the many different ways in which CO₂ can be stored in geological media only a few of these methods are available in the Skagerrak region. A primary screening of potential options in the Skagerrak and surrounding areas was compiled by Bjørnsen *et al.* (2012) and is briefly summarized below.

- Permian sandstones of the Rotliegend unit along the STZ and northern Jylland.
- Triassic and Jurassic sandstones of the Skagerrak, Gassum, Haldager sand and Frederikshavn formations present in eg. the SG and the STZ.
- Rhaetian – Hettangian salt diapirism

6.2 Assessment and further screening of storage options

6.2.1 Rotliegend sandstone

The Roetliegend sandstone unit was believed to be able to act as a trap formation in which CO₂ could be

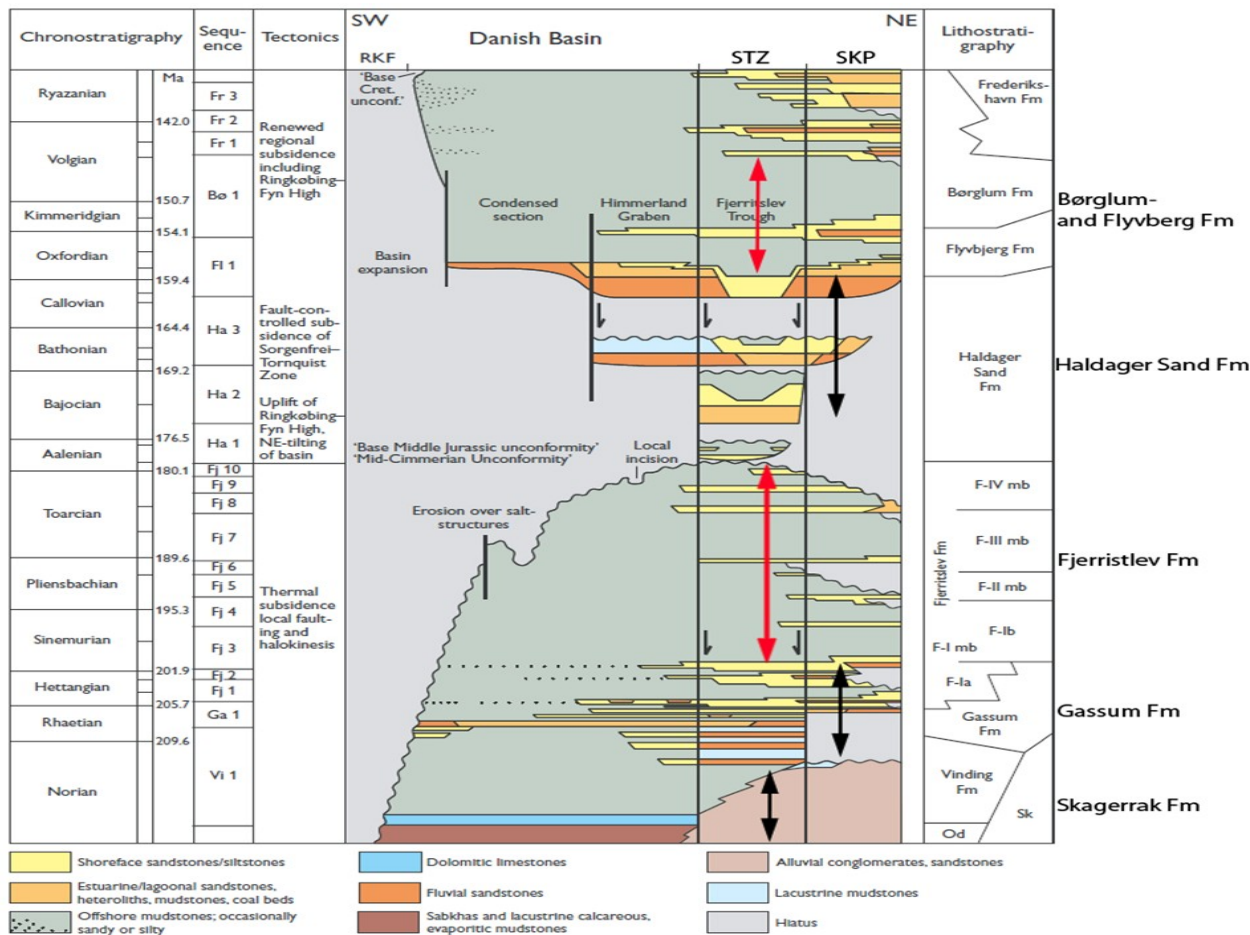


Figure 8: Stratigraphic cross section from the SW located Ringkøbing–Fyn High throughout Danish Basin and to the Skagerrak – Kattegat platform presenting rough distribution of Triassic, Jurassic and lowest Cretaceous sedimentary rock. The major formations are presented along with the depositional environment, lithology as well as relative age. Note the numerous hiati and relatively less sediment thickness in the SKP compared to the STZ and the Danish Basin due to the limited accommodation space as a result of relatively low subsidence rates (Modified from Nielsen, L. H.).

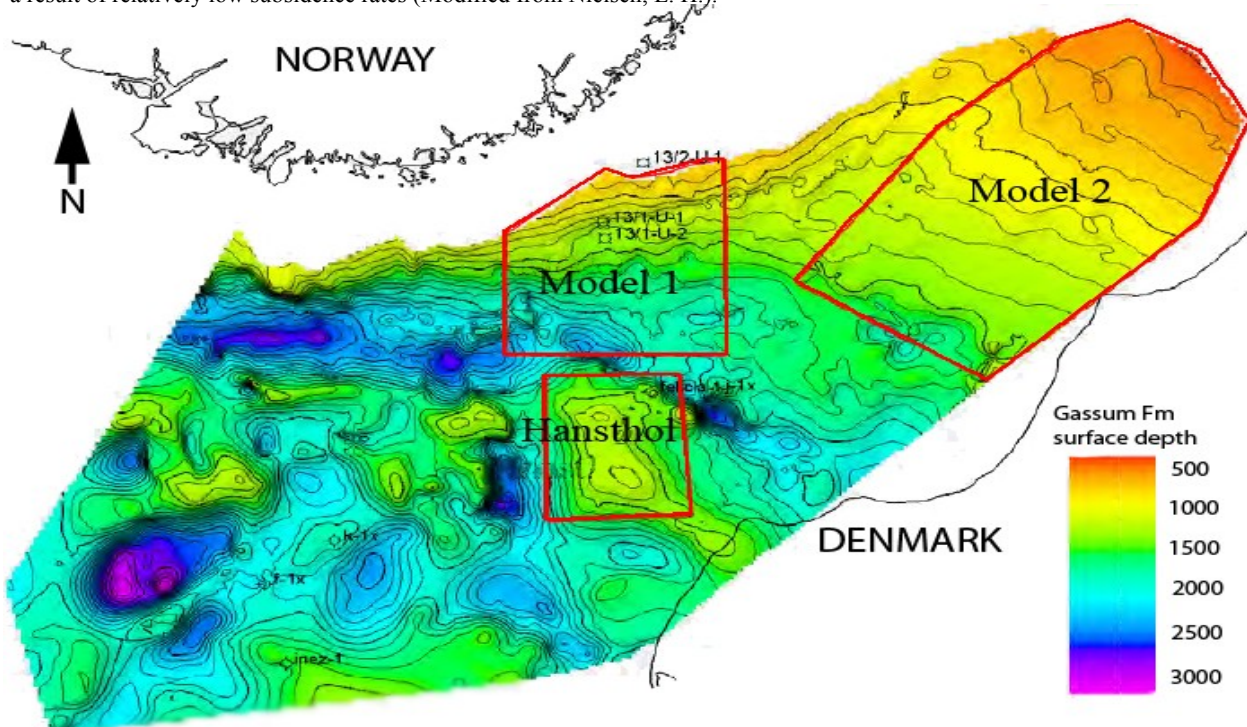


Figure 9: Seismic model showing the depth to the top of the Gassum Fm in the Skagerrak and adjacent North Sea. The locations of the evaluated areas Model 1, 2 and Hansthol are delimited by red lines. Note the unmistakable NE tilt in the Skagerrak and the evident uplifted domal structures due to salt diapirism at the Hansthol structure and further west. Modified from Bjørnsen *et al.* (2012).

stored. The overlying Zechstein halites as well as the Middle Triassic marl- and claystones are most likely impermeable and could therefore act as a seal. Aggregative, the two formations could enable geological CO₂ storage similar to that described in Figure 1 A (Bjørnsen *et al.* 2012). This possibility has however been dismissed due to three main reasons as follows.

- A large content of volcanoclastic material in the sandstone as much of the sediment was an erosional product of the contemporary evolving plateau lavas.
- Excessive burial of the sandstone
- Excessive thermal conditions accompanied with the Late Carboniferous – Early Permian rifting and coeval massive igneous activity

All of the above mentioned points contribute to increased cementation of the sandstone with reduced porosity and permeability as a result (Bjørnsen *et al.* 2012). Moreover, as is mentioned in the geological prerequisites chapter, the optimal burial depth is between 800 – 2500 m while the Rotliegend sandstones are located at depths often exceeding 5 km (Figure 7). Due to these circumstances, this option is deemed unsuitable for CO₂ storage (Bjørnsen *et al.* 2012).

6.2.2 Triassic—Jurassic sequences

Considering the large abundance of Mesozoic sandstones eg. the Skagerrak, Gassum and Haldager sand formations which may act as reservoir rocks and the thick vast mudstones of the Fjerritslev and Børglum & Flyvbjerg formations which could behave as seals suggests that the prospects of finding suitable plays are good (Figure 8). The Mesozoic plays have not undergone any significant tectonics and is compared to the Palaeozoic formations (Figures 6 and 7) more likely to be well preserved and structurally intact which furthermore reduces the possibility of CO₂ leakage through the seal.

If leakage should occur through the thick mudstones of the Fjerritslev Fm and the Flyvbjerg & Børglum formations it is likely that the up to 200 m thick quaternary sequence composed of mud (Bjørnsen *et al.* 2012), (Figure 12 A and B), will prevent further vertical migration. Quaternary pre- postglacial muds of similar thickness compose a seal in the newly discovered Peon shallow gas field which houses an estimated 15 – 30 billion m³ of methane gas, hence it can be considered a very effective seal (Bjørnsen *et al.* 2012, Statoil.com, 2012)

The Mesozoic sequence is tilted (Figure 7 and 9) due to onshore uplift and offshore subsidence, partly due to differences in postglacial rebound magnitudes. This property opens up for the possibility CO₂ storage in sloping aquifers as suggested by Fang *et al.* (2010). Cretaceous inversion tectonics, which is significant in the North Sea and Western Europe, is partly responsible for the presence of hydrocarbon bearing aquifers in these areas (Kockel, 2003). The Skagerrak

area however inhibits very little of this structural feature and thus largely lacks anticlinal aquifers with the exception being anticlinal structures related to halite tectonics in the westernmost Skagerrak.

6.2.3 Zechstein halite domes

The Permian Zechstein halites have due to the viscous low density properties of deeply buried salts given rise to large scale salt tectonics (Figure 7 and 9) in the westernmost Skagerrak and bordering Norwegian Danish Basin (Hospers *et al.* 1988). These salt movements have resulted in large domal structures which caused superimposing Mesozoic strata to attain an anticlinal form while retaining both the trap and the seal features. These features could prove to be excellent structural traps in which CO₂ can be stored.

Based on these premises one can conclude that the most promising sites for CO₂ storage in the Skagerrak area are the sloping Mesozoic plays in the Skagerrak Graben area and the anticlinal Mesozoic successions in the western Skagerrak. Similarly the screening of potential storage sites in the report by Bjørnsen *et al.* (2012) suggested three potential storage sites for CO₂ located in the above mentioned areas which are delineated in Figure 9.

6.3 Evaluation of storage options

To be able to evaluate the possibility for CO₂ storage in the sites presented in Figure 9 a number of properties of each site the must be investigated and evaluated, these involve:

- Potential of CO₂ storage based on injectivity and storage capacity.
- Safety aspects such as adequate sealing, geological stability and basin pressure.
- Cost, mainly based on the amount of drilling injection and exploration wells needed.

Following this evaluation a summarizing chapter will try to rank the sites based their properties.

Table 1: Various sets of data from the Gassum Fm showing eg. consistently high porosity values. The temperatures are above the required 31,1 °C and the pressure most likely surpasses the 7,38 MPa needed for gaseous CO₂ to transcend into supercritical form (Bjørnsen *et al.* 2012).

Well	Depth [m]	Porosity [%]	Permeability [mD]	Temperature [°C]	Salinity [ppm NaCl]
F-1x	2,100	20,4	90	71	175,000
K-1x	2,000	23,7	220	68	175,000
J-1x	1,800	20,1	85	62	160,000
Felicia-1	1,600	-	-	56	150,000
Børglum-1	1,450	28,6	650	51	140,000
Thisted-1	800	27	470	32	90,000
Mors-1	2,800	21,8	130	92	240,000
Inez-1	1,700	22,7	170	60	150,000
Sæby-1	1,100	23,4	200	41	110,000
Terne-1	1,200	17,7	40	44	120,000
Ronde-1	2,700	15,1	15	90	160,000
Vedsted-1	1,900	24,1	240	65	170,000

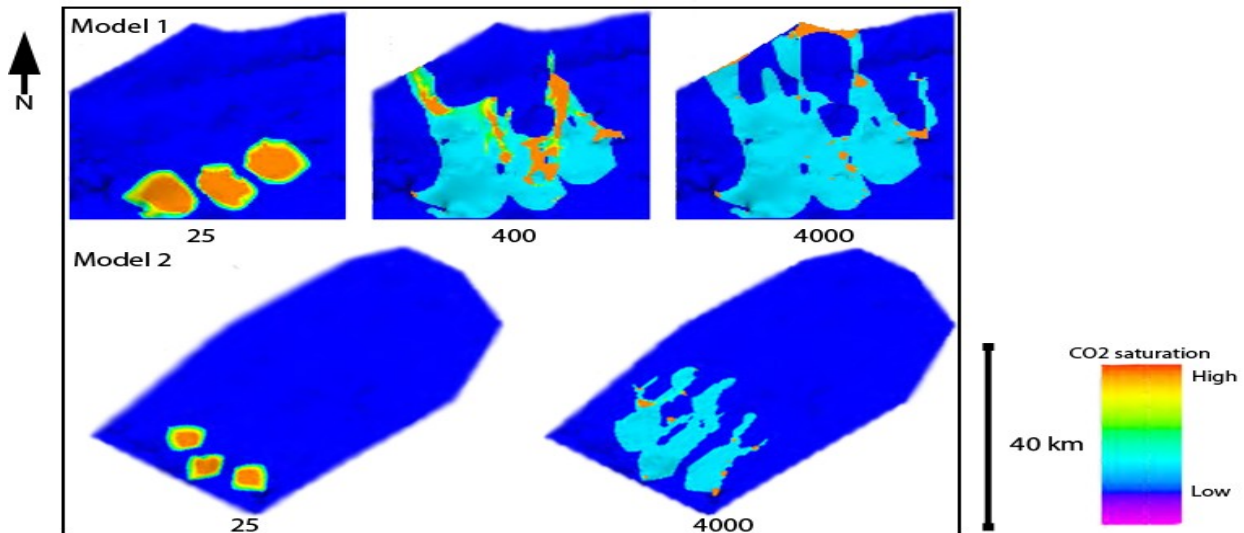


Figure 10: Estimated CO₂ plume migration in model 1 (above) and model 2 (below) after 25, 400 and 4000 years respectively. Modified after Bjørnsen *et al.* (2012).

6.3.1 Storage potential

The storage potential of a saline aquifer, as in the case of the Gassum and Haldager Sand formations, is mostly controlled by the storage capacity and the injectivity of the formation (Cinar *et al.* 2009). The storage capacity determines the amount of CO₂ that can be stored in a formation and is largely dependent on the volume, porosity and the volumetric and microscopic displacement efficiencies of the formation (Cinar *et al.* 2009). According to Fang *et al.* (2010) and Bachu *et al.* (2007) the evaluation of storage capacity of a saline aquifer is very difficult due the different trapping mechanisms acting on separate time scales it can however momentarily be achieved by numerical modeling which has been done in the report by Bjørnsen *et al.* (2012). Modeling of the potential storage volumes of an aquifer might also be obstructed by the presence of aquifer heterogeneities, faults, geochemical parameters and temperature (Erlström, 2011).

While the storage capacity is largely a volumetric unit of measurement, the injectivity is a parameter which quantifies the possibility of introducing a fluid to a formation, (in this case supercritical CO₂), and at which rate the fluid can be injected. The injectivity is determined mainly by the permeability and the fracture characteristics of the formation, especially in the exact proximity of the site of injection (Fang *et al.* 2010; Cinar *et al.* 2009).

Geological reservoir models for the selected sites presented by Bjørnsen *et al.* (2012) are based mostly on the parameters mentioned above. However as exact measurements many parameters are hard to measure in situ they are based on e.g. formulas as in the case of permeability data which were derived from empiric porosity data from the Gassum, Haldager Sand, and the Skagerrak formations (Bjørnsen *et al.* 2012). The temperature data were based on a model which assumed a surface temperature of 8°C and a temperature gradient of 30°C/km. Porosity data and

the permeability formula used in the models were determined from well logs and core samples which were supplied along with other reservoir parameters, such as reservoir water salinity data, by the GEUS (Bjørnsen *et al.* 2012). All of the above mentioned parameters regarding the Gassum Fm are supplied in Table 1 below.

According to Erlström (2011) the needed porosity for CO₂ storage to be suitable varies between a minimum of 10 – 15% with optimal conditions being between 20 – 30% porosity. The mean porosity in the Gassum Fm according to data from 12 wells located in adjacent areas is 22.5% which can be considered excellent (Bjørnsen *et al.* 2012). The relationship between porosity and permeability derived by GEUS suggests permeabilities between 15 and 650 mD with a mean of 210 mD (Bjørnsen *et al.* 2012). Erlström (2011) suggests that sandstones with permeability values close to or exceeding 100 mD are suitable for CO₂ storage, it is therefore likely that injectivity will be sufficiently high to allow for CO₂ storage in the Gassum Fm. The calculated temperatures and pressures at this depth in the Gassum Fm are almost certain to exceed the needed 31.1 °C and 7.38 MPa needed for the CO₂ to be in a supercritical state. The mean temperature in the data compiled by (Bjørnsen *et al.* 2012) is 61°C and the pressure is calculated to exceed 7.38 MPa is present on the order of 800 m of depth, compared to the planned injection depth of 2000 m (Bjørnsen *et al.* 2012). The thickness of the Gassum Fm in the Skagerrak Graben varies between 50 – 300 m but the average seems to be about 125 m (Bjørnsen *et al.* 2012). Erlström (2011) recommends a minimum thickness of 20 m for the trap, depending on author this value varies, eg. Fang *et al.* (2010) and IPCC (2007) proposes that a reservoir rock thickness of >10 m is sufficient. The seal integrity needs to be preserved to prevent leakage and the cap rock needs to be thick enough to withstand a large increase in reservoir pressure following injection of CO₂. Since the injectivity of a

reservoir is highly individual, the increase in reservoir pressure is likewise specific for each site. This poses a demand to develop scenarios and model on how much pressure the seal can withstand before fracturing which is directly related to both the former parameters and of course the thickness of the cap rock. Erlström (2011) proposes a >100 m thickness of the caprock to eliminate leakage. This thickness is most certainly reached by the Fjerritslev Fm, and most likely also by the Flyvberg- and Børglum formations as well as the uppermost 100 – 200 m of Quaternary till and muds (Bjørnsen *et al.* 2012). Furthermore, the Mesozoic formations are sloping, open aquifers of model 1 and 2 (Figure 9), which means that formation pressure will not increase at the same rate as in a closed aquifer, such as the Hanstholm structure and thus more CO₂ may be injected.

There are a number of reasons to why the Gassum Fm is ranked over the Haldager sand Fm regarding CO₂ storage potential. Primarily, the relatively shallow top surface of the Gassum Fm in the NE Skagerrak (Figure 9) means that the Haldager Sand Fm is located even closer to the surface, which could possibly result in insufficient pressure and temperature which prevents CO₂ from going into supercritical state. Moreover the sealing capacities of the formations overlying the Gassum Fm are superior to those of the Haldager Sand Fm, especially since the latter lacks the thick Fjerritslev Fm seal. Lastly, the thickness of the Gassum Fm averages about 125 m thick in the Skagerrak Graben, compared to the Haldager Sand Fm which often is very thin, (0 – 30 m) in the same location.

Conclusively the formation of choice for storage of CO₂ in the Skagerrak is the Gassum Fm, in which Bjørnsen *et al.* (2012) made three separate models for as many sites which are shown in Figure 9. Full information regarding model parameters and relationships are not presented in their full extent in Bjørnsen *et al.* (2012). A separate technical report will later supply all details and the matter will therefore not be discussed further in this thesis besides what has already been presented earlier in this chapter.

6.3.2 Model results

If no other reference is mentioned, all of the information below is based on the Carbon Capture and Storage in the Skagerrak/Kattegat region Final report by Bjørnsen *et al.* (2012).

The three models presented by Bjørnsen *et al.* (2012), (Figure 9) include two dipping traps represented by Model 1 and 2 and the anticlinal Hanstholm structure. Models 1 and 2 represent open or semi-closed boundary conditions to the NW and N respectively, the Hanstholm structure however is a closed reservoir. All three models assumed a total of 250 MtCO₂ injected over a period of 25 years and simulated the following CO₂ plume migration over 4000 years while taking the main trapping mechanisms into account. In all models three wells were used respectively in which 3.33 MtCO₂ was injected an-

ally, equivalent to 10 MtCO₂/yr. The injection depth in was slightly larger in model 1, 2410 m, compared to 1708 m in model 2, as a natural consequence of the mentioned tilted nature of the Gassum Fm (Bjørnsen *et al.* 2012). The results from models 1 and 2 are shown in Figure 10 which show the injection points located down-flank of the dipping formation to control plume migration.

The CO₂ plume, distinguishable from the elevated CO₂ saturation in the formation water, has migrated to the open boundary of the formation after 4000 years in model 1. After 4000 years about 74.5% of the injected CO₂ has been capillary bound, about 18% has been dissolved in formation water and the remainder of the injected CO₂ has escaped from the trap. Model 2 shows more promising results as migration has been spatially limited and after 4000 years all injected CO₂ has been either capillary bound, (76%), or dissolved in formation water, (24%), hence all injected CO₂ is immobile after 4000 years according to these model simulations. Injection into the Hanstholm structure was performed at depths of 1000 – 1200 m. The CO₂ plume migrated as expected towards the top of the structural trap where 12.5% was dissolved in formation water with the remainder being capillary or structurally trapped after 4000 years.

6.3.3 Safety aspects

There are substantial physical, geomechanical and geochemical uncertainties regarding CO₂ storage in the Skagerrak that need to be addressed and investigated prior to an actual project launch. Some of these uncertainties are raised in the report by Bjørnsen *et al.* (2012) which summarized include:

- Increasing reservoir pressure following injection of CO₂ eventually exceeding fracture pressure.
- The exact geometries of the trap and seal formations and potential lateral migration of CO₂ between the two.
- Leakage through undetected fractures and faults in the seal and furthermore leakage through injection wells.
- Exact CO₂ plume migration pathways.

The uncertainties regarding rapidly increasing reservoir pressure were assessed in the report. The main pressure component that is discussed is the bottom hole pressure (BHP) which is directly related to the injectivity which in turn relates to the permeability and thus porosity of the reservoir rock. The event of the BHP rising and exceeding a certain pressure level may result in fractures in the seal. To avoid fracturing of the seal during injection and thus subsequent leakage of CO₂ a safe pressure increase must be estimated. The safe pressure is mainly determined by the relation between the hydrostatic and the lithostatic pressure as in the the pressure exerted by the formation fluids and

the pressure applied by the overlying bedrock. At greater depths the difference between the two increases which allows a higher BHP before fracturing takes place. In this case the safe pressure increase is assumed to be around 75% of the lithostatic pressure. The model derived BHP in model 1 and 2 suggests increases of around 80 bar at the start of injection which later increase to up to just over 90 bar (Bjørnsen *et al.* 2012). In the case of the BHP rising excessively, several actions can be taken to reduce it, for instance a certain amount of the CO₂ can be injected in the overlying Haldager Sand Fm which will reduce the BHP in the Gassum Fm. The CO₂ injection can also be distributed over a higher number of wells, as the BHP increase is very local.

The modelled BHP in the Hanstholm structure structure exceeds 160 bar which is considered to be too high, as a consequence, even though the structure is voluminous enough to allow storage of some 250 MtCO₂ it does seem to be unsuitable due to mentioned BHP issues. The difference in BHP between the Hanstholm structure and the dipping formations in models 1 and 2 most likely can be attributed to the open – semi closed reservoir characteristics of the latter as opposed to the closed reservoir of the former.

It is stated in the report that a more detailed characterisation of the trap, the seal and the overlying sediments are required to identify important parameters regarding storage capacity and safety. One might suggest that one of the key steps which may allow further progress is to recover a number of cores from the Skagerrak Graben area which, as mentioned earlier, has never been done before.

6.3.4 Cost

It is hard to estimate the cost of CO₂ storage in the Skagerrak Graben, however the main component is the actual drilling and construction of the wells. The actual cost is strongly influenced by the reservoir properties porosity and permeability, favourable properties will result in the need for fewer wells and allow increased storage volumes and thus lower costs, thus the cost is highly variable and needs extensive exploration and evaluation. Secondary lower costs are monitoring during and after the injection process, exploration wells and decommissioning.

7 Conclusions

To be able to fulfill the various climate goals regarding atmospheric CO₂ it is necessary to look into all possible ways in which CO₂ emissions can be reduced by cost efficient means CO₂ storage in deep aquifers is currently undergoing heavily investigations over the entire globe and is thought to be feasible option which is implementable in a large amount of different areas. CO₂ storage in the Skagerrak and adjacent areas has been evaluated in the report by Bjørnsen *et al.* (2012) which come to the conclusion that the Mesozoic sandstones in the Skagerrak Graben could be used to store

at least 250 MtCO₂ over 25 years. This figure corresponds to a storage of 10 MtCO₂ annually, which is equivalent to approximately 70% of the >0.3 MtCO₂/year point source emissions within the dotted circle in figure 3 (Bjørnsen *et al.* 2012). Further site studies and models especially focused on formation pressure and CO₂ migration pathways will be needed to exactly determine the storage potential of this site.

The most promising approach is considered to be injection of CO₂ in down dipping open shoreface sandstones of Hettangian – Sinemurian age of the Gassum Fm which is covered by thick mudstones of the Fjerritslev Fm of Early Jurassic age and muds of Quaternary age. The CO₂ is according to models expected to be well contained within the formation over a course of 4000 years after which the CO₂ is immobile. However the availability of data is sparse and comprehensive further studies of the lithology and structural elements in the area are needed to fully evaluate the possibilities for CO₂ storage in the Skagerrak.

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 Accessed 8th May 2012.

10 Appendix

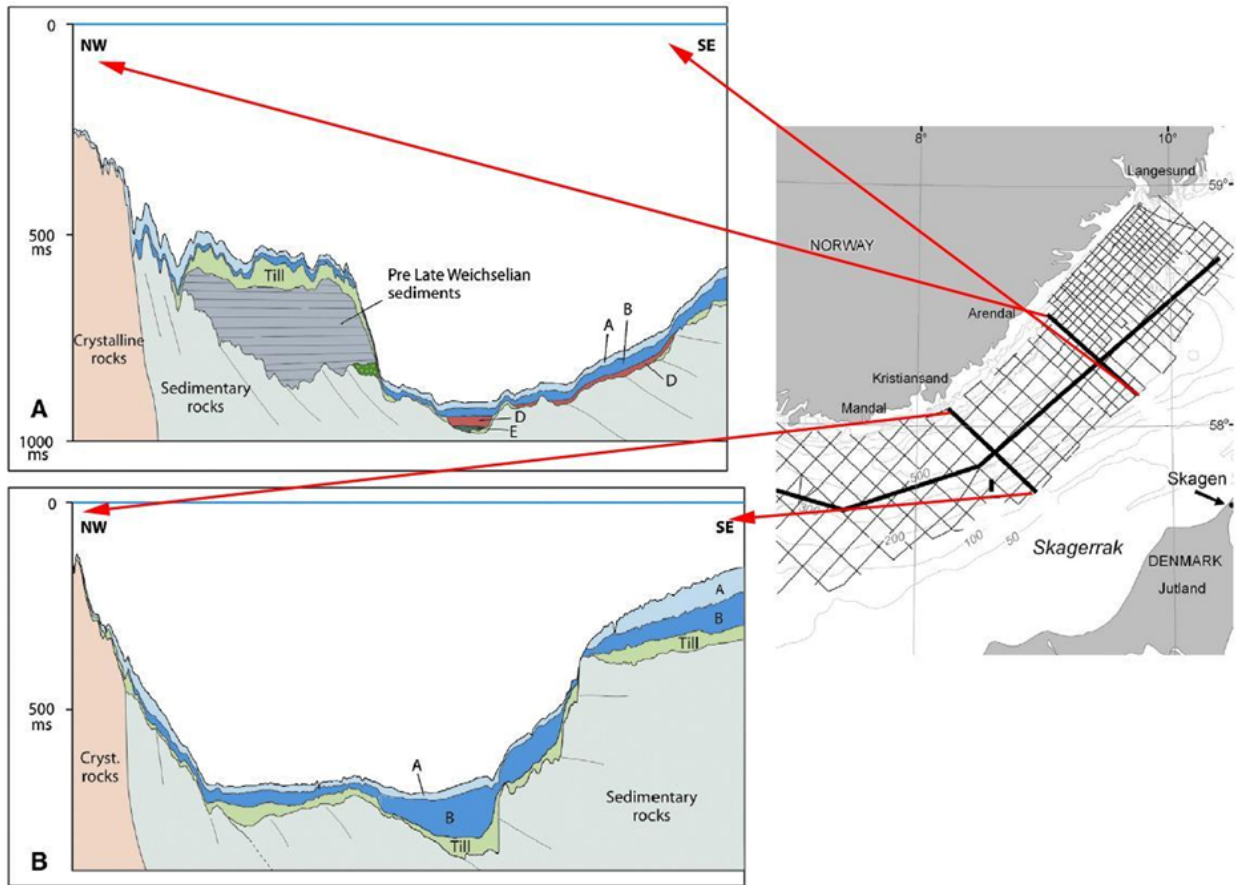


Figure 11: Profile of quaternary successions in the Norwegian channel interpreted from seismic profiles. Pre Late Weichselian sediment is lacking except for on the ‘Arendal Terrace’ to the left in profile A. Weichselian sedimentary cover is present as sequences E, D and Holocene post glacial muds are present as A and B. Modified from (Rise *et al.*)

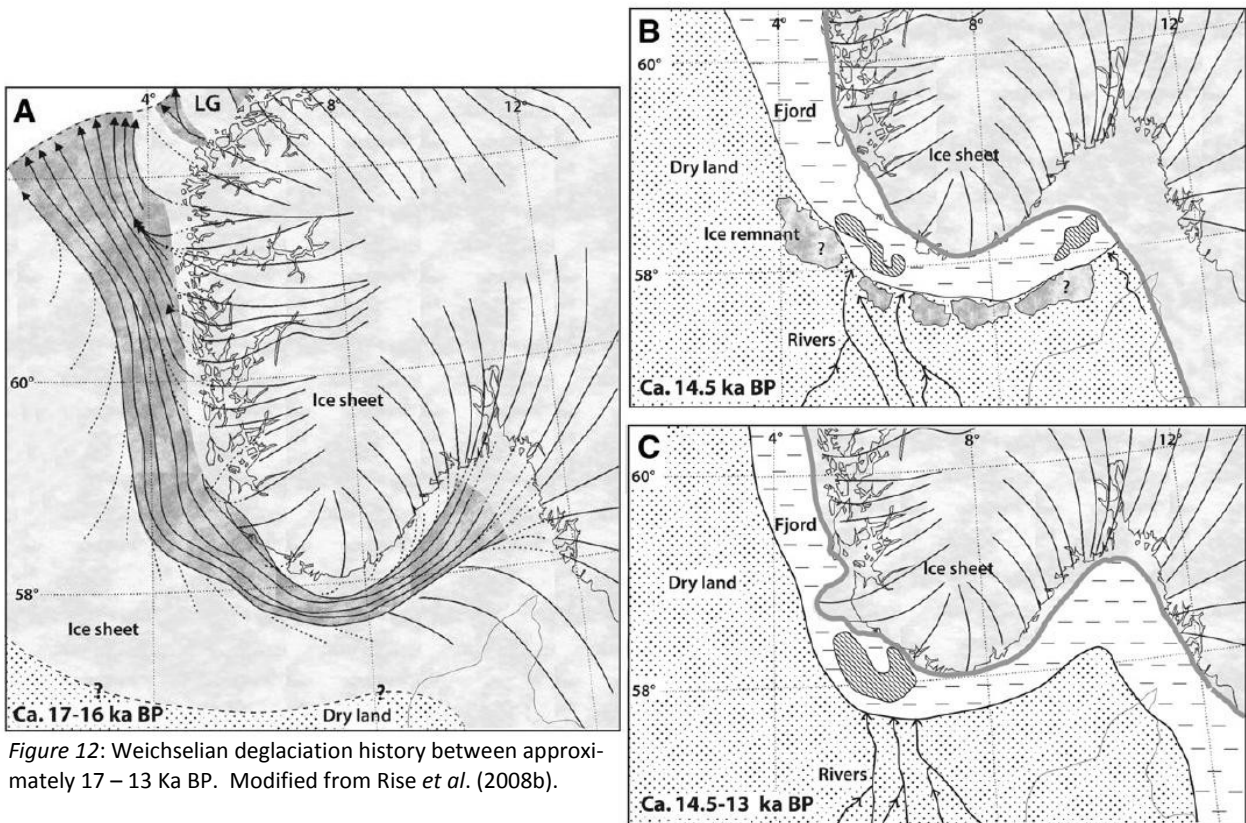


Figure 12: Weichselian deglaciation history between approximately 17 – 13 Ka BP. Modified from Rise *et al.* (2008b).

10.1 Comprehensive geological setting and history of the southern margin of the Fennoscandian Shield

10.1.1 Precambrian

Since the Latest and most significant Precambrian deformation, the Sveconorwegian orogeny (1200 – 950 Ma) the Baltic shield was left with a N – S oriented fault system, the Sveconorwegian deformation front (Thybo, 1997) by large, although, the northern Skagerrak region exhibits a typically NE – SW trending fracture direction (Lindh, 1980; Ro *et al.* 1990a). (Berthelsen, 1978) as cited in (Ro *et al.* 1990b) imply that the Precambrian Sorgenfrei-Tornquist Zone, with its northwestern continuation, the Fjerritslev Fault Zone (FF), (Figure 3) was a relatively unstable transition zone between the stable Fennoscandian Shield and the deep sedimentary basins of the NW Europe. Lateral movement amongst the STZ and FF was comparatively small and was most likely caused by crustal thinning (Liboriussen *et al.* 1987). The extensional tectonics, likely accompanied with the presence of a foreland basin related to the Sveconorwegian mountain range gave rise to the Precambrian sedimentary basin predecessor to the Oslo Rift, at around 650 Ma (Ro *et al.* 1990b, Liboriussen *et al.* 1987, Ro *et al.* 1990a).

10.1.2 Palaeozoic

10.1.2.1 Cambrian – Silurian

The Fennoscandian Shield, denuded the Sub-Cambrian peneplain, was during Early Palaeozoic a shallow continental shelf environment. A Cambrian – lower Ordovician eustatic sea level rise gave rise to a thin widespread sedimentary cover (Ro *et al.* 1990a). The Caledonian orogeny, initiated during the Middle – Late Ordovician slightly reactivated the STZ and formed a series of horsts and Graben structures along the fault zone, eg. the Fjerritslev through (Ro *et al.* 1990a). The crustal loading applied marginal to the Baltic plate, eg. south of the Ringköping Fyn High (illustrated as a dotted area in southern Denmark on Figure 3) due to the Caledonian orogeny caused development of pronounced foreland basins in the Oslo Rift and less such in the Skagerrak and adjacent areas (Michelsen & Nielsen, 1993).

The formation of foreland basins in the Skagerrak, Kattegat and present Oslo Graben areas was followed by periodically rapid sediment deposition in the predecessor to the Oslo Rift which is indicated by thick Cambrian – Silurian sediment (Ro *et al.* 1990a). Meanwhile the Skagerrak, the Kattegat and the STZ along with neighboring areas subsequently evolved into sedimentary basins (Liboriussen *et al.* 1987). Thick sequences of Cambrian, Ordovician and Silurian sedimentary marine deposits were deposited in these areas. Around 2 km of these sediments are preserved in the Skagerrak and locally in the STZ up to 6 km of sediment is preserved, indicating that these basins were major depocenters (Ro *et al.* 1990a). According

to Michelsen & Nielsen (1993), sedimentation was catalyzed by Late Silurian rapid subsidence in the Skagerrak Kattegat regions and the present day Oslo Graben. The undeformed Early Palaeozoic sediment present in the Skagerrak, Kattegat and present day Oslo Graben regions supports the theory that the above mentioned regions area were likely a stray of rapidly subsiding foreland basin corresponding to the Caledonian orogeny which induced deposition of massive upper Silurian shales, especially in the present day Oslo Graben (Michelsen & Nielsen, 1993; Liboriussen *et al.* 1987).

During Late Silurian time most of Denmark was subject to uplift originating from persisting tectonic activity related to the Caledonian orogeny. This event along with probable infill of the foreland basins resulted in widespread profound erosion of the Palaeozoic sedimentary bedrock (Liboriussen *et al.* 1987). The belief that most of the implicated regions were situated above the sea level as a consequence of uplift is further supported by data from (Ro *et al.* 1990b), showing that upper silurian marine sediment followed by Late silurian continental-, and according to Heeremans (2004) deltaic sediment is present in the Oslo Graben, indicating large scale Late Silurian uplift and regional relative regression. Furthermore Devonian sediments are accordingly not apparent in Denmark or within the present day Oslo Rift.

10.1.2.2 Devonian – Middle Carboniferous

The general tectonic situation in the Devonian – Middle Carboniferous was most likely a further minor extension along the STZ companionated by slow subsidence (Thybo, 1997). The distribution of Early – Middle Carboniferous sediment is most likely very patchy as it according to well data from Michelsen & Nielsen (1993) is missing from large areas of the Kattegat and Skagerrak. Well data from Liboriussen *et al.* (1987) indicate complete lack of concerning sediment short of a well on the island of Falster, southernmost Denmark, Carboniferous rocks might therefore have covered the Kattegat/Skagerrak region as well as Denmark. The hiatus which connotes the lack of a stratigraphic record of the Devonian – Middle Carboniferous makes reconstruction of the regional tectonic situation difficult.

10.1.2.3 Late Carboniferous – Permian

In Late Carboniferous time, (320-300) Ma, large parts of NW Europe was subject to a large scale tectonic event, the Variscan orogeny which as a consequence of the collision of the Euramerica and the Gondwana formed the supercontinent Pangea (Thybo, 1997). The tectonic setting which originally was characterized by minor extensional movements was altered and a dextral wrench tectonic regime took place along the STZ (Figure 5) (Heeremans, 2004). The Variscan wrench tectonics reactivated the STZ which caused the Palaeozoic basin infill to become transected by a complex and extensive fault and rift system (Liboriussen *et al.*

al. 1987).

Contemporary with the episodes of rifting, and as a reason of the former, widespread magmatic events occurred in the NW Europe which formed widespread plateau lavas eg. along the eastern margin of the STZ from the Kattegat platform and especially in the Oslo Rift (Heeremans, 2004). The main extrusions of plateau lavas continued throughout the Early – Middle Permian and initiated from the southern regions and further propagated northwards and terminating with the formation of cauldrons and volcanoes in the central Oslo Graben (Ro *et al.* 1990a; Ro *et al.* 1990b).

While it is certain that the Oslo Rift, in reality the Skagerrak- and Oslo Graben, formed during the Late Carboniferous – Permian tectonic events the exact tectonic movements that were active are not as clear (Fannavol, 1994). Even though the formations are much related it is suggested that the Oslo Graben formed by as a pull apart basin (Ro *et al.* 1990a) whereas the NW bounding fault, (Fault B, Figure 4), of the Skagerrak Graben, may have formed as a cause of sinistral oblique slip faulting according to Fannavol, S. (1994). One might propose the possibility of a synergic tectonic action, featuring both extensional- and oblique slip faulting events. Regardless of the exact tectonic history, the Late Carboniferous rifting and Graben formation and large scale tilting which in turn allowed preservation of Cambrian – upper Silurian sediments in both the Oslo and the Skagerrak Graben (Figure 6) (Ro *et al.* 1990a). The main rifting phase was most prominent during Early – Middle Permian times and formed the tilted Graben structures shown in Figure 6 (Heeremans, 2004). The down-tilted grabens are most likely filled with Early – Middle Permian sedimentary rocks (Heeremans, 2004). While post and pre rift sediments are not distinguishable in Figure 6, the more recent sediments are displaced towards the encompassing faults pre rift as the older Palaeozoic strata have been subject to considerably erosion in the central parts of the Graben (Heeremans, 2004).

The domal mid-rift feature shown in Figure 6 is probably an effect of a conjugated movement of the two Skagerrak Graben boundary faults A and B. It might also relate to an intrusion of plutonic rock in the central parts of the rift, similarly to the situation in the Oslo Rift (Ro *et al.* 1990b; Heeremans, 2004). The Late Palaeozoic sediment deposited along the down tilted boundary faults most likely originates partly from the erosion of fault scarps and partly of volcanoclastic material, a syn- post depositional erosional product from the contemporaneous massive plutonic rock extrusions in the region (Heeremans, 2004).

This lithostratigraphic unit is known as the Rotliegend, it is present in the form of thick widespread volcanoclastic sediment in adjacent areas, eg. 650 m of upper Carboniferous – Early Permian reworked volcanoclastic sediments within the STZ (Heeremans, 2004) and 1500 m of similar sediment in northern Jylland (Michelsen & Nielsen, 1993).

Towards the Middle – Late Permian thermal

relaxation and subsequent subsidence, perhaps enhanced by a second active tectonic mechanism according to Van Wees *et al.* (2000) began to set in further west towards the north sea (Heeremans, 2004). The relative transgression allowed deposition of clastic and volcanoclastic sediment belonging to the Rotliegend unit over wide areas of northern Europe (Heeremans, 2004).

Towards the Late Permian, during a time of tectonic quiescence, evaporates of the Zechstein unit were deposited in the Danish basin and in the North Sea, SW of the FFZ (Figure 7) (Ro *et al.* 1990a). The Zechstein series consists of up to 1000 m of halites along with sulphate and carbonate banks in the Danish basin and thins out towards the STZ zone. The Zechstein series is more or less absent in the Skagerrak (Liboriussen *et al.* 1987).

10.1.2 Mesozoic

During Early Mesozoic time NW Europe was subject to an Early Triassic rifting phase involving reactivation along the STZ under an extensional regime (Liboriussen *et al.* 1987). Ro *et al.* (1990b) suggests however that there was no or very slight reactivation of the Skagerrak Oslo Graben faults. The crustal extension induced a rapid subsidence along the FFZ, (Figure 3) which allowed accumulation of some 6000 m of Triassic – Jurassic sediment on the sloping Precambrian shield, (Figure 7) (Liboriussen *et al.* 1987). This hypothesis is in agreement with the findings of (Michelsen & Nielsen, 1993) who emphasize the difference in sediment thickness between the relatively thin sequences resting on the Skagerrak – Kattegat platform to the massive Triassic sandstones located along the STZ and the NW-ward continuation the FFZ (Figure 7 and 8). Michelsen & Nielsen (1993) considers that the divergence in sediment thickness stems from greater subsidence rates and subsequent sedimentation in the STZ and the FFZ compared to the Skagerrak. The rapid subsidence is attributed primarily to thermal cooling and local faulting (Nielsen, 2003).

Both Crustal extension and coincidentally subsidence rates decreased in the northern Denmark during the Late Triassic, however according to Liboriussen *et al.* (1987) the tectonic regime established in the Late Triassic with relative tectonic quiescence and only minor extension remained throughout the Jurassic and Early Cretaceous (Liboriussen *et al.* 1987).

10.1.2.1 Norian – Rhaetian

The thick Late Triassic sandstone sequences are very well mapped, especially in the North Sea due to their hydrocarbon bearing tendencies. Essentially the same transgressive features as well as major unconformities are present in both the North Sea and the Skagerrak – STZ region and the events are considered to be synchronous (Liboriussen *et al.* 1987). The depositional regime is however considered to be slightly different as the deep water conditions in the North sea never quite were present in the Skagerrak – Kattegat –

STZ region (Liboriussen *et al.* 1987). The Skagerrak – Kattegat, STZ and the Danish basin region were in Late Triassic time on the contrary constituted by a shallow epicontinental sea according to Nielsen (2003) where deposition of marine sediments started following a Norian (Late Triassic) transgression.

The Norian – Rhaetian transgression led to the accumulation of 50 – 200 meters of claystones, marls and carbonates in the Southern and central parts of the Danish basin, visible as a blue layer belonging to the Vinding Formation (Fm) in Figure 8 (Nielsen, 2003). The depositional regime in the northern parts of the Danish basin as well as the Skagerrak and the FFZ was at the same time dominated by alluvial sedimentation of arkosic sandstones interbedded with lacustrine claystones, together forming the Skagerrak formation which reaches a maximum thickness of about 1000 m at the FFZ (Figure 8) (Nielsen, 2003).

10.1.2.2 Rhaetian – Hettangian

The Skagerrak formation is superimposed by widespread sheets of shoreface sandstones of great lateral extent as well as paralic sediment representing the Gassum formation (Figure 8), which were deposited during pulse-like regression events throughout the Rhaetian – Hettangian, (Latest Triassic – earliest Jurassic). During periods of stable relative sea level mudstone interbeds were deposited especially but not only in the deeper STZ and Danish basin which is clearly shown in Figure 8. The thickness of the Gassum Fm in the Skagerrak area is relatively uniform and undisturbed apart from the SW parts which are locally domed as a result of salt tectonism of the Zechstein unit. However as is apparent in Figure 7 it thins out towards the NE which contributes to the variation in thickness which usually is between 350 – 150 m (Bjørnsen *et al.* 2012). The depositional environment was modified by reason of these events and was likely varying has been suggested by authors such as Berthelsen (1978) to have been deltaic and tidally influenced shallow marine environments. Both the Skagerrak- and the Gassum formation are represented in Figure 4 and 6 as the red widespread sedimentary sheet. The Gassum formation was partially deposited during the Sinemurian, and thus also corresponds to the lowermost parts of the green unit in Figure 4 and 6 (Nielsen, 2003).

10.1.2.3 Hettangian – Late Sinemurian

The depositional environment was altered during the Hettangian – Early Sinemurian due to a piecemeal basin deepening leading to successively more- and eventually fully marine conditions. The shoreface sandstones of the Gassum Fm which by this time constituted a storm dominated shelf area were subsequently overlaid by thick uniform mud- and claystones which covered the entire Kattegat – Skagerrak, the Danish basin and North Sea, (Figure 8), short of the margin areas of the basin along the Swedish – Norwegian western coast. The latter areas were subject to

sediment trapping and therefore sandstones similar to those in the Gassum Fm were accumulated inshore, distinctly visible in Figure 8, due to the transgressive nature of the basin at this time (Nielsen, 2003).

This Early Jurassic thick mainly marine sequence is known as the Fjerritslev Formation (Nielsen, 2003) is well defined in Figure 8 and constitutes a major part of the green areas in Figures 4 and 6. The Early Jurassic Sea eustatic level rise resulted in continuous accumulation of marine sediment until Late Toarcian – Early Aalenian, (Early – Middle Jurassic), in the above mentioned areas short of the RKF (Nielsen, 2003). The Fjerritslev formation ends abruptly with an erosional surface which developed as a result of Aalenian – Bathonian, (Middle Jurassic) uplift. The uplift was centered along the RKF (Figure 3) which led to a restricted basin which later contracted and was finally confined to the deepest parts of the STZ, the more marginal areas were subject to deep erosion.

10.1.2.4 Middle Jurassic – Early Cretaceous

The roughly Middle Jurassic Haldager sand Fm, supposedly deposited in a braided fluvial and deltaic environment according to eg. (Berthelsen, 1978) erosionally overlies the Fjerritslev Fm and is composed of paralic and shallow marine coarse – fine grained as well as pebbly sand- and mudstones on the SKP and in the STZ where the maximum thickness is 150 m which as usual thins out towards the NE, (Figures 4, 7 and 8) (Nielsen, 2003). The Haldager sand Fm is not quite as thick as the Gassum Fm in the Skagerrak but usually is on the order of 30-70 m thick (Bjørnsen *et al.* 2012)

Transgressive mudstones and sandstones with a spatial distribution similar to the Haldager sand Fm were deposited as the Flyvberg Formation (Figure 8), during Oxfordian time, (Late Jurassic) (Nielsen, 2003). The Flyvberg Fm was later overlaid by Kimmeridgian – Ryazanian, (Late Jurassic) marine mudstones belonging to the Børglum formation, (Figure 8) during an expansive and deepening phase of the basin (Nielsen, 2003). Similarly to the Fjerritslev Fm, the mostly marine Flyvberg- and Børglum formations are also associated by shoreface and respective paralic sandstones along the N – NE basin margins as seen in Figure 8. The clastic sediments related to the Børglum Fm later transforms into the Fredrikshavn formation as seen in Figure 8 (Nielsen, 2003). These formations equate to the yellow parts of Figure 6.

10.1.2.5 Late Cretaceous – Early Cenozoic

During the Late Cretaceous sea level was high (Nielsen, 2003) due to regional transgression, and tropical climate reigned which allowed accumulation of chalk deposits in the areas west of the STZ as seen in Figure 4 (Liboriussen *et al.* 1987). Late Cretaceous – Early Cenozoic inversion events which stemmed from the alpine orogeny were greatest in the SW eg. The North Sea, the Danish basin and less pronounced in the Skagerrak hence this inversion is only scarcely

manifested by the lack of chalk deposits above the FFZ in Figure 7 (Rasmussen, 2009; Ro *et al.* 1990a). The compressional tectonic regime remained more or less pronounced until Early Oligocene, (Middle Tertiary) and reactivated the former fault zones with a dextral movement (Rasmussen, 2009). As a consequence of the inversion tectonics and possibly the presence of a mantle plume in the North Sea area, the Fennoscandian Shield is believed to have been uplifted and subjected to erosion followed by high sediment influx to SW areas up until Early Miocene (Rasmussen, 2009). This may explain the spatial distribution of the sediment shown in Figure 4 in which Late Cretaceous – Tertiary sediments are located farther away from the present coastline due to erosion of older sediment and shoreline displaced to the SW due to uplift (Rasmussen, 2009).

By reason of the above mentioned, Cenozoic sediments are largely absent or limited to thin successions in the SW of the Skagerrak area (Nielsen, 2003). Cenozoic successions are however present in the North Sea with greatly varying thickness due to varying depocenter locations (Nielsen, 2003).

10.1.4 Quaternary

The most prominent Quaternary feature in the Skagerrak is the upwards 800 m deep Norwegian channel off the S-SW coast of Norway (Longva *et al.* 2008). The Norwegian channel has episodically during the Quaternary been a transport route for large scale ice streams followed by severe glacial erosion which removed most pre-Weichselian glacial deposits as well as substantial amounts of Mesozoic sedimentary bedrock (Rise *et al.* 2008b). The channel has subsequently been infilled partly with Weichselian glacial till but mainly syn- and post depositional glacial sediment as it has been a sediment trap of fine grained sediment coming from both the North Sea and the adjacent glaciated areas (Longva *et al.* 2008; Rise *et al.* 2008b). The till visible in Figure 11 was partly eroded or reworked as the Ice sheet retreated towards the NE (Figure 12 A and B) and is now present as a 25 – 50 m thick layer directly on the Mesozoic erosional surface (Figure 11 A and B), with the thinner regions located in the eastern areas due to severe erosion (Rise *et al.* 2008b). Following the retreating ice sheet, unit E (Figure 11 A) accumulated as a result of proximal glaciofluvial streams transporting sediment from the ice flanks to the deepest parts of the Norwegian channel, namely at the section in Figure 11 A) (Rise *et al.* 2008b). Melt-water from the Inactive melting ice observable in Figure 12 B produced the fan-like glaciofluvial sediments of unit D in Figure 9 B (Rise *et al.* 2008b).

When the ice margin reached the Norwegian southern coast, roughly where it is situated in Figure 12 C, it remained there for several thousand years (Rise *et al.* 2008b). The depositional regime during the following 13 Ka is characterized by the establishment of a cyclonic ocean circulation in the Skagerrak in-

cluding an inflow of Atlantic water as well as an outflow of Baltic waters. Stable hemipelagic sedimentation was present during the Holocene giving rise to units B and furthermore A (Figure 11 A and B) which consist with glaciomarine and postglacial muds (Rise *et al.* 2008b).

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