DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/57**

Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark. Phase 1, report no. 6

Subsurface distribution of Jurassic and Cretaceous fine-grained formations based on seismic mapping

Anders Mathiesen, Helle H. Midtgaard & Lars Hjelm

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/57**

Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark Phase 1, report no. 6

Subsurface distribution of Jurassic and Cretaceous fine-grained formations based on seismic mapping

Anders Mathiesen, Helle H. Midtgaard & Lars Hjelm

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

Preface

The present report is a contribution to a major geological project with the purpose to investigate whether suitable geological sites for a deep repository for the Danish radioactive waste can be identified. The Geological Survey of Denmark and Greenland (GEUS) has been given the task to identify, map, and characterize formations of low permeable rocks occurring with continuous lateral extension at 500 meters depth with thicknesses of 100 meters or more. This report is part of a series of ten reports presenting the results of the first phase of the project, which is carried out mainly as a desk study.

The geological characterisation and evaluation will provide the geological basis for the selection of two sites where, during the second phase of the geological project, detailed geological site investigations will be carried out. These two sites will be selected through a process of information sharing and dialogue between the Ministry of Higher Education and Science (MHES) and the local municipalities. The new geological data generated in the project's second phase will be used as input to a safety case when a disposal solution has been developed by the Danish Decommissioning (DD). The safety case must demonstrate that the geological properties in combination with the engineered barriers of the repository can provide the required safety for disposal on both short and long term.

In a preceding feasibility study, it was concluded that at 500 meters depth potential host rocks occur in claystones in the Jurassic and Lower Cretaceous sections, in Upper Cretaceous chalk and marl, and in Precambrian crystalline basement rocks. In this phase of the geological project, the geological properties and subsurface conditions related to these stratigraphic intervals and rock types are reviewed, and the potential host rocks' capability to retard radionuclides is investigated by conceptual 1D numerical modelling. In addition, natural processes potentially influencing short and long-term stability are identified and described.

Information gathered in the geological reports no. 2-8 forms the basis for a subdivision of Denmark into 11 areas where each area is characterized by the potential host rock type occurring at 500 meters depth, the barrier rocks in overlying sections, and the structural framework. The areas are defined to enable characterization and evaluation of the Danish subsurface at depths to 500 meters. The evaluation is based on requirements and criteria for deep geological disposal, which are defined based on international experience and recommendations. Each area is characterized and evaluated with regards to whether the geological properties and conditions are favourable for deep disposal of the Danish radioactive waste. The results of the project's first phase are presented in the following ten geological reports:

1. Requirements and criteria for initial evaluation of geological properties and conditions
2. Geological setting and structural framework of Danish onshore areas
3. Upper Cretaceous – Paleocene chalk, limestone and marl distribution and properties
4. Jurassic and Lower Cretaceous claystone distribution, sedimentology, and properties
5. Precambrian crystalline basement distribution and properties
6. Subsurface distribution of Jurassic and Cretaceous fine-grained formations based on seismic mapping
7. Evaluation of long-term stability related to glaciations, climate and sea level, groundwater, and earthquakes
8. Conceptual 1D modelling of nuclide transport in low permeable formations
9. Karakterisering og evaluering af geologiske egenskaber og forhold i 500 meters dybde (In Danish)
10. Characterisation and evaluation of geological properties and conditions at 500 meters depth (This report is an English translation of report no. 9, to be published late 2022)

This report is Report no. 6. It presents seismic interpretation and mapping of the regional subsurface distribution of major stratigraphic units with emphasis on Jurassic and Cretaceous units of low permeable sedimentary deposit.

Table of contents

0. Dansk sammendrag (In Danish)

I 2018 vedtog Folketinget, at en langsigtet løsning for håndtering af Danmarks radioaktive affald skal indeholde lokalisering for et muligt dybt geologisk slutdepot, som kan tages i brug senest i 2073 (Folketingets beslutning B90; Danish Parliament, 2018). Det radioaktive affald består af cirka 10.000 m^3 lavradioaktivt affald og mindre mængder af mellemradioaktivt affald, inklusiv 233 kg særligt affald, men intet højradioaktivt varmegenererende affald. De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS) har af Folketinget fået tildelt opgaven med at undersøge, om der eksisterer områder i en dybde omkring 500 meter i den danske undergrund, der har de nødvendige geologiske egenskaber for etablering af et sikkert slutdepot for det radioaktive affald.

Det geologiske slutdepotprojekt omhandler de geologiske forhold, der skal tages i betragtning inden en eventuel beslutning om etablering af et dybt geologisk slutdepot for det danske radioaktive affald. De geologiske undersøgelser udføres sideløbende med aktiviteter hos Uddannelses- og Forskningsministeriet (UFM), der er overordnet ejer af slutdepotprojektet, og Dansk Dekommissionering (DD), som har ansvaret for at opbevare affaldet, indtil det skal slutdeponeres (MHES, 2021). Socio-økonomiske forhold, endeligt depotkoncept og -design, sikkerhedsforhold m.v. er ikke en del af det geologiske projekt, men varetages af UFM.

Retningslinjer for identificering af områder egnede til dyb geologisk slutdeponering
Internationale anbefalinger til de geologiske undersøgelser, der skal lede til identificering af en egnet lokalitet for dyb geologisk deponering af radioaktivt affald, er præsenteret af bl.a. det Internationale Atom Energi Agentur (IAEA, 2011) og Norris (2012) – her oversat til dansk:

"At identificere og kortlægge lav-permeable bjergarter, der udgør tilstrækkeligt tykke formationer (mere end 100 meter), og som har en kontinuert lateral udbredelse (flere kilometer i hver retning) indenfor studieområdet. Formationen skal være homogen og må ikke indeholde betydelige diskontinuiteter så som store forkastninger og sprækker. Formationen skal være så mineralogisk homogen og ensartet som muligt. De geologiske forhold skal være stabile på både kort sigt og indenfor en længere tidshorisont afhængigt af affaldets karakter."

Projektet vil følge retningslinjer fra IAEA (IAEA, 2011; IAEA, 2018a; IAEA, 2018b), Det Nukleare Agentur under OECD (NEA, 2005; NEA, 2008; NEA, 2012) og EU-direktiver indenfor området (EU, 2011).

Som bemærket af IAEA (IAEA, 2018a; IAEA, 2018b), er det ikke muligt at udpege ét enkelt område som det bedst egnede baseret på de geologiske egenskaber, idet det er umuligt at undersøge og karakterisere alle naturlige variationer af de geologiske egenskaber ned til 500 meters dybde indenfor et givent område. Opgaven er derimod at identificere et egnet område, der samlet set kan opfylde de definerede krav til sikkerhed og funktionalitet af depotet, samtidig med at etableringen af et geologisk slutdepot i området er teknisk mulig og accepteret af beslutningstagere og interessenter.

Omfanget af de geologiske undersøgelser, der er nødvendige at udføre, er defineret på basis af erfaringer fra lignende projekter i bl.a. Frankrig (ANDRA, 2005), Sverige (SKB, 2007), Schweiz (SFOE, 2008; Nagra, 2017), Holland (COVRA 2017), og Finland (POSIVA, 2017a og b). Kontakter er i løbet af projektet etableret til flere af disse organisationer med henblik på udveksling af erfaringer samt rådgivning og kvalitetssikring for det geologiske slutdepot-projekt. Som et resultat af dette internationale samarbejde, blev der i første fase af slutdepotprojektet gennemført et review af de definerede geologiske kriterier (præsenteret i Rapport nr. 1), hvor kommentarer og anbefalinger er afrapporteret i Blechschmidt et al. (2021).

På baggrund af flere årtiers undersøgelser af de lokale geologiske forhold har nogle lande besluttet at etablere et dybt slutdepot i marine lersten (ANDRA-Frankrig, COVRA-Holland, Nagra-Schweiz). I Sverige (SKB) og Finland (POSIVA) er det besluttet at etablere dybe geologiske slutdepoter i krystallinsk grundfjeld. Mange andre lande arbejder stadig med lokaliseringsprojekter, og udover krystallinsk grundfjeld og lersten er også kalksten, mergel og salt vurderet som mulige bjergarter for deponering afhængigt af de lokale geologiske forhold.

Det geologiske projekt vedrørende et muligt slutdepot i 500 meters dybde

Forud for det igangværende geologiske projekt blev en screening af den danske undergrund foretaget med henblik på at undersøge, om lavpermeable bjergarter findes i 500 meters dybde i den danske undergrund. Denne screening viste, at i 500 meters dybde findes jurassiske og kretassiske lagserier, der indeholder tætte formationer af lersten og kalksten samt prækambrisk grundfjeld bestående af granit og gnejs. Alle disse bjergartstyper kan under de rette omstændigheder have geologiske egenskaber, der gør dem egnede som værtsbjergart for et dybt geologisk slutdepot (Gravesen, 2016). Baseret på dette arbejde blev undersøgelserne i nærværende projekts første fase igangsat.

Det geologiske slutdepotprojekt blev påbegyndt i januar 2019 og forventes at forløbe over en 7-årig periode. Projektet udgør den geofaglige del af det samlede projekt om et muligt dybt geologisk slutdepot, som er defineret i Folketingets beslutning B90 (Danish Parliament, 2018). Det geologiske projekt varetages af GEUS' personale med bidrag fra eksterne forskningsinstitutioner, konsulentfirmaer og internationale eksperter, hvor det er nødvendigt. På grundlag af en karakterisering og evaluering af undergrundens geologiske egenskaber i projektets første fase, skal to lokaliteter udvælges til detaljerede geologiske undersøgelser i projektets anden fase. Uddannelses- og Forskningsstyrelsen (UFS) har ansvaret for at tilrettelægge og gennemføre en dialogproces, der inden udgangen af 2022 kan føre til afklaring af muligheden for at etablere et partnerskab mellem UFM og én eller flere kommuner om gennemførelsen af detaljerede geologiske undersøgelser.

I projektets første fase er de forskellige bjergarter kortlagt og deres egenskaber er beskrevet i det omfang, der findes data. Det skal i den sammenhæng bemærkes, at den tilgængelige information er ujævnt fordelt både geografisk og geologisk. De eksisterende data fra 500 meters dybde er hovedsageligt indsamlet fra tidligere olie- og gasefterforskningsboringer og relaterede seismiske undersøgelser og i mindre grad fra geotermiske, geotekniske og videnskabelige undersøgelser. De fleste dybe boringer i Danmark har haft som hovedformål at påvise tilstedeværelsen af sandsten og karakterisere deres reservoiregenskaber, hvorfor det er meget sparsomt med data fra de lavpermeable bjergarter som lersten og kalksten, der kan anvendes som værtsbjergarter, og som nærværende slutdepotprojekt har fokus på. Den nuværende kortlægning af undergrundens geologi er derfor behæftet med varierende grad af nøjagtighed og pålidelighed for de forskellige parametre, særligt for de lavpermeable bjergarter, som er vigtige for et geologisk sludepot. Gennemgangen af de eksisterende data har bidraget til at identificere områder med manglende geologiske data og informationer, hvor det er vigtigt at sikre indsamling af nye data i den næste fase af projektet.

I projektets anden fase skal detaljerede geologiske undersøgelser, som nævnt, foretages på to valgte lokaliteter. Undersøgelserne vil omfatte indsamling af seismiske profiler med geofysiske metoder og boring af dybe borehuller. I borehullerne udtages bl.a. borekerner og vandprøver, og der indsamles petrofysiske målinger for efterfølgende analyser med henblik på karakterisering af forseglingsegenskaberne og geotekniske egenskaber. Disse data vil indgå bl.a. i modellering af stoftransport, bestemmelse af geokemisk retardation, seismisk kortlægning og vurdering af geoteknisk stabilitet. De geologiske og geotekniske egenskaber vil også have indflydelse på hvilket depotdesign, der er teknisk muligt og sikkerhedsmæssigt forsvarligt i undergrunden. De indsamlede data og analyser vil efterfølgende indgå i en sikkerhedsvurdering, der skal afklare, om det samlede depotkoncept med de geologiske barrierer i kombination med de konstruerede barrierer kan levere den nødvendige sikkerhed for deponering på både kort og lang sigt.

Opsummering af rapport nr. 6: **Seismisk kortlægning af finkornede jurassiske og kretassiske formationers udbredelse i undergrunden** (Subsurface distribution of Jurassic and Cretaceous fine-grained formations based on seismic mapping)

Den danske undergrund består af geologiske formationer og sedimentære aflejringer, der er dannet i løbet af mere end 600 millioner år. Udbredelsen af de sedimentære aflejringer er betinget af den geologiske ramme, hvor de vigtigste aflejringsbassiner er det Danske Bassin, det Nordtyske Bassin og Skagerrak-Kattegat Platformen, som er afgrænset at Ringkøbing-Fyn Højderyggen i syd og Sorgenfrei-Tornquist Zonen mod nord.Sedimenterne består af vekslende litologier af grovkornet sand, saltsten, sand, lersten, kalk og glaciale aflejringer. På Bornholm findes hovedsaligt krystallinsk grundfjeld af granit og gnejs, og sedimenter findes kun bevaret på den sydlige del af øen. Seismiske data er generelt ikke egnede til kortlægning af krystallinske bjergarter, og Bornholms undergrund er derfor ikke beskrevet i denne rapport, men i Rapport nr. 5 (jf. reference i Kapitel 9.1), der omhandler det krystallinske grundfjeld.

De vigtigste data til kortlægning af de dybere dele af den danske undergrund er seismiske data kombineret med data fra dybe boringer (mere end 500 meter). Seismiske data og dybe boringer er hovedsageligt indsamlet som led i olie- og gasefterforskning og geotermiske undersøgelser. De eksisterende data er derfor koncentreret i nogle områder af landet, hvor data i andre områder er meget spredt. Kvaliteten af data er stærkt varierende og de ældre seismiske data er generelt af ringere kvalite. Herudover er kvaliteten af data i intervallet 0–1000 meter også bestemt af det specifikke formål med undersøgelserne, hvor dataindsamling til f.eks. olieefterforskning typisk har været fokuseret på dybereliggende lag og den mulige tilstedeværelse af reservoirbjergarter med høj porøsitet. Eksisterende data fra geologiske bjergarter i dybder omkring 500 meter under terræn, hvor egnede bjergarter til et slutdepot skal identificeres og kortlægges, er således sparsomme.

Seismiske data indsamles på land ved at sende lydbølger ned i undergrunden. Når lydbølgerne møder geologiske lag-grænser, reflekteres en del af lyden, og en del fortsætter længere ned og reflekteres ved næste laggrænse. Mikrofoner på landoverfladen optager de reflekterede lydbølger, og hastigheden hvormed de reflekteres registreres og omsættes til seismiske profiler i millisekunder, der efterfølgende kan omregnes til dybder i meter. Det er nødvendigt at kortlægge alle overliggende geologiske formationer i lagserien for at kunne beregne dybden til de dybereliggende lag. Ligeledes er det nødvendigt at have både geofysiske, litologiske og stratigrafiske data fra boringer i et punkt, hvor en eller flere af de seismiske linjer er indsamlet. Dette gør det muligt at korrelere de geologiske informationer direkte til de seismiske profiler, og således er det muligt at kortlægge laggrænserne over større områder.

Ved indsamling af nye seismiske data er det vigtigt, at der også udføres boringer, som de kan korreleres til, så de seismiske profiler kan omsættes til geologiske data. Ligeledes er det yderst vigtigt, at nye seismiske data indsamles og processeres med fokus på intervallet 0–1000 meter, så der opnås bedst mulig opløselighed i de seismiske profiler. Dette giver mulighed for at foretage en mere detaljeret seismisk-stratigrafisk kortlægning og tolkning, herunder kortlægning af mulige intervaller med en værtsbjergart med en tykkelse på 100 meter eller mere. Det vil desuden give mulighed for at kortlægge udbredelsen af eventuelle forkastninger i et specifikt undersøgelsesområde.

Størstedelen af den danske undergrund består i 500 meters dybde af kalksten fra Kalkgruppen og i mindre grad lersten fra Jura og Nedre kridt intervallerne og, som nævnt tidligere, krystallinsk grundfjeld på Bornholm.

Dybden til toppen af Kalkgruppen er i store dele af landet mellem 0 og 300 meter bortset fra midt-Vestjylland, hvor den lokalt ligger 700–900 meter under terrænoverfladen. Tykkelsen af Kalkgruppen varierer fra nogle få hundrede meter til mere end 1000 meter i det Danske Bassin. Basis af Kalkgruppen er sammenfaldende med toppen af Nedre Kridt lagpakken, som består af lersten, siltsten og sandsten, og dybden til toppen af Nedre Kridt varierer fra nogle få hundrede meter til mere end 2000 meter i det Danske Bassin i det nordlige Jylland. I Sønderjylland er Nedre Kridt – Øvre Jura lagpakken ikke tilstede. Tykkelsen i den øvrige del af landet er typisk op til nogle få hundrede meter bortset fra Nordjylland, hvor den lokalt, i områder nær saltstrukturer, kan være mere end 1000 meter tyk. Top Fjerritslev Formationen repræsenterer toppen af Nedre Jura lagpakken, der hovedsageligt består af finkornede, lerrige sedimenter. Top Fjerritslev Formationen forekommer lokalt på 400-600 meters dybde, men i størstedel af landet ligger den dybere end 1000 meter. Tykkelsen varierer på samme måde som Øvre Jura – Nedre Kridt pakken med de største tykkelser i Nordjylland, hvor den lokalt er mere end 1000 meter og 0–400 meter i den øvrige del af landet.

Når lokaliteter for de detaljerede geologiske undersøgelser i slutdepotprojektets næste fase skal besluttes, bør de seismiske data gennemgås i detalje for en eventuelt mere detaljeret lokal seismisk tolkning af formationernes laterale kontinuitet, herunder forekomst af forkastninger, for at sikre at formationerne har den nødvendige horisontale og rumlige udbredelse på lokaliteten. Ved fremtidig indsamling af nye seismiske data på de to lokaliteter, der bliver udvalgt til detaljerede geologiske undersøgelser, forventes det, at kvaliteten af de seismiske data kan øges betydeligt ved at sikre, at indsamlingsparametrene er designet og tilrettelagt efter de lokale forhold i undergrunden. Dette vil give mulighed for mere detaljeret og nøjagtig kortlægning af geologiske formationer i undergrunden samt identifikation og kortlægning af eventuelle forkastninger på lokaliteten.

1. Introduction

In 2018, the Danish Parliament agreed that the long-term solution for Denmark´s radioactive waste should include a deep geological repository operating no later than 2073 (Danish Parliament, 2018). The waste is temporarily stored by the Danish Decommissioning (DD) on the Risø peninsula. It amounts to more than 10,000 m^3 and comprises mostly low-level radioactive waste (LLW), and a minor volume of medium-level waste MLW), including 233 kg special waste – but no high-level radioactive material (HLW).

The Geological Survey of Denmark and Greenland (GEUS) has been given the task by the Danish Parliament to investigate whether areas can be identified where potential host rock with suitable properties for geological disposal is present at 500 meters depth. The task is carried out in parallel with activities by the Danish Ministry of Higher Education and Science (MHES), being the project owner, and DD, being responsible for management of the radioactive waste including storage of the waste and final disposal.

The geological project was initiated in 2019 and is expected to be carried out within a period of approximately seven years. The bulk of the workload will be undertaken by staff members at GEUS, with contributions from external consultancy companies, organisations, and experts as needed. The geological siting project comprises two major phases. The current first project phase is a desk study with the purpose to map and characterize geological properties and conditions of potential host rocks in the Danish subsurface, mainly based on existing data. In the second project phase of the geological project, detailed geological investigations will be carried out at two specific sites to investigate whether the geological properties are suitable for safe disposal of radioactive waste in a deep geological repository at these specific sites. The two sites must be selected in a dialogue-based process between MHES and the local municipalities. Subjects and conditions, such as socio-economic issues, activities relating to civil participation, disposal facility design, safety cases, and other non-geological issues will be addressed and handled separately by MHES and DD with contributions from GEUS where relevant.

1.1 Guidelines for identification of deep geological repository sites

International recommendations on geological studies required to identify suitable sites for deep disposal of radioactive waste have been presented by e.g. the International Atomic Energy Agency (IAEA, 2011) and Norris (2012) as follows:

"*To identify and map layers of low-permeable rock types that are sufficiently thick (more than 100 meters) and which have a continuous lateral extension (several km²) throughout the entire study area. The rock body should also be sufficiently homogeneous and represent no significant discontinuities like fractures and faults. Furthermore, the rocks should be as mineralogical homogeneous and uniform as possible. The geological conditions should be stable in the short term as well as in the long term.*"

These recommendations as well as experience from siting projects in other countries have been used to identify investigations that need to be performed in the Danish project. Experience from other countries include France (ANDRA, 2005), Holland (COVRA, 2018), Switzerland (SFOE, 2008; Nagra, 2017), Sweden (SKB, 2007) and Finland (POSIVA, 2017a, b).

In some countries, based on several decades of comprehensive subsurface studies, it has been concluded that marine claystones and clay rich carbonates (marl) may constitute suitable host rocks for a final geological disposal. Therefore, extensive research on clay deposits is continuously ongoing and makes available significant amounts of data and experiences that may be valuable for this project (e.g. ANDRA-Belgium, COVRA-Holland, Nagra-Switzerland). In the Czech Republic, a former limestone mine is used for disposal of institutional waste comprising radioactive material similar to the components in the Danish waste. In other countries, including Sweden, Finland, and Norway, it has been decided to establish final repositories in crystalline bedrock. When relevant, the current project in Denmark will draw on others experiences and cooperate with relevant radioactive waste disposal organisations. Furthermore, the project will follow guidelines from IAEA (IAEA 2011; IAEA 2018 a,b), the Nuclear Energy Agency (NEA (OECD), 2005; NEA 2006; NEA, 2008; NEA, 2012) and the EU directive regarding this field (EU, 2011).

As noted by the IAEA (2018 a, b), the impossibility of finding “the safest site” based on rock properties should be emphasised, because it is not possible to investigate and determine the detailed nature of every possible site. Instead, the key to find a suitable site will be to have it fulfil the required level of safety and performance, and that establishing a repository here is also acceptable to decision makers and stakeholders.

1.2 The deep geological repository project

A geological screening of the Danish subsurface layers present at 500 meters depth was carried out prior to initiation of the current geological siting project, to investigate whether low permeable rocks occur at this depth. The screening showed that the Jurassic and Cretaceous stratigraphic intervals at 500 meters depth comprise chalk, limestone, marl, and claystone, and the Precambrian basement comprises crystalline rocks in terms of gneiss and granite, which may all potentially provide a host rock for a deep geological repository (Gravesen, 2016). Based on this work, it was recommended to further analyse and characterize the geological conditions and barrier effectiveness of the geological formations at depths to 500 meters below the surface, which resulted in a decision to initiate the first phase of the present project.

The first phase of the present geological siting project comprises a geological review of all data available in the GEUS archives, the drilling-sample storage facilities, and from literature. The data have been used to map and describe relevant properties of the rock types identified at depths to around 500 meters, as well as natural processes potentially influencing the short- and long-term geological stability. The results form the basis of a subdivision into geologically different areas which are characterised and evaluated regarding the areas’ potential suitability for deep disposal as described in the project’s Report No. 9 (cf. Chapter 7.1 for reference).

The geological desk studies were carried out as separate work packages and presented in a number of reports (Reports No. 2-7; cf. Chapter 7.1 for references) addressing the following issues: overview of the onshore geological setting in Denmark; subsurface mapping based on seismic data and well data; a geological description of the three rock types chalk, claystone and crystalline basement, respectively, and issues potentially influencing long-term geological stability, such as climate conditions, possible glaciations, earthquake risks and groundwater conditions. Based on the results of the geological desk studies, conceptual 1D numerical modelling was performed to identify properties and conditions with high importance for the rocks' barrier-effectiveness for retardation of the radionuclides (Report No. 8; cf. Chapter 7.1 for reference).

Information on the subsurface geological formations onshore Denmark is quite scattered and of highly varying quality. The archives and databases comprise 2D seismic data of different vintages and quality as they are acquired for different purposes. Well data exist mainly from deep wells drilled for hydrocarbon exploration, some geothermal wells, and other technical/scientific drillings. Thus, as the data from various regions of Denmark varies in vintage, quality and level of detail, the current picture is by no means comprehensive. However, the geological desk studies combined with some new sedimentological and stratigraphic studies, and initial sensitivity studies from the conceptual 1D modelling have proven highly valuable; both in detailed mapping and identifying rock types, as well as in identifying major data gaps and critical parameters, for which it is important to obtain information during the next phase of the project.

The characterisation and evaluation carried out in this first phase of the project provide the geological basis for selection of two sites for detailed geological investigations in the second phase of the project. A dialogue-based process for the site selection is managed by MHES.

As part of the detailed investigations in the second phase of the project, new data and information will be collected at the two sites to further evaluate whether the geological properties and conditions are favourable for deep disposal. Thus, the second phase sets off with planning and preparation for the investigations, which include acquisition of seismic data and the drilling of deep boreholes (deeper than 500 meters) at each site. The extensive data sampling program will, among others, include drill-cores, well logs, and groundwater samples - thus, providing samples and measurements for laboratory analyses and various other studies. Based on the new data, a characterisation and evaluation of the geological suitability of the two sites will be made. This characterisation will also be used by DD for identification of a suitable repository design and for evaluation of the combined retention capacity of the engineered and the geological barriers as input to a safety case.

2. Structural elements of the Danish subsurface

The geological record of the subsurface consists mainly of sediments that have been deposited within the last 600 million years of Earth history. The structural framework is made up of several structural highs and basins separated by significant faults (Michelsen and Nielsen, 1993). The most important structural elements in the onshore and near coastal areas are shown in Figure 1 and include:

- The Danish Basin
- The North German Basin
- Sorgenfrei–Tornquist Zone
- Ringkøbing–Fyn High
- Skagerrak–Kattegat Platform

The Danish Basin is the easternmost part of the larger Norwegian-Danish Basin, formed by extension of the crust during the Early Permian period. The basin extends beneath most of the Danish land area and the inland waters and is characterized by an up to 9 km thick sedimentary record, which in many places is bounded by NW–SE trending faults. To the northeast and east the basin is bounded by the Fennoscandian Border Zone, which include the Sorgenfrei–Tornquist Zone and the Skagerrak– Kattegat Platform. The Sorgenfrei–Tornquist Zone is a northwest-southeast oriented block-faulted zone extending from Skagerrak across northern Jylland, through the Kattegat, parts of the Øresund and Skåne to Bornholm. To the north and northeast, the bedrock/basement occurs at shallow depths as the Skagerrak–Kattegat Platform, forming a transition from the deep Danish Basin to the bedrock in Norway and Sweden. To the south, the Danish Basin is separated from the North German Basin by the Ringkøbing-Fyn High, which is part of a regional WNW-ESE trending high of shallow bedrock. Locally this high is intersected by narrow north-south oriented grabens and associated troughs. Across the Ringkøbing-Fyn High, the sediment thickness is reduced to about 1 kilometer due to limited deposition on the structural high and erosion on the flanks. The North German Basin also formed from crustal extension during the early Permian time. The North German Basin extends across Southern Jylland, parts of the Småland Sea and the Lolland-Falster area, where the sedimentary section is up to 4 km thick.

The sediments in the Danish Basin, the North German Basin and the Fennoscandian Border Zone consists of alternating lithologies reflecting the significant variation in depositional environments over several hundred million years of sedimentation (Japsen et al., 2007). After an initial deposition of Rotliegend coarse-grained clastic sediments followed a long period of subsidence, during which hundreds of meters of Zechstein salt was deposited in the basins. Subsequently sand, mud, carbonate and minor salt formations were deposited during the Triassic and Early Jurassic times.

Regional uplift in the Middle Jurassic time period led to significant erosion, especially on the Ringkøbing–Fyn High. In the same time period fault-related subsidence continued in the Sorgenfrei–Tornquist Zone, associated with deposition of sand and mud. Regional subsidence re-occurred during the latter part of the Middle Jurassic and continued until the Late Cretaceous-Paleogene period, when a change in the tectonic regime occurred related to the Alpine deformation and the opening of the North Atlantic which resulted in uplift and erosion.

The Upper Jurassic-Lower Cretaceous sediments encompass sandstone, mudstone and siltstone and is succeeded by thick deposits of Upper Cretaceous carbonate and limestones (Figure 2). The thick records of sediments deposited in the basin centres during the Mesozoic led to remobilisation of the underlying less dense salt layers, that were plastically deformed and locally forming salt diapirs possibly initiated by fault activity along basin margins. In some areas the sedimentary layers overlying the rising salt were moved upwards, or alternatively the layers are pierced by the rising salt. One example is the southern margin of the Sorgenfrei-Tornquist zone (see Figure 2) towards the Danish Basin, where a large salt diapir dissects through all sections except for the uppermost part of the Chalk Group. Increased subsidence at the flanks of the salt structures (in the rim zones) caused a thickening of layers deposited contemporaneously with the main phases of salt remobilisation. The salt movement occurred contemporaneously with fault activity in many places.

Figure 1. *The most important structural elements in southern Scandinavia, including the Danish Basin, the Sorgenfrei–Tornquist Zone, the Skagerrak–Kattegat Platform, the Ringkøbing–Fyn High, and the northernmost part of the North German Basin. Modified figure from Nielsen (2003). The red line shows the location of the geological profile shown in Figure 2.*

Figur 1 (forrige side). De væsentligste strukturelle elementer i det sydlige Skandinavien inklusiv det Danske Bassin, Sorgenfrei–Tornquist Zonen, Skagerrak–Kattegat Platformen, Ringkøbing–Fyn Højderyggen og den nordligste del af det Nordtyske Bassin. Modificeret figur fra Nielsen (2003). Den røde linje viser placeringen af det geologiske profil som er vist i Figur 2.

The structural framework of the subsurface can be illustrated with geological profiles that are constructed vertical sections through the subsurface. The profiles give an insight into the structural elements of the subsurface, including the position of faults and salt structures as well as the thickness, extent and continuity of geological layers. Figure 2 is a geological profile showing the large-scale structures through the central and northern Jylland area. The section is based on composite seismic profiles forming the background images. Sections of the subsurface that contain potential sandstone reservoirs that can be seismically mapped are highlighted. Also highlighted are the following series of layers: the Zechstein Group, which contains thick salt deposits that locally have moved upwards to form salt diapirs or salt pillows; the clay dominated Fjerritslev Formation as well as the Cretaceous and Danian sequence of chalk and limestone deposits.

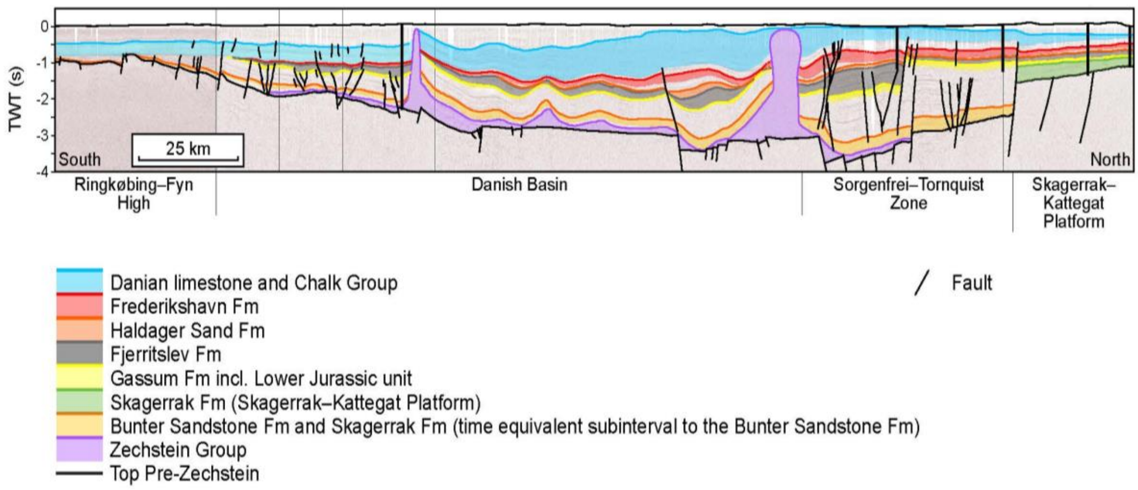

***Figure 2.** Geological profile in TWT (TwoWayTraveltime, seconds) illustrating the structural elements and presence of thick records of sediments (up to 5 kilometers thick) in the Danish Basin and slightly thinner in the Sorgenfrei-Tornquist Zone. The blue layer is the Chalk Group, yellowish, greenish and reddish layers are interbedded sandstones and mudstones and the purple layer at the base is the Zechstein Salt.*

***Figur 2.** Geologisk profil i tid (TWT, tovejstid i sekunder) som illustrerer de strukturelle elementer og tilstedeværelsen af tykke sedimentære lagpakker (op til 5 kilometer tykke) i det Danske Bassin og lidt tyndere i Sorgenfrei-Tornquist-zonen. Det blå lag er Kalkgrupppen, gullige, grønlige og rødlige er lag af sandsten og lersten og det nederste lilla lag er Zechstein Salt.*

3. Geological and geophysical data

The most important data that provide information about the Danish deep subsurface geology is data from deep wells, gravimetric data, and seismic reflection data (Figure 3). Most of these data has been acquired through oil and gas exploration activities and to a lesser degree also through assessment of natural gas storage, ground water exploration and geothermal exploitation (Weibel et al., 2020). The wells provide detailed information about the geology in a local area around the well whereas seismic surveys provide images of the subsurface geology in larger areas and to greater depths, but with less accuracy than boreholes. Gravimetric data can be used for mapping of the depth to dense basement rocks (gneiss and granite) and provide a regional perspective.

Figure 3 illustrates the scattered and very unevenly distribution of data, varying from areas covered by closely spaced seismic lines to areas with very long distance between the seismic lines. This of course has a significant impact on the level of geological details locally, the confidence in the seismic interpretation and thus the prediction of the presence of, and depth to the various geological boundaries and formations.

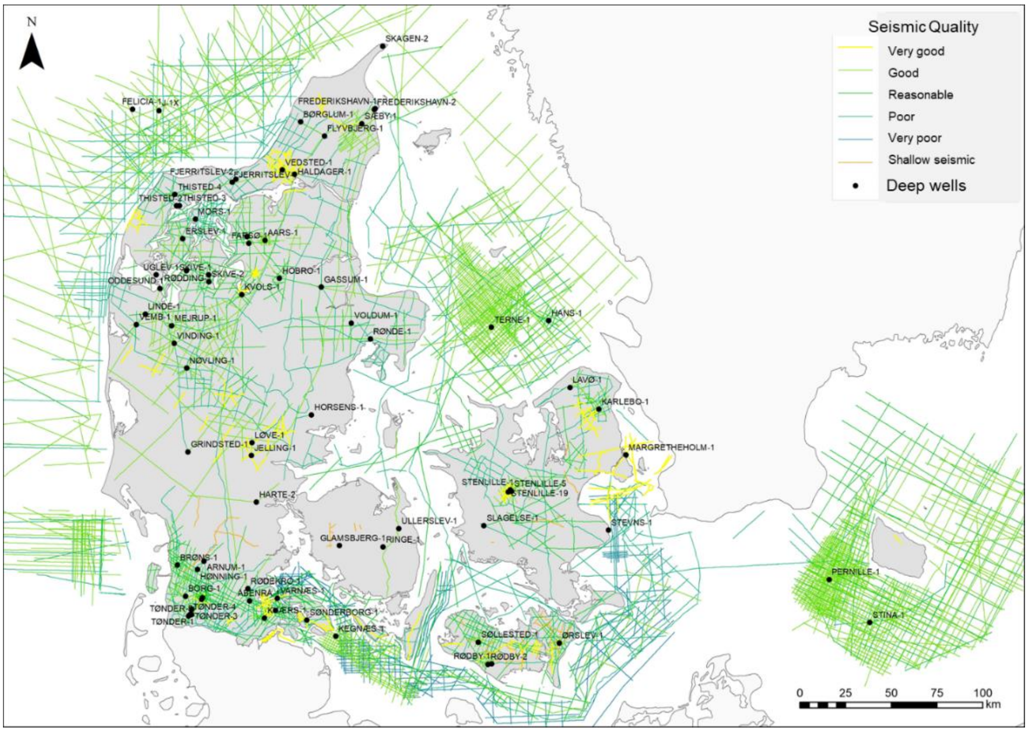

__Figure 3.__ Seismic data coverage and quality, and location of deep wells. The seismic quality is indicated with colours and the quality correlates to a large extent with the age of the seismic acquisition, thus most recent data are usually of highest quality.

__Figur 3.__ Seismisk datadækning og kvalitet samt placeringen af dybe boringer. Kvaliteten af de seismiske data er indikeret med farver og kvaliteten er i høj grad relateret til i hvilket år de seismiske data blev indsamlet, hvor de nyeste data generelt er af højeste kvalitet.

Wells contribute with information about the depth to, and composition of the geological layers (e.g. lithology, bedding, heterogeneity, porosity, permeability and stratigraphy), the temperature and pressure of the formation, and geochemistry of the pore fluids.

Mapping of the subsurface based on seismic data tied to well data provides information on the spatial distribution of significant geological boundaries, the thicknesses of formations and, when layers terminate abruptly or thickness change abruptly, the presence of faults. This information about the subsurface architecture of the geological layers and boundaries can be used to interpret the structural development and depositional history. The understanding of the geological development can subsequently be used to predict the geology away from wells such as the depth to and presence of a geological host rock for deep disposal.

Seismic data is usually referred to mean sea level (MSL), thus, the initial seismic depth maps show the level to the mapped seismic surface with reference to MSL. As the current project has focus on lithologies and geological formations occurring at depths to 500 meters below ground level (terrain) all depth maps in the present report have been topographically adjusted to show meters below ground level (GL) by adding the terrain surface height above MSL to the depth surface maps in MSL.

3.1 Methods for acquisition of seismic data

The available seismic data combined with information on depths and lithostratigraphy compiled from wells have formed the basis for seismic mapping of the Danish onshore and near coastal areas.

Seismic data is generated by sending sound waves from a sound source down into the subsurface. On land, the sound waves are most often created using vibrators mounted on large, specialized vibrator vehicles (Figure 4). The sound waves travel at different speeds in different rock types, and when they meet transitions between different geological layers, some of the sound waves will be reflected back to the surface where they are recorded by very sensitive microphones (geophones) distributed across away from the seismic source on the terrain surface (Figure 5). By recording the time (seconds) it takes from the sound wave is emitted to the echoes returning (reflected) from the layers to the surface, a measure of depth to layer boundaries is obtained. The method is in principle the same used in radars or an ultrasound scanner.

Figure 4. *Vibrator vehicles at work. By using multiple vehicles that use their vibrators synchronously, the sound waves are amplified to the subsurface. This provides a better seismic signal and thus a more detailed picture of the subsurface.*

Figur 4. *Vibratorkøretøjer i arbejde. Ved at bruge flere køretøjer, som anvender deres vibratorer synkront, forstærkes lydbølgerne til undergrunden. Herved opnås et bedre seismisk signal og dermed et mere detaljeret billede af undergrunden.*

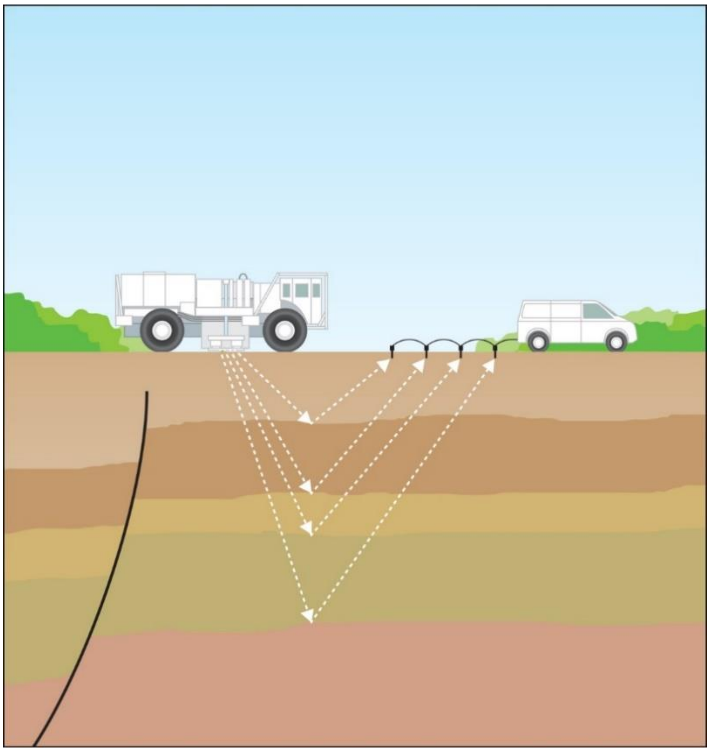

Figure 5. *Illustration of the principle of seismic data acquisition. The vibrator vehicle on the left sends an acoustic signal (sound wave) to the subsurface using vibrators as the ones shown in Figure 4. Parts of the acoustic signal are reflected to the surface each time the acoustic signal meets a layer boundary on its way down into the subsurface. The reflected acoustic signals are recorded by geophones on the terrain surface and collected, processed and translated into a preliminary version of a seismic profile in the vehicle to the right.*

Figur 5 (forrige side). Figuren viser hvordan seismiske data indsamles. Vibratorkøretøjet til venstre sender et lydsignal ned i undergrunden ved hjælp af vibratorer, som vist i Figur 4. Dele af lydsignalet reflekteres tilbage til overfladen, hver gang det seismiske lydsignal møder en markant laggrænse på sin vej ned gennem undergrunden. De reflekterede lydsignaler registreres af geofoner på terrænoverfladen og indsamles, tolkes og omsættes til en foreløbig udgave af et seismisk profil i køretøjet til højre.

The recorded information is processed using powerful computers, which translate the recorded sound waves into e.g. a 2-dimensional vertical seismic reflection profile, thus generating an indirect picture of the geological layers in the subsurface (Figure 6). The 'depth' to the layers is initially recorded and presented in milliseconds, as these are primary data, but for practical reasons they are also converted into depths in meters. As the travel velocity of the sound waves depend on the density, compaction, porosity, fluid composition and burial depth of the different rock types, the Time to Depth conversion is not simple and often associated uncertainty although petrophysical data from wells locally provide key information in converting the seismic TWT (two-way travel time) to meters.

4. Interpretation and mapping of the Danish subsurface

An overview of the database is given in Figure 3 showing the location of deep wells and seismic data. The figure illustrates the very scattered and unevenly distribution of wells and seismic lines as well as the varying seismic quality.

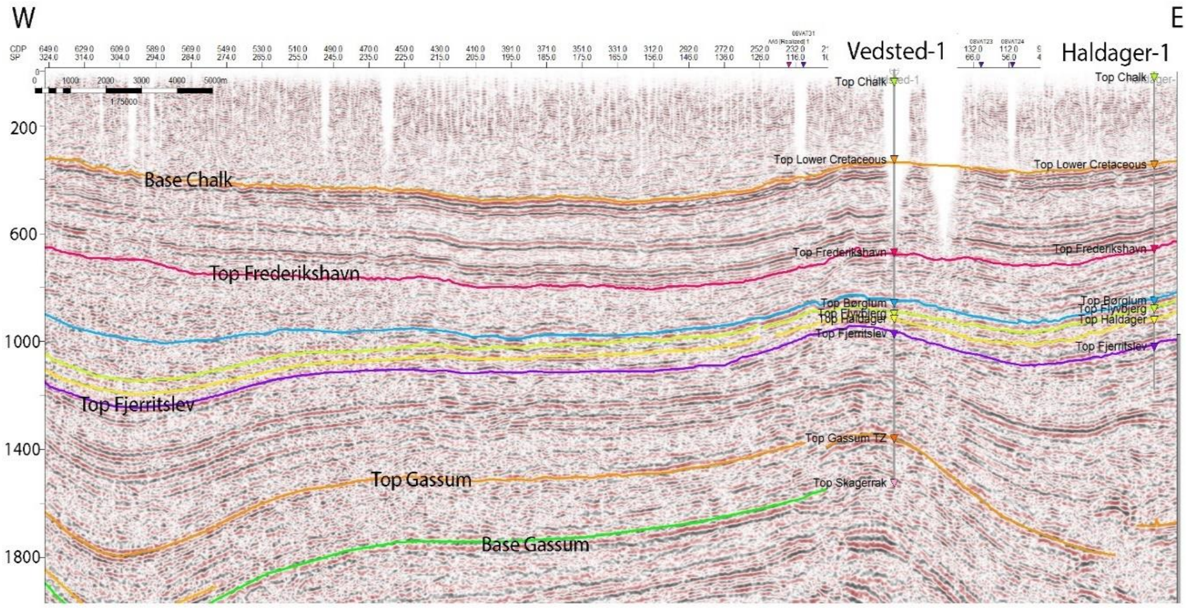

Figure 6. *Example illustrating the interpretation in Time (TWT, milliseconds) of part of the DNJ-500 seismic profile. The coloured seismic horizons correspond to lithostratigraphic boundaries in Figure 8. Notice the well tie to the Vedsted-1 and Haldager-1 (most eastward). Depth scale is milliseconds.*

Figur 6. *Eksempel som illustrerer tolkningen i Tid (TWT, millisekunder) langs en del af seismiske linje DNJ-500. Farvelagte seismiske horisonter repræsenterer kortlagte lithostratigrafiske grænser i Figur 8. Bemærk 'well ties' til boringerne Vedsted-1 og Haldager-1 (længst mod øst). Dybdeskala er millisekunder.*

4.1 Data coverage, quality, resolution, and confidence

The seismic data has been acquired by various geophysical companies in relation to hydrocarbon exploration, deep geothermal projects, storage for natural gas and for various research projects. The data is predominantly 2D data apart except from three 3D surveys that were acquired related to potential specific locations for storage of natural gas and oil exploration; the small 3D surveys are not shown in Figure 3. The seismic data from the early days were acquired by dynamite and the processing of these data was extremely simple, whereas the recent data has been acquired digitally by state of the art using an array of vibrators and state of the art data processing as illustrated in Figures 4 and 5.

In Figure 3, the quality of the seismic lines is indicated by different colors. Seismic profiles of different quality (i.e. year of acquisition) are shown in Figure 7 illustrating that the number of well-defined and continuous seismic reflections that can be used for interpretation of the lithological boundaries and stratigraphic boundaries is closely related to the vintage of the seismic data.

To a large extent the quality reflects the year in which the seismic data was acquired. Seismic data from the period 1960–1970 are generally of poor quality with low seismic resolution and the data is mainly used for mapping of the most significant (high amplitude) seismic reflectors. Seismic data acquired in the period 1971–1980 generally provide good information with higher seismic resolution on depth relations for most reflectors. Identification of complex fault patterns is a challenge, and very limited seismic resolution results in lack of internal subdivision of the lithostratigraphic units. Seismic data from 1981–1990 are generally of good quality with reasonable seismic resolution and high energy amplitudes, and the data provide more information on the seismic architecture. The most recent data from post-1990 is generally of very good quality with higher resolution rendering the better detailed information on internal structures and identification of faults. As exploration activities for oil onshore Denmark in the last 30 year has been very limited so has the acquisition of deep seismic data. Some seismic surveys have been acquired in the search for ground water reservoirs, but these target the much shallower near surface layers providing seismic data that is far from optimal for mapping of intervals at depths to 800 meters.

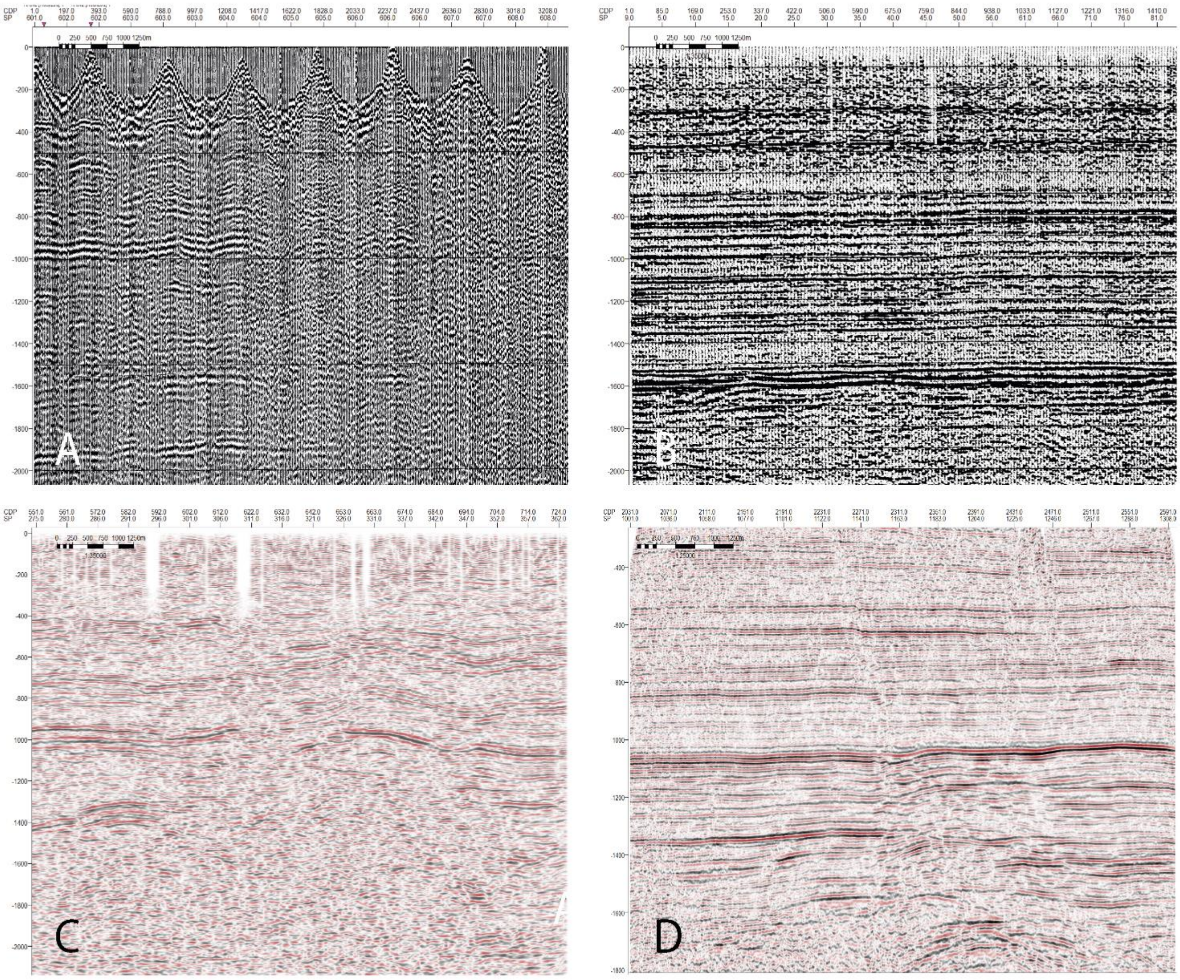

Figure 7. *Examples of seismic profiles based on seismic data acquired in different time periods (depths are given in time, milliseconds).* ***A****: Poor quality seismic profile based on seismic data collected in 1962. Seismic line AA6 (Survey SSL6267).* ***B****: Reasonable quality seismic profile based on seismic data collected in 1978. Seismic Line 7803 (Survey WGS78).* ***C****: Good quality seismic profile based on seismic data collected in 1981. Seismic line DNJ_34 (Survey DNJ8183D).* ***D****: Very good quality seismic profile with high resolution based on seismic data collected in 2013. Seismic line HILG_05 (Survey HILLEROED-2D-2013).*

Figur 7. *Eksempler på seismiske profiler baseret på seismiske data indsamlet i forskellige tidsperioder. I de viste eksempler er dybderne angivet i tid (millisekunder).* ***A:*** *Seismisk profil af ringe kvalitet baseret på seismiske data indsamlet i 1962. Seismisk linje AA6 (Survey SSL6267).* ***B:*** *Seismisk profil af rimelig kvalitet baseret på seismiske data indsamlet i 1978. Seismisk linje 7803 (Survey WGS78).* ***C:*** *Seismisk profil af god kvalitet baseret på seismiske data indsamlet i 1981. Seismisk linje DNJ_34 (Survey DNJ8183D).* ***D:*** *Seismisk profil af meget god kvalitet med stor opløselighed (detaljegrad) baseret på seismiske data indsamlet i 2013. Seismisk linje HILG_05 (Survey HILLEROED-2D-2013).*

4.2 Mapping of the lithostratigraphic units

Comprehensive mapping and interpretation of the Danish subsurface in onshore areas has been carried out for various purposes. This includes mapping and interpretation of all well-defined seismic horizons in the deep onshore and near costal subsurface areas. Due to uneven seismic and well database the interpreted horizons and resulting surfaces are all to be regarded as "Near" surfaces, where "near" indicates that the seismic horizon may not correspond exactly to the upper or lower boundary of a given lithostratigraphic formation. Rather it represents a significant lithological boundary that is interpreted to coincide with the stratigraphic boundary or occur very close to (Figure 8).

Based on the regional seismic interpretation and mapping, seismic depth and thickness maps have been generated for the most significant, laterally continuous, mappable seismic horizons (Figure 8). Each seismic map is gridded as 200x200 meter grids using a search radius of 50 kilometers, thus extrapolating data for the maps into areas where the seismic data coverage is poor which causes a larger degree of uncertainty away from well ties and seismic data. Using a large search radius can result in artificial highs or lows on the interpreted surfaces. This uncertainty will be transferred into the thickness maps as they are generated as the depth difference between two surfaces. This method causes considerable uncertainty locally where the seismic units are thin (less than 50 milliseconds corresponding to thicknesses of about 60–80 meters), in faulted areas and in areas where data coverage or quality is poor. Thus, the presented maps can be used to identify large scale depth and thickness trends whereas detailed local interpretation are needed in areas of potential interest including lateral continuity of formations, presence of faults and depth conversion.

In northern Jylland salt diapirs occur due to mobilisation of Zechstein salt (Figure 8) which has resulted in disruption of the post Zechstein layers and the generation of structural features such as piercing, faulting, folding etc. These local disruptions complicate the seismic interpretation in areas affected by salt mobilization, especially when the distance between the seismic lines is large.

Depth maps have been generated for each of the regionally mapped seismic horizons as indicated in Figure 8 (Unit B to Unit F). The maps were produced and checked for obvious artefacts by checking the depth and thickness at well locations and by comparing the maps to the interpreted seismic profiles. Where data quality and coverage are good the resulting regular grids representing the interpreted and mapped (TWT) horizons generally tie well to the corresponding stratigraphic markers in the wells.

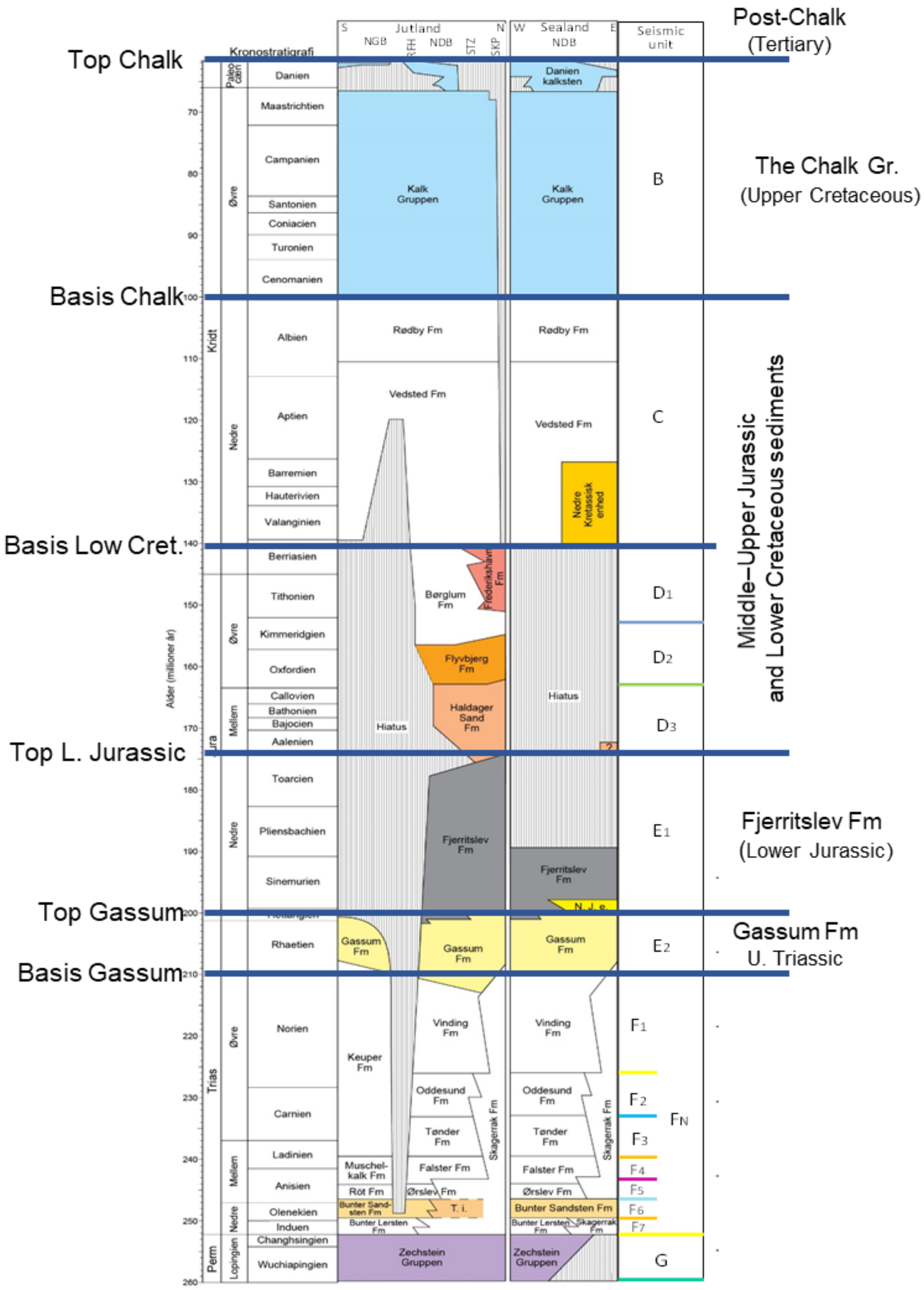

Figure 8. *Regionally interpreted seismic markers indicated on a stratigraphic overview of the Danish onshore area with lithostratigraphic subdivision. Seismic Units B to D have been mapped.*

Figur 8. *De regionale seismiske markers er vist på en stratigrafisk oversigt af de danske landområder med en lithostratigrafisk inddeling og de tolkede seismiske enheder B to E.*

4.3 Conversion from TWT (time) to depth

Depth conversion is based on a multi-layered velocity model build of stratigraphic intervals characterised by simple velocity functions following (Figure 9):

$$V = V_0 + kZ$$

where V_o refers to velocity, K is the velocity gradient, and Z is depth. The mapped horizons were interpreted in the time domain and were afterwards depth-converted from milliseconds (Two Way Time - TWT) to meters using a regional time-depth relationship following this simple function and based on velocities from available check-shot data and data derived from seismic travel times from the onshore wells. In this conversion, the depths of the seismic horizons were, as far as possible, "locked" in the wells, so that the depth to each horizon matches the depth to the corresponding lithostratigraphic boundary in the wells. In general, the depth conversion uncertainty increases away from the wells and with increases depth; typically, being 5–20% depending on data coverage, investigated depth, data quality and complexity of the subsurface (Figure 3).

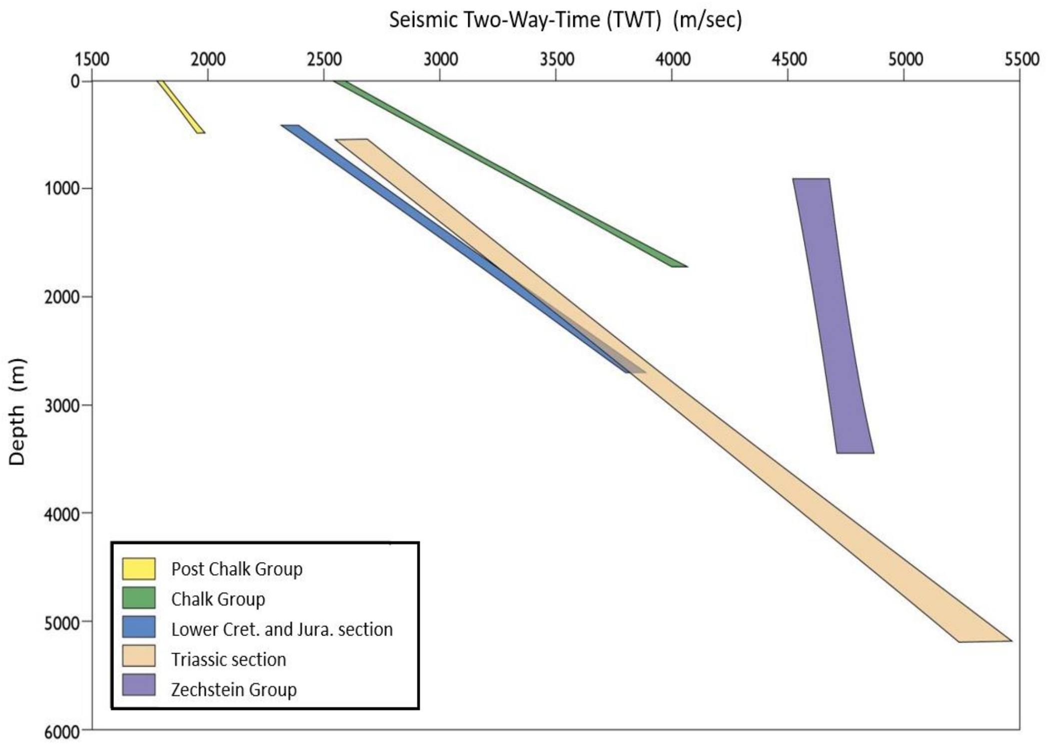

***Figure 9.** Illustration of the regional seismic velocity model used for depth conversion. The model comprises five layers, each with depth-dependent seismic velocities. For each layer in the model, the coloured fields show the area within which most of the velocities are expected to plot.*

***Figur 9.** Illustration af den landsdækkende seismiske hastighedsmodel, der er anvendt til dybdekonverteringen. Modellen indeholder fem lag, hver med dybdeafhængige seismiske hastigheder. For hvert lag i modellen viser det farvede område, området hvor størstedelen af hastighederne forventes at plotte.*

5. Seismic characteristics of the lithostratigraphic units

Well defined seismic markers of laterally widespread extension have been mapped regionally. In some areas a further seismic sub-division can be made as indicated in Figure 8, but since these markers are not widespread in the Danish subsurface, they have not been used for the producing of regional depth and thickness maps.

The Top of the Chalk Group seismic horizon is defined by a high amplitude and high continuity reflection associated with a high impedance contrast. Generally, very few logs have been run through wells in the upper part of the Chalk Group. All seismic to well correlations are based solely on the TWT converted well-tops compiled by Nielsen and Japsen (1991). The differences between the picked seismic interpretation and the well tops are between 0 and 20 meters (corresponding to 0–25 ms). Overall, the top Chalk reflector is picked with an accuracy of ca. 50 ms, corresponding to about 40–50 meters. However, in areas where to top of the chalk is very shallow the old conventional seismic data is struggling in imaging the near surface and thus the picking the top chalk is difficult.

The Chalk Group (seismic Unit B) includes Upper Cretaceous and Danian chalk deposits (Figure 8) and comprises up to 2000 meters of calcareous sediments, mostly chalk, with intercalations of marl and flint where the lower parts in particular seems to be argillaceous with a high content of marl. Generally, the Chalk Group is characterized by low gamma ray level (<10 GAPI) and low sonic transit times compared to the surrounding seismic units. Using a log suite comprising either a gamma ray or a sonic log, the base of the Chalk can be established with a precision of about 2–3 meters; depending on the vintage and quality of the log (Andersen et al., In Prep).

The top of the Lower Cretaceous (coincident with Base Chalk) can be picked on a high amplitude, and high continuity reflection with high impedance contrast at the base of the Chalk Group (Figure 6). The seismic Unit C is equivalent to the Lower Cretaceous unit and is penetrated in all deep wells, except the Hans-1 and Skagen-2 wells (see Figure 3 for location). In the north-eastern parts of Denmark, the Lower Cretaceous Vedsted Formation comprises mostly sand- and claystone, while the Vedsted Formation is absent in boreholes from the southern part of Danish-Norwegian Basin. To the southwest, the Lower Cretaceous Rødby Formation is dominated by marly sediments.

The Top of the Upper Jurassic Frederikshavn Formation (seismic Unit D) is picked on a relatively continuous and well-defined reflection mostly of low to moderate amplitude. In the southern part of the Danish Basin the top is seen as an angular unconformity resting directly on Jurassic and Triassic strata. Unit D is divided into D1 corresponding to the Frederikshavn Formation, D2 corresponding to the Børglum and Flyvbjerg Formations and D3 corresponding to the Haldager Sandstone Formation (Figure 8).

The Frederikshavn Formation comprises silt- and sandstones with some calcareous intercalations and it is present in most wells in the northern and central part of Jylland and in the Terne-1 well. Unit D includes a package of mostly parallel or sub-parallel internal reflectors, mostly of low-moderate amplitude and relatively continuous, bounded upwards by the base of Unit C or Late Cimmerian Unconformity/hiatus (Figure 8). Zones of complex seismic architecture and internal unconformities are common as seen on the seismic profiles.

The Børglum and Flyvbjerg Formations are both thin, with maximum drilled thicknesses of 147 meter and 137 meters observed in the Mors-1 and Fjerritslev-2 wells, respectively. The combined thickness of the two formations is usually less than 100 meters (Nielsen and Japsen, 1991) corresponding to 2-4 seismic cycles. The Børglum Formation is made up of dark grey and greenish marine claystones (e.g. Mors-1 and Borglum-1)(Michelsen, 1978; Michelsen et al., 2003), while the Flyvbjerg Formation is mainly a marine succession of sand-, silt and claystones, gradually changing in the northern and eastern part of the Danish Basin to be dominated by glauconitic and calcareous sandstones (e.g. Mejrup-1) (Michelsen et al., 2003). The Børglum and Flyvbjerg Formations are present in wells in the northern and central part of Jylland and in the Terne-1 wells, and absent on the Ringkøbing-Fyn High and in the North German Basin (Figure 15). Overall, the Børglum and Flyvbjerg Formations do not extend as far south as the overlying Frederikshavn Formation (seismic unit D1). Identification of the Børglum and Flyvbjerg Formations is based on lithological and biostratigraphic analysis and petrophysical log interpretations. Generally, the petrophysical log patterns through the Børglum Formation reflect fairly clean claystones (e.g. low gamma ray and low spontaneous potential responds) while logs through Flyvbjerg Formation is characterized by varying gamma ray and spontaneous potential log responds, reflecting a mixed lithology and a downward change to a more sandy lithology at the base of the formation (Michelsen, 1978; Michelsen et al., 2003). The mapped thickness of the unit is up to about 100-200 meter in the northern part of the Danish Basin, while maximum thickness is 50 meters towards the south. Thicknesses of more than 200 meter is only seen within rim-synclines related to salt structures in the central part of the Danish Basin.

The underlying Haldager Sandstone Formation is less than 50 meters thick in most wells and has a maximum thickness in Haldager-1 and Terne-1 wells with 155 meters and 173 meters respectively. The Haldager Sandstone Formation comprises intercalated sandstones, and siltstones with some claystones. It is present in wells in the northern part of Danish-Norwegian Basin, but pinch-out towards the Ringkøbing-Fyn-High and is only 4 meters thick in the Horsens-1 well. The seismic interpretation indicates that the Haldager Sand Formation is absent in large areas within the North Jylland Saltdome Province. Generally, the petrophysical logs through Haldager Sandstone Formation are characterized by patterns indicating interbedding of sandstones, siltstones and claystones, most characteristically seen on gamma ray and spontaneous potential logs.

The Top of the Upper Triassic - Lower Jurassic section (seismic Unit E) is divided into E1 and E2, corresponding to the Fjerritslev and Gassum Formations. In the northern and eastern parts of the Danish-Norwegian Basin, the Fjerritslev Formation interfingers with the upper part of the sandy Gassum Formation. Unit E1 is present throughout most of the Skagerrak-Kattegat Platform, the Sorgenfrei-Törnquist Zone and the Danish-Norwegian Basin, and further south into the Brande Trough and small patchy areas in the North German Basin. In the Fjerritslev-2 well, the formation is about 900 meters thick and comprises shallow marine and marginal marine calcareous claystones and siltstones while fine grained sandstones form a minor constituent. Generally, the Fjerritslev Formation is characterized by log patterns indicating homogeneous tight claystones.

The base of Unit E1 is defined as a continuous reflection of moderate to high amplitude, which correlates to a lithological boundary between dominantly claystones of the Fjerritslev Formation above and clean sand beds in the underlying Gassum Formation.

The seismic Unit E2 corresponds to the Gassum Formation and is found throughout most of the area. In general, the formation is about 100–200 meters thick and consists of deltaic sandstones interbedded with marginal marine mudstones (Bertelsen, 1980). The unit is diachronous, the unit being of Rheatian age in the southern part of the Danish-Norwegian Basin, Rhaetian-Hettangian age in the Skagerrak-Kattegat Platform and Rhaetian-Sinnemurian age towards the Øresund area (Figure 8).

The base of seismic Unit E2 is generally picked at or just below a distinct, relatively continuous high amplitude seismic reflection that correlates to the base of the sand dominated Gassum Formation.

6. Depth and thickness maps for major lithostratigraphic units

Based on the seismic interpretation depth and thickness maps have been generated for the mapped seismic horizons and seismic Units B, C, D and E as indicated in Figure 8. The maps are presented in the Figures 10–17.

In order to generate maps of the geological formations occurring 500 meters below ground level and deeper, it is necessary to generate depth maps for all overlying shallower seismic-stratigraphic units in order to estimate the depth and thicknesses at deeper levels and stratigraphic intervals. The generated maps of the seismic units are also used for unravelling the geological development and to reveal large scale geological and structural features of the subsurface.

Mapping confidence and depth prediction is more certain in the areas with good data coverage, i.e. closely spaced 2D seismic lines of newer vintages and good well ties (Figure 3). Good well ties are normally achieved for newer wells where data quality often is better and more comprehensive than in the oldest wells.

The largest uncertainty on the depths occurs in areas where the distance between seismic lines is tens of kilometers and/or the quality is very poor, and where good well ties are absent (Figure 3). In the area trending west-east from south-central Jylland across Fyn and southern Sjælland, east Jylland and west Sjælland the seismic and well data coverage is poor. On Bornholm, very few onshore seismic data exist, as most of the islands subsurface is composed of granite and gneiss where seismic data is generally not useful for subsurface mapping.

The Top Tertiary (Base Quaternary) depth map illustrates that the Tertiary sediments generally occur no deeper than to 300 meters. The Quaternary section is only a few tens of meters thick in central Jylland and eastern Sjælland where base of the Tertiary sediments occurs only a few tens of meters below ground level (Figure 10).

The thickness map of the Cenozoic section without the Quaternary sediments (Figure 11) shows that quite significant thicknesses occur in western, central and southern Jylland with thicknesses up to 1000 meters, whereas the thinnest deposits of 100 meter or less occur on Sjælland and in northern Jylland.

The Top Chalk depth map and the Chalk Group thickness map (Figure 12 and 13) show that Chalk sediments occur as deep as 1000 meters locally in the western and central part of Jylland. Quite significant Chalk thicknesses occur in central part of the Danish Basin and along the north coast of Sjælland with thicknesses exceeding 2000 meters, whereas the thinnest deposits of 500 meters or less occur on in North German Basin and in northern Jylland. The Base Chalk depth map (Figure 14) shows that the base of the Chalk sediments occurs deeper than 2000 meter in the central part of the Danish Basin.

Thickness of the Lower Cretaceous section (Figure 15) shows it is generally very thin in southern parts of Denmark, with thicknesses mostly below 100 meters. In northern Jylland thicknesses may locally reach 1000 meters or more, typically adjacent to salt structures.

The Top Jurassic depth map (Figure 16) shows that the Jurassic sediments generally occur at depths 600 meters to more than 1000 meters. Only locally in southeastern Denmark it occurs at 500 meters depth.

Since the Lower Cretaceous section is generally rather thin a combined thickness map of the Lower Cretaceous and Jurassic intervals has been made (Units C and D_1 to D_3). It shows that generally thin to very thin deposits (0–200 meters) are found in southern Sjælland, parts of Fyn and in southern Jylland. Locally in the central part of the Danish Basin in northern Jylland the section may reach thicknesses of more than 1500 meters (Figure 18).

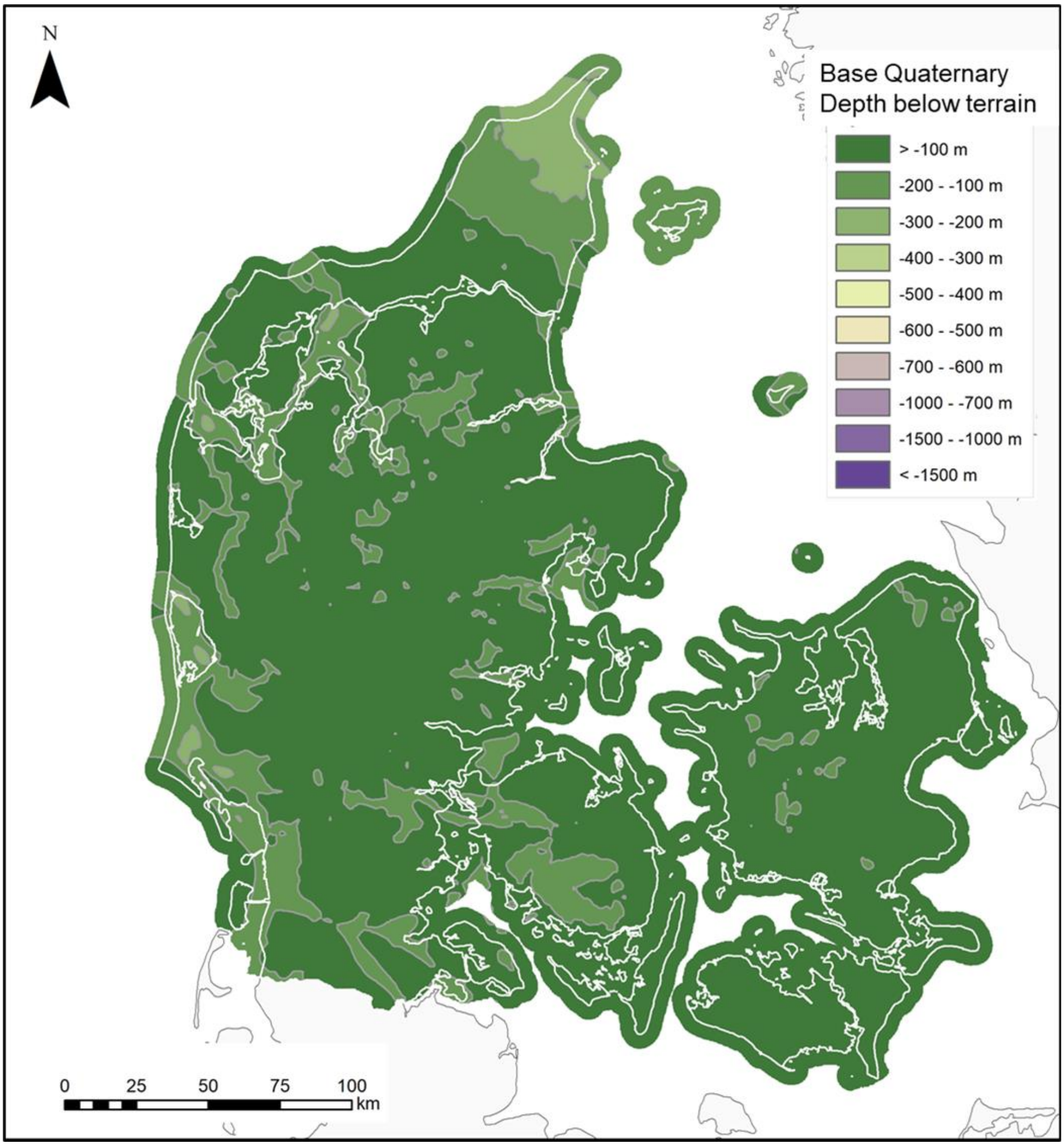

Figure 10. *Base Quaternary depth map in meters below terrain (Ground Level). The map also represents an approximate thickness of the Quaternary sediments and is based on data from shallow wells (modified after Binzer and Stockmarr 1994).*

Figur 10. *Dybden til Basis Kvartær fladen i meter under terræn. Kortet viser således en tilnærmet tykkelse af de Kvartære sedimenter og er baseret på boredata (modificeret efter Binzer og Stockmarr, 1994).*

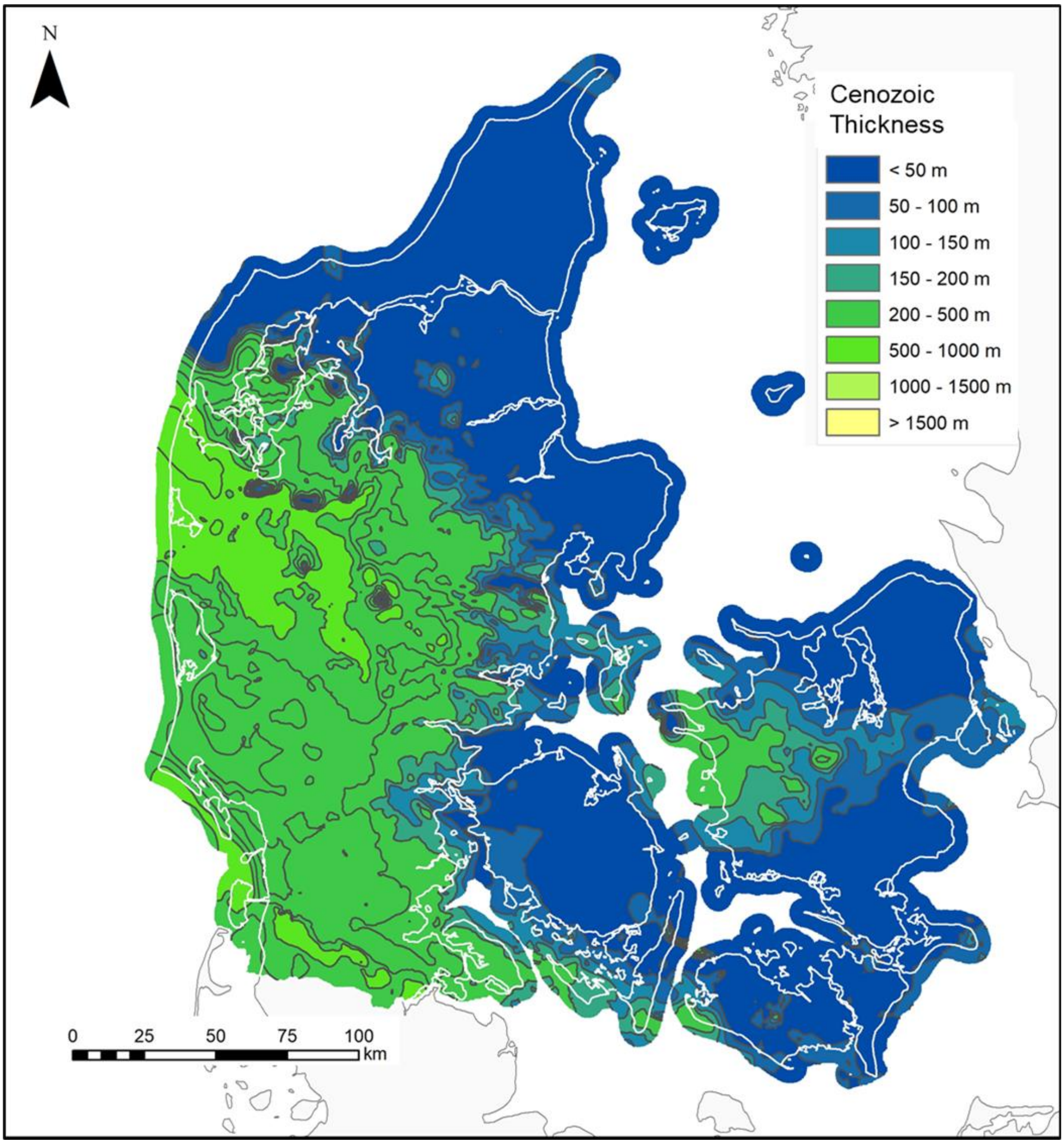

Figure 11. *The map shows the thickness of the Cenozoic sediments in meters (Quaternary section excluded).*

Figur 11. *Tykkelsen af den Kænozoiske lagpakke i meter, uden tykkelsen af den kvartære lagserie.*

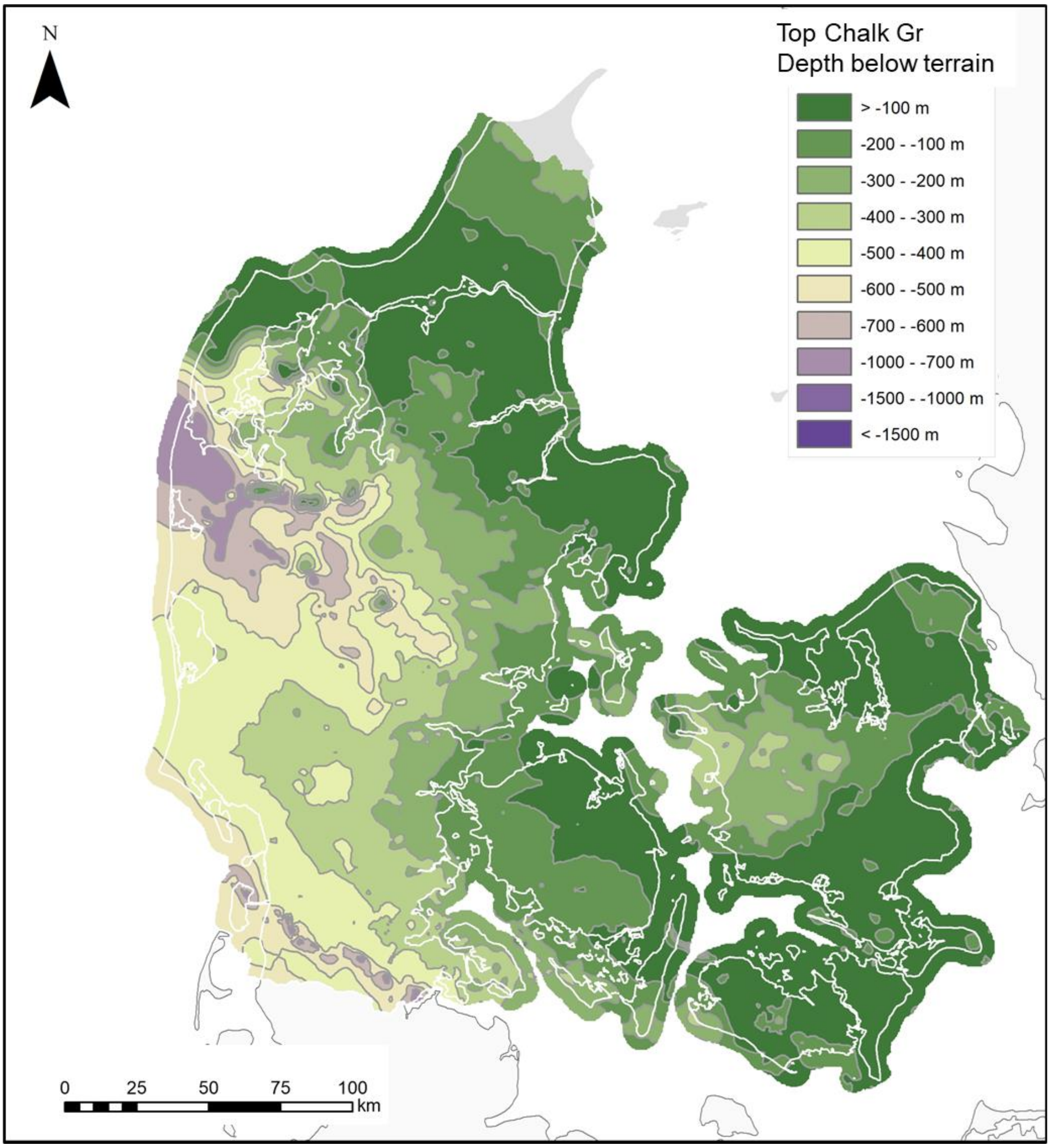

Figure 12. *Top Chalk Group depth map in meters below terrain*

Figur 12. *Dybden til Top Kalkgruppen i meter under terræn.*

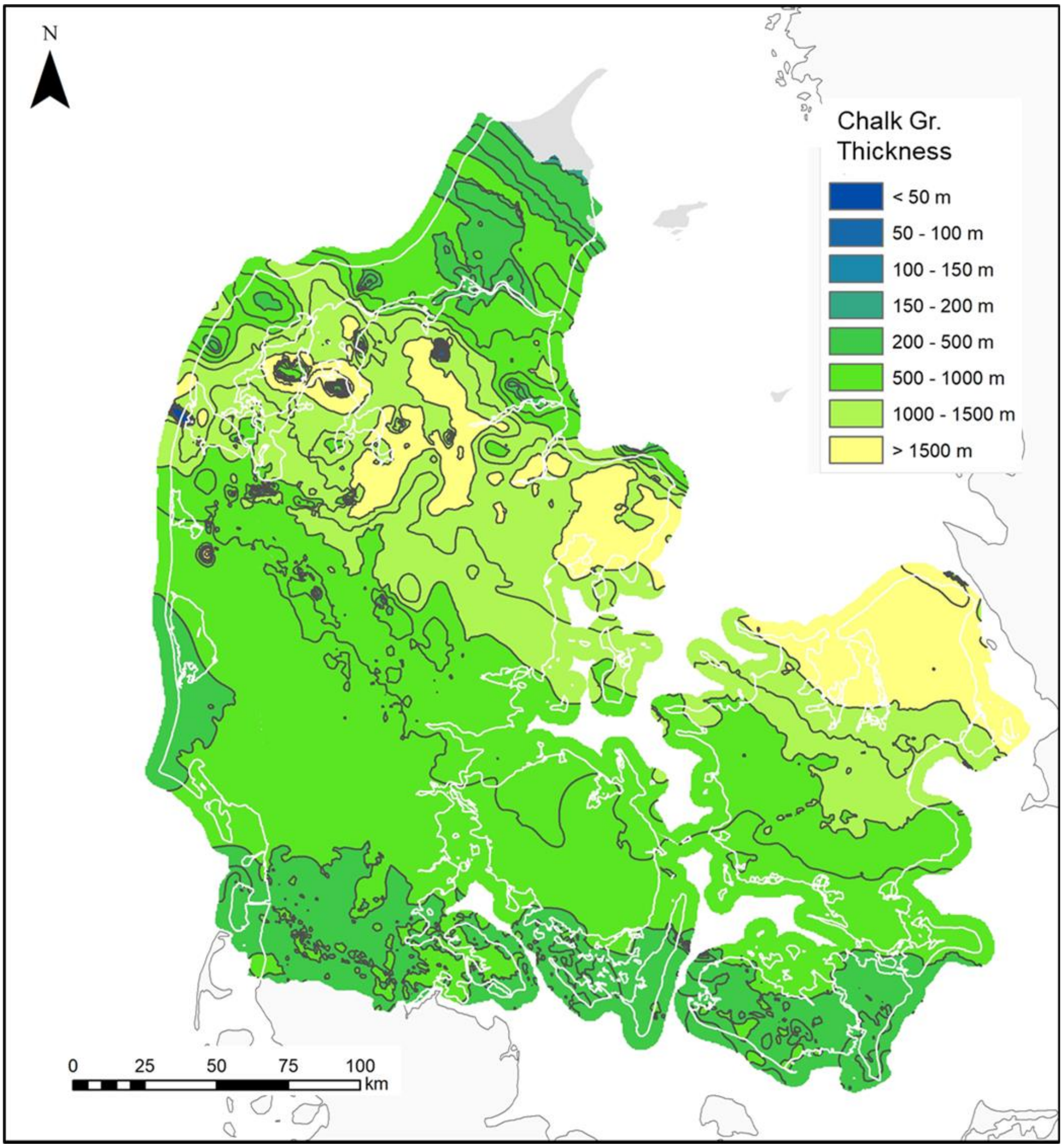

Figure 13. *Thickness of the Chalk Group (Unit B in Figure 8). Note that the thickness in the central parts of the Danish Basin is more than 1500 meters (yellow areas)***.**

Figur 13. *Tykkelsen af Kalkgruppen (Unit B i Figur 8). Bemærk at tykkelsen i den central del af det Danske Basin er mere end 1500 meter (gule områder).*

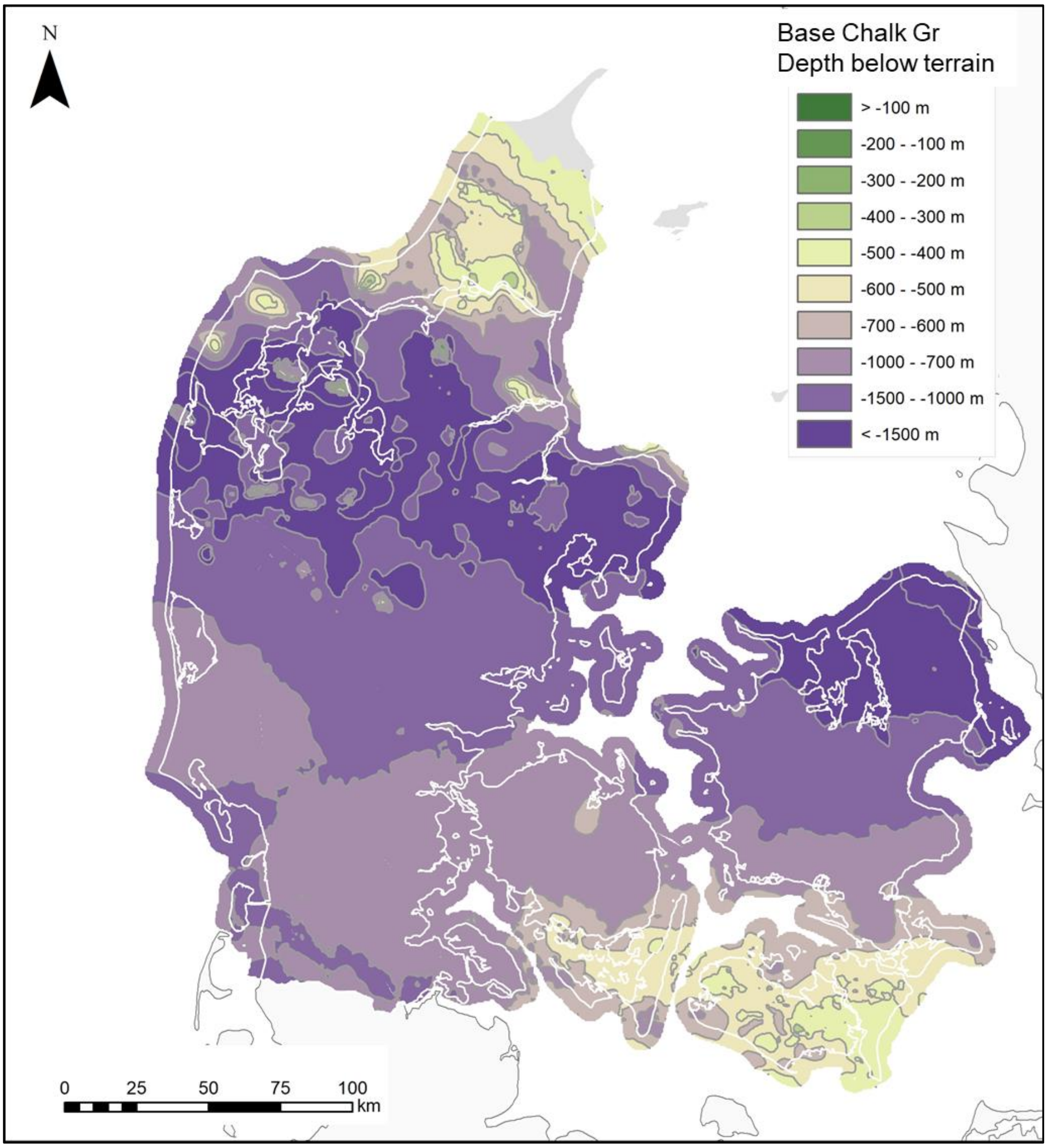

Figure 14. *Base Chalk Group depth map (corresponding to Top Lower Cretaceous) in meters below terrain.*

Figur 14*. Dybden til Basis Kalk Gruppen (svarende til Top Nedre Kridt) i meter under terræn.*

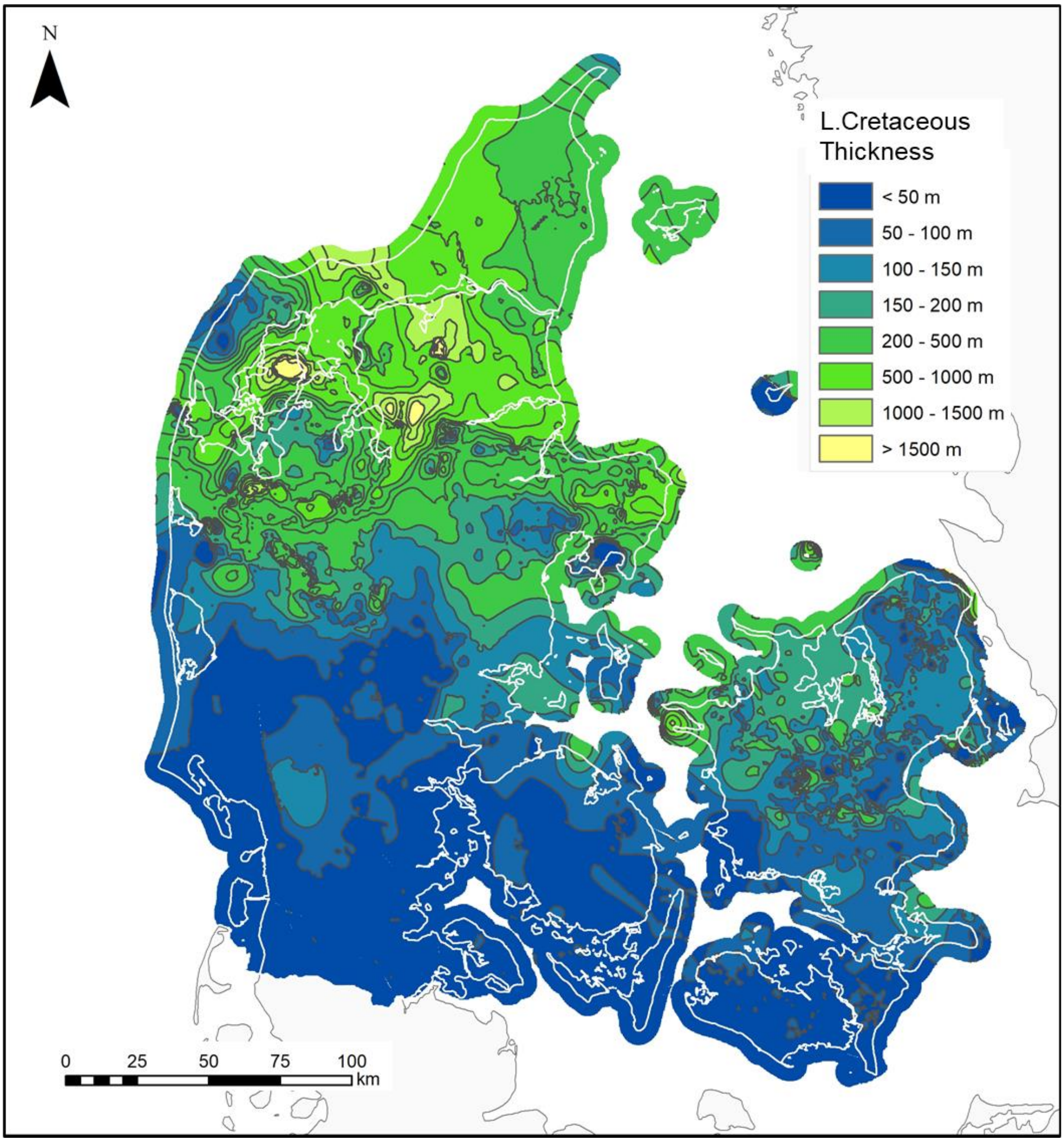

Figure 15. *The thickness of the Lower Cretaceous, i.e. thickness between Base Chalk Gr. and Base Lower Cretaceous (i.e. Top Jurassic, Figure 8).*

Figur 15. *Tykkelsen af intervallet mellem Basis Kalkpakken og Basis Nedre Kridt (Figur 8).*

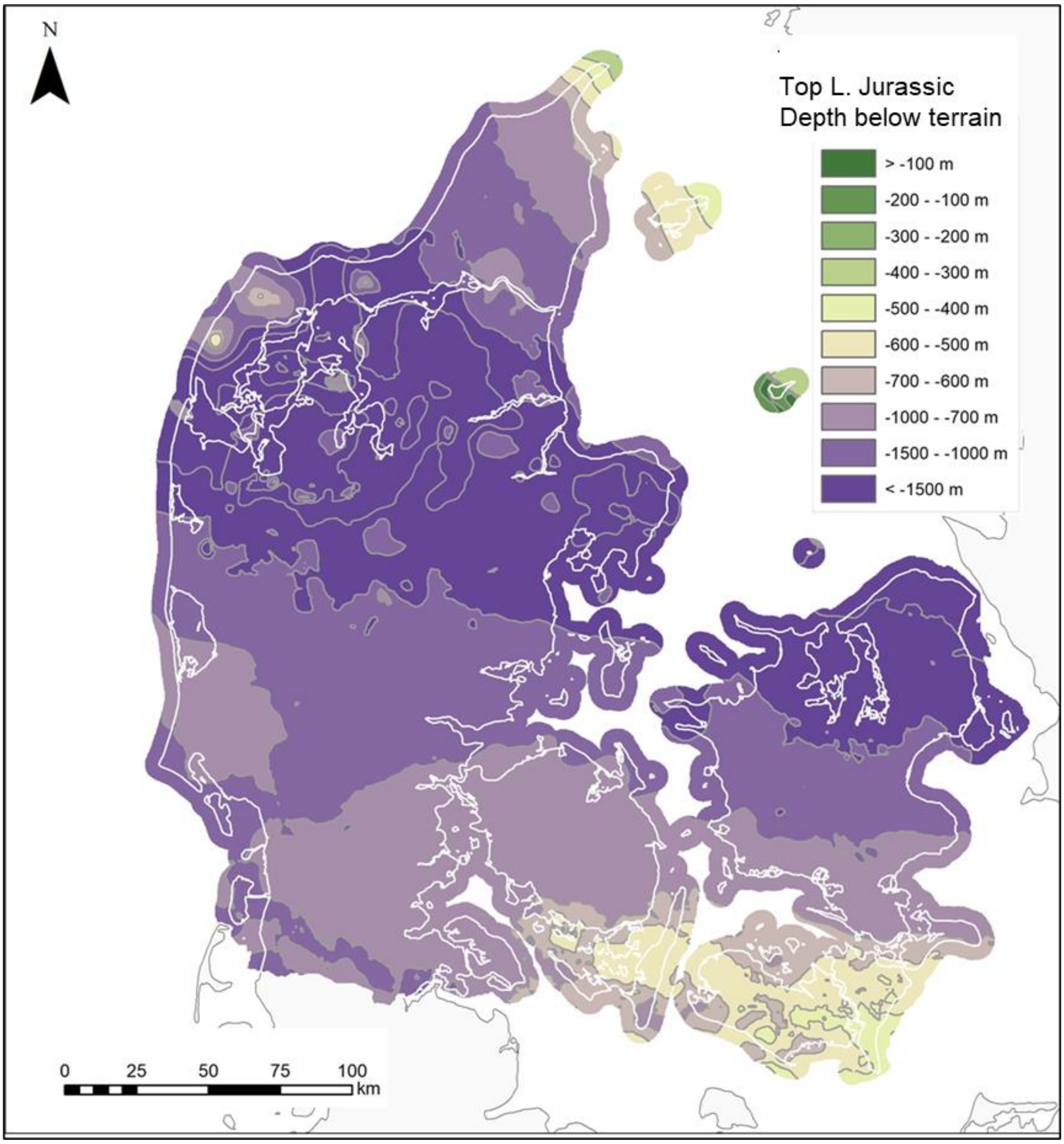

Figure 16. *Top Lower Jurassic depth map in meters below terrain.*

Figur 16. *Dybden til Top Nedre Jura i meter under terræn.*

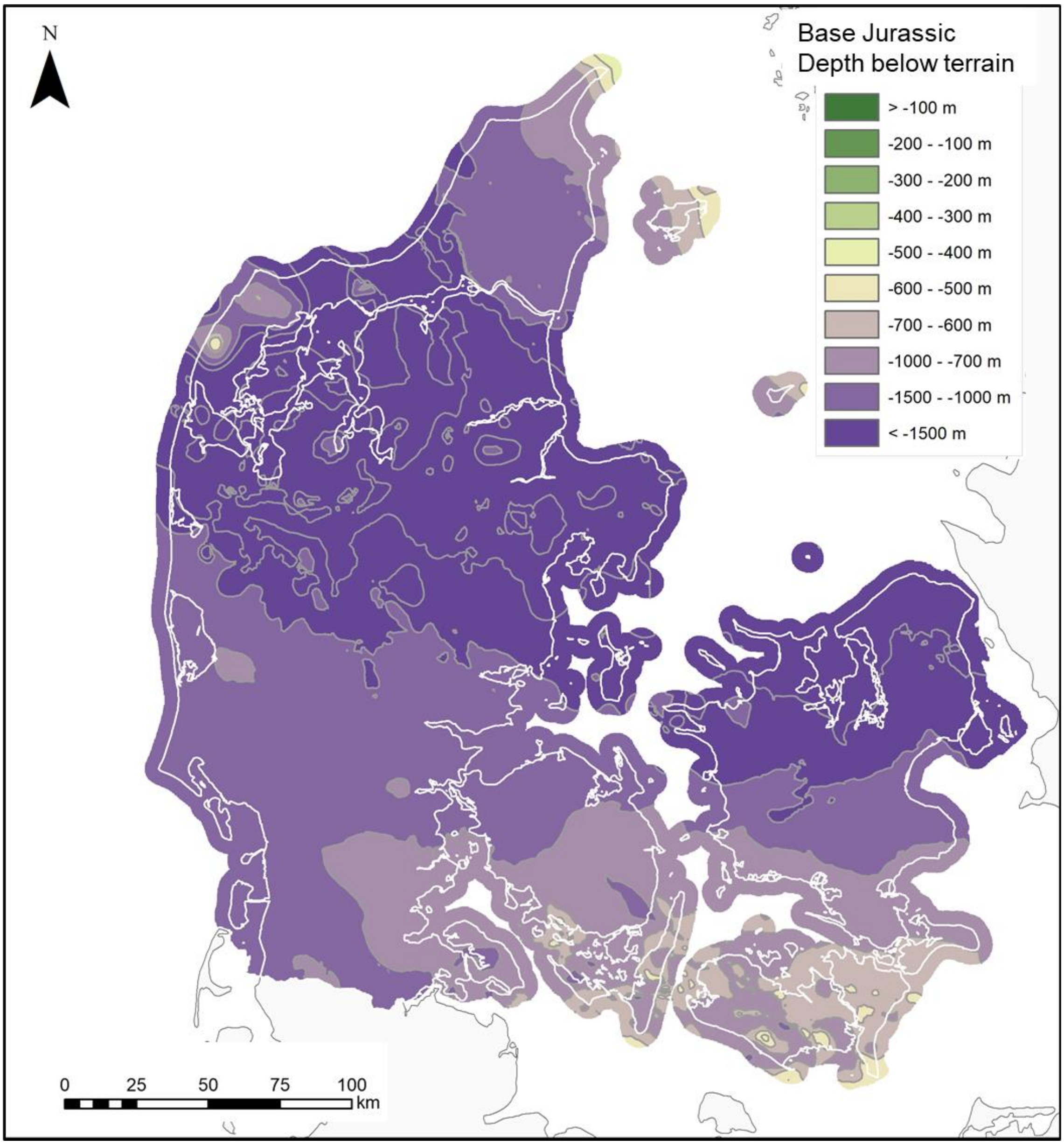

Figure 17. *Base Jurassic depth map in meters below terrain (Ground level, GL).*

Figur 17. *Dybden til Basis Jura i meter under terræn.*

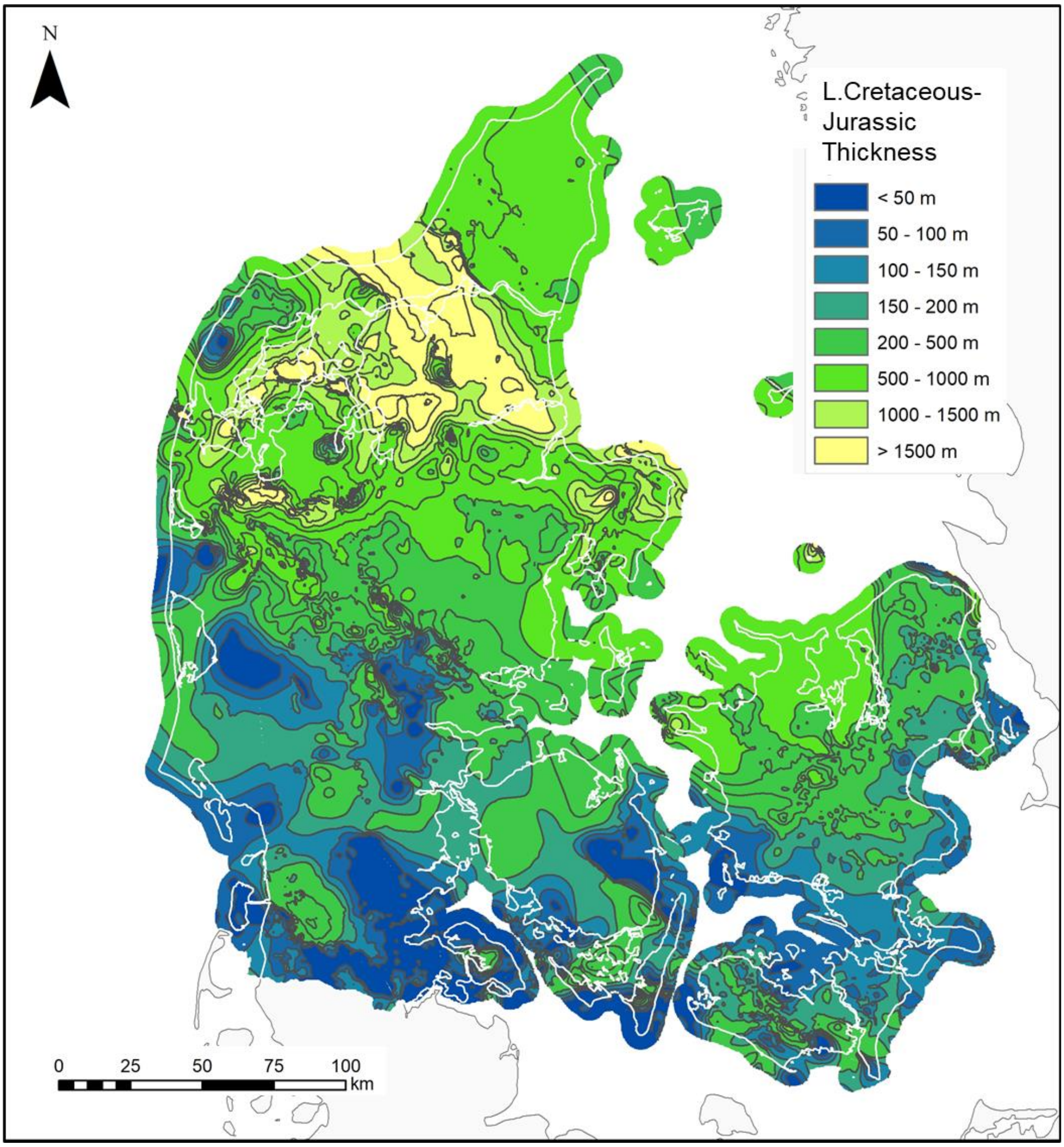

Figure 18. *Thickness of the combined Lower Cretaceous and Jurassic sections.*

Figur 18. *Samlet tykkelse af Nede Kridt og Jura Formationerne.*

7. Considerations for future acquisition of seismic data

Onshore in Denmark, seismic surveys and data from deep wells, primarily related to exploration for oil and gas in the subsurface, have been collected since the nineteen sixties. Due to a growing interest in exploiting the Danish subsurface these data have been used in various recent projects of geothermal interests and potential CO_2 storage to map the distribution of, and depth to major, significant lithostratigraphic units.

Even though a good general regional understanding of the Danish subsurface exist, further data are needed to fill in the major gaps in order to reduce uncertainty on both the depth structure maps and thicknesses as well as allowing for stratigraphic subdivision and a mapping of thinner stratigraphic/lithological units with high confidence. Further, mapping of faults based on a scattered data set is highly uncertain, and the interpreted location and extent of faults is highly uncertain.

Seismic data acquired for preliminary investigations related to possible thermal storage in Chalk aquifers in the greater Copenhagen area shows a high quality enabling detailed stratigraphic and structural interpretations (Kristensen et al., 2017). The high seismic resolution of new seismic data is expected to allow for a more detailed seismic interpretation of intra-Chalk mappable reflectors including marl layers (Figure 19) when tied to well-log picks identified from petrophysical logs in the wells.

Prior to the acquisition of new seismic lines in a local area, the general structural setting and seismic-stratigraphic complexity must be assessed and described to enable an optimum design of the acquisition to ensure a good data quality which is fit for the purpose. A new local study should thus assess the density and quality of existing seismic and well data, as this has an impact on the interpretation of the new seismic lines. Similarly, the new study must assess the nature and complexity of the subsurface, as this also has effect on the acquisition of the new seismic lines. Geological conditions such as the presence and orientation of faults, depth to, thickness and lithological composition of the subsurface layers is of crucial importance for the mapping and characterization of geological formations and lithologies at depths around 500 meters, as well as in the overburden.

Often, the orientation of new seismic lines will follow roads when possible, to reduce the inconvenience to the local environment and to improve data quality. The new lines should be laid out, such that at least one of the lines tie to a well, possibly, via existing seismic lines. In this way, data from wells can be transferred to the new seismic lines, including top and base of stratigraphic/lithological units, prior to the seismic subsurface mapping, characterization and interpretation.

To achieve a high degree of accuracy and a good seismic resolution, it is important that all relevant data acquired is available for processing and subsequent potential geophysical modelling, depth conversion and other geophysical studies. Data types such as seismic pre-stack data, density (Vp / Vs) and velocity data (including VSP and check-shot surveys), together with drill cores and relevant log suites are all very important to ensure a good result and should always be included when new data are collected.

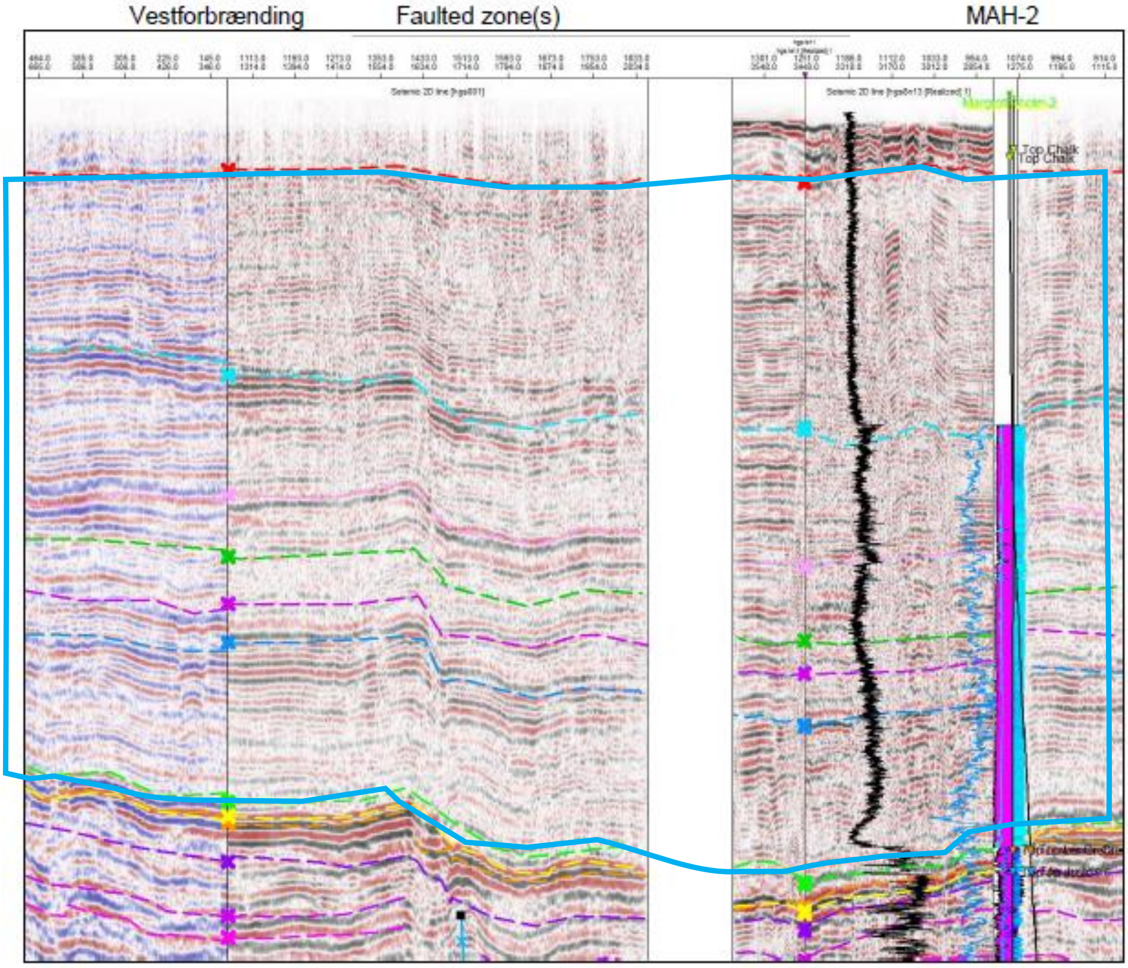

Figure 19. *Composite seismic section from the Copenhagen area showing the presence of several mappable seismic markers within the Chalk Group (marked by light blue rectangle) illustrating that the intra-chalk horizons are found structurally higher towards the west (left side of the section), and that the Intra-chalk section is faulted. The black log curve at Margretheholm well illustrates the gamma-ray signal.*

Figur 19. *Sammensat seismisk sektion fra Københavnsområdet der viser at Kalk Gruppen (indenfor lyseblå markering) indeholder adskillige veldefinerede seismiske reflektorer som kan korreleres til boringer og muligvis kan kortlægges ud i et større område. Den sorte log kurve til venstre for Margretheholm-1 borelokaliteten er en gamma-log.*

8. Summary

Seismic data onshore Denmark is unevenly distributed across the Danish land and nearshore areas. The data quality is highly varying with the most modern data seismic and well data being generally of high quality. On Bornholm, seismic data has been acquired only in a very few places since most of the island consist of crystalline basement.

The existing data has been acquired for various purposes such as hydrocarbon exploration, gas storage and geothermal interests. Most of the previous studies were focused on mapping of potential reservoirs with high porosity and permeability and have had less focus on formations occurring at shallower depths. Therefore, detailed data to characterize seal and barrier properties of rocks around 500 meters depth are few.

For the purpose of the geological repository project, the existing seismic and well data have allowed for mapping of the major subsurface formations with varying confidence. As a consequence, the depth and thicknesses of formations are associated with varying degree of certainty, depending on the density of seismic data and the vintage of the surveys.

Regionally extensive and well-defined seismic markers representing Top Chalk, Base Chalk, Top Fjerritslev (Top Lower Jurassic), and Base Fjerritslev (Base Jurassic) have been mapped. The Tertiary and Quaternary sections were mapped mainly from the extensive water well data base, thus being of high confidence and with a greater level of detail across the entire country.

Top Chalk occurs at 0-100 meters depth in large parts of Denmark, but in central-west Jylland the Top Chalk occurs locally at depths of 700-900 meters. The thickness of the Chalk Group varies from a few hundred meters to more than 1000 meters in the Danish Basin. Base Chalk depth varies from a few hundred meters to more than 2000 meters in the Danish Basin (Northern Jylland). In southern Jylland the Lower Cretaceous and Upper Jurassic sediments are absent. Elsewhere, the thickness is a few hundred meters except from north Jylland where locally, adjacent to salt structures, it exceeds 1000 meters. Top Fjerritslev Formation occurs at shallowest depths in southeastern Denmark, where it is present around 400-600 meters depth. The greatest depths are found in the Danish Basin in northern Jylland, where it exceeds 3000 meters. Greatest thicknesses of the Fjerritslev Formation are also found in the Danish Basin, where it locally exceeds 1000 meters. In most areas, the Fjerritslev Formation thickness is 100-600 meters, and in southern Jylland and large parts of Fyn, the formation is absent. In many areas, the Upper Jurassic section is absent or very thin below seismic resolution, whereas the top of the Lower Jurassic (Top Fjerritslev Formation) is well defined and laterally widespread. Therefore, thickness maps have been produced for the combined Lower Cretaceous and Upper Jurassic sections, and for the Lower Jurassic section.

Thick units of chalk and marl occur at depths around 500 meters in eastern Jylland, Fyn, Sjælland and Lolland-Falster, and adjacent islands. In areas where the chalk and marl sections occur from near surface to depths of more than 500 meters, this lithology could constitute the host rock and at the same time the shallower parts of the Chalk Group could provide the additionally required tight barrier rocks in the overlying sections (ECZ).

Sections of Lower Jurassic mudstone have greatest thicknesses in northern Jylland and Sjælland, but generally they occur at depths greater than 500 meters, which is too deep to provide a host rock with the given requirements.

The Upper Jurassic and Lower Cretaceous mudstone sections occur at depths around 500 meters locally in northern Jylland and Lolland-Falster areas where the total combined section (Upper Jurassic – Lower Cretaceous) may reach thicknesses greater than 100 meters. However, sand beds occur frequently interbedded in these mudstone sections. As a result, homogeneous claystone formations with thicknesses of 100 meters or more have not been identified. Presence of laterally widespread sand layers may pose a risk to the barrier effectiveness. In case a site with host rock in the Jurassic–Lower Cretaceous section is chosen for detailed geological investigations in the project's next phase, detailed investigations are needed to identify sites either without sand or where sand layers do not harm the host rock properties of the mudstone.

The seismic interpretation presented here provides a regional mapping of laterally widespread seismic-stratigraphic surfaces. More detailed and focused local interpretations of formation continuity, presence and characteristics of faults, depth conversions and tie to well data should be made as part of the selection of specific sites for detailed geological studies in the project's next phase. In the next phase detailed site investigations will be made with the purpose to confirm the presence of laterally continuous, low permeable host rocks as well as tight rocks in the overlying shallower levels, which can provide additional barriers. When new seismic data is acquired, it is the expectation that optimized acquisition parameters will provide a better seismic resolution (than most of the existing surveys) for the depth interval 0-1000 meters. A detailed seismic mapping depends on good well ties, which will allow for a local, more detailed seismic mapping of stratigraphy and the architecture of lithological units. This will enable the identification of interbedded units of chalk, limestone, marl and sandstones, mapping of the architecture as well as identification and mapping of faults. The identification and detailed mapping of faults is important to avoid sites with potentially active faults or subsurface discontinuities caused by the presence of fault planes.

9. References

Andersen, M.S., Boldreel L.O., Vosgerau, H., Mathiesen, A., Kamla, E. & Nielsen, L.H., *In Prep.* Development of the Northern European Platform (Upper Palaeozoic-Cenozoic of the Danish onshore area) based on seismic and well data.

ANDRA, 2005: Evaluation of the feasibility of a geological repository in an argillaceous formation. The geological medium: the Meuse/Haute-Mare site. Dossier 2005 Argile, 57-105.

Bertelsen, F., 1980. Lithostratigraphy and depositional history of the Danish Triassic. Danmarks Geologiske Undersøgelse Serie B 4: 59 pp.

Binzer, K. & Stockmarr, J., 1994. Geologisk kort over Danmark: Prækvartæroverfladens Højdeforhold: Det danske landområde samt Kattegat, indre farvande og farvandet omkring Bornholm. Danmarks Geologiske Undersøgelse, 1994. Kortserie 44, 10 pp.

COVRA, 2017: Opera Safety Case. Covra, 146 pp.

DD, 2020: https://www.dekom.dk/affaldshaandtering/#affald-1

Danish Health Authority, 2020: Responsible and Safe Management of Radioactive waste, Denmark, 68 pp.

Dansk Dekommissionering, 2021: Generiske depotkoncepter – indledende overvejelser. Notat 6 sider. Publikationer - Dansk Dekommissionering, https://dekom.dk/publikationer/

Danish Parliament, 2018: Betænkning over Forslag til folketingsbeslutning om en langsigtet løsning for Danmarks radioaktive affald. Beslutningsforslag B90, 11 pp.

Danish Parliament, 2018: Parliamentary resolution B 90: Proposal for parliamentary resolution on a long-term solution for Denmark´s radioactive waste, 11 pp.

EU, 2011: Rådets Direktiv 2011/70/EURATOM af 19. juli 2011 om fastsættelse af en fælles ramme for ansvarlig og sikker håndtering af brugt nukleart brændsel og radioaktivt affald, L 199, 48-56.

Gravesen, P., 2016: De geologiske forhold i ca. 500 m´s dybde. Foreløbig redegørelse udarbejdet på eksisterende data. GEUS-NOTAT nr. 05-VA-16-08. Til: Uddannelses- og Forskningsministeriet V/ Merete Storr-Hansen og Ole Kastbjerg Nielsen, 24 pp.

IAEA, 2011: Geological Disposal Facilities for Radioactive Waste. IAEA Safety Standards. Specific Safety Guide No. SSG-14, 101 pp.

IAEA, 2018a: Roadmap for Developing a Geological Disposal Programme, IAEA NUCLEAR ENERGY SERIES; Draft, 83 pp.

IAEA, 2018b: The Management of Site Investigations for Radioactive Waste Disposal Facilities. IAEA NUCLEAR ENERGY SERIES; Draft, 263 pp.

Japsen, P., Green, P.F., Nielsen, L.H., Rasmussen, E.S. & Bidstrup, T., 2007. Mesozoic-Cenozoic exhumation events in the eastern North Sea Basin: a multi-disciplinary study based on palaeothermal, palaeoburial, stratigraphic and seismic data. Basin Research 19: 451-490

Kristensen, L., Mathiesen, A., Nielsen, C.M., Bjerager, M., Ditlefsen, C.B., Møller, I., Rasmussen, P., Nielsen, L.H., Sheldon, E., Laier, L. & Sonnenborg, T., 2017. Examining the possibilities of establishing thermal storage in the chalk/limestone aquifer in the greater Copenhagen area. Phase 1 of project HTES, High Temperature Energy Storage. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2017/22.

MHES, 2021: Ansvars- og rollefordeling for lokalisering af områder til geologiske undersøgelser vedrørende et slutdepot for radioaktivt affald. Uddannelses- of Forskningsstyrelsen, notat 2 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. & Nielsen, L.H., 1993. Structural development of the Fennoscandian Border Zone, offshore Denmark. Marine and Petroleum Geology 10: 124-134.

Michelsen, O., Nielsen, L.H., Johannessen, P., Andsbjerg, J. & Surlyk, F., 2003. Jurassic lithostratigraphy and stratigraphic development onshore and off- shore Denmark. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin 1: 147-216.

NAGRA, 2017: Technical Reports. www.nagra.ch/en/cat/publikationen. (Switzerland).

NEA (Nuclear Energy Agency, OECD), 2005: Clay Club Catalogue of Characteristics of Argillaceous Rocks, No. 4436, 71 pp.

NEA, 2008: Moving Forward with Geological Disposal of Radioactive waste. A Collective Statement by the NEA Radioactive Waste Management Committee (RWMC). OECD, NEA No. 6433, 21 pp.

NEA, 2012: Geological Disposal of Radioactive Wastes: National Commitment, Local and Regional Involvement. A collective Statement of the OECD Nuclear Energy Agency" Radioactive Waste Management Committee", Adopted March 2011, NEA/RWM (2011)16, 17 pp.

Nielsen, L.H., 2003. Late Triassic - Jurassic development of the Danish Basin and Fennoscandian Border Zone, Southern Scandinavia. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin 1: 459-526.

Nielsen, L.H. & Japsen, P., 1991. Deep wells in Denmark 1935-1990. Lithostratigraphic sub division. Danmarks Geologiske Undersøgelse, Ser. A 31: 179 pp.

Norris, S., 2012: An introduction to geosphere research studies for the UK geological disposal programme. Mineralogical Magazine vol.76 (8), 3105-3114.

ONDRAF/NIRAS & ANDRA (eds.) 2015: Clays in geological disposal systems. Brochure Published on occasion of the 6th international conference "Clays in Natural and Engineered Barriers for Radioactive Waste Confinements", Brussels, Belgium, 8 pp.

POSIVA, 2017a Final Disposal. Selecting the Site: The Final Disposal at Olkiluoto. www.posiva.fi/en/final_Disposal. (Finland).

POSIVA, 2017b: Geologic disposal of spent nuclear fuel in Olkiluoto, 12 pp.

SKB, 2007: RD &D Programme 2007. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste, 510 pp.

Weibel, R., Olivarius, M., Vosgerau, H., Mathiesen, A., Kristensen, L., Nielsen, C.M & Nielsen, L.H., 2020. Overview of potential geothermal reservoirs in Denmark. Netherlands Journal of Geosciences, Volume 99, e6.

9.1 Literature from the project on deep geological disposal

Title of the report series:

Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark

1. Requirements and criteria for initial evaluation of geological properties and conditions (Midtgaard, H.H., Hjelm, L., Jakobsen, R., Karan, S., Kjøller, C., Nilsson, B. & Poulsen, M.L.K.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 51 pp.

2. Geological setting and structural framework of Danish onshore areas (Gravesen, P., Pedersen, S. A. S. & Midtgaard, H. H.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 72 pp.

3. Upper Cretaceous chalk and Paleocene limestone distribution and properties (Jakobsen, P.R., Frykman, P. & Jakobsen, R.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 76 pp.

4. Jurassic and Lower Cretaceous claystone distribution, sedimentology, and properties (Pedersen, G. K, Lauridsen, B., Sheldon, E. & Midtgaard, H. H.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 106 pp.

5. Precambrian crystalline basement distribution and properties (Gravesen, P., Jakobsen, P. R., Nilsson, B., Pedersen, S.A.S. & Midtgaard, H. H.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 97 pp.

6. Subsurface distribution of Jurassic and Cretaceous fine-grained formations based on seismic mapping of (Mathiesen, A., Midtgaard, H. H. & Hjelm, L.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 49 pp.

7. Evaluation of long-term stability related to glaciations, climate and sea level, groundwater, and earthquakes (Sandersen, P., Binderup, M., Larsen, T. & Nilsson, B.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 112 pp.

8. Conceptual 1D modeling of nuclides transport in low permeable formations (Kazmierczak, J., Karan, S. & Jakobsen, R.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 99 pp.

9. Karakterisering og evaluering af geologiske egenskaber og forhold i 500 meters dybde (Midtgaard, H.H., Hjelm, L., Jakobsen, R., Karan, S., Kjøller, C., Nilsson, B. & Poulsen, M.L.K.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, 186 pp.

10. *(Translation of report no. 9): Characterization and evaluation of geological properties and conditions at 500 meters depth (Midtgaard, H.H., Hjelm, L., Jakobsen, R., Karan, S., Kjøller, C., Nilsson, B. & Poulsen, M.L.K.), https://www.geus.dk/natur-og-klima/land/deponering-af-radioaktivt-affald, in prep.*

9.2 Literature from previous projects on the Danish radioactive waste

Low- and intermediate level radioactive waste from Risø, Denmark. Location studies for potential disposal areas. Published in GEUS Report Series.

Report No. 1. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2010: Data, maps, models and methods used for selection of potential areas. GEUS Report no. 2010/122, 47 pages.

Report No. 2. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2010: Characterization of low permeable and fractured sediments and rocks in Denmark. GEUS Report no. 2010/123, 78 pages.

Report No. 3. Pedersen, S.A.S. & Gravesen, P.., 2010: Geological setting and tectonic framework in Denmark. GEUS Report no. 2010/124, 51 pages.

Report No. 4. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Bornholm. GEUS Report no. 2011/44, 85 pages.

Report No. 5. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Falster and Lolland. GEUS Report no, 2011/45, 76 pages.

Report No. 6. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Sjælland. GEUS Report no. 2011/46, 85 pages.

Report No. 7. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Langeland, Tåsinge and Fyn. GEUS Report no. 2011/47, 119 pages.

Report No. 8. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of Areas. Eastern Jylland. GEUS Report no. 2011/ 48, 117 pages.

Report No. 9. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Limfjorden. GEUS Report 2011/49, 138 pages.

Report No. 10. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Nordjylland. GEUS Report 2011/50, 51 pages.

Report No. 11. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Dansk og engelsk resume. Danish and English resume. GEUS Report no. 2011/51, 64 pages.

Low- and intermediate level radioactive waste from Risø, Denmark. Studies of the six sites (Omegnsstudier). Published in GEUS Report Series.

Rapport nr. 1. Gravesen, P., Nilsson, B., Binderup, M. Larsen, T. & Pedersen, S.A.S., 2012: Lav- og mellem radioaktivt affald fra Risø, Danmark. Omegnsstudier. Rapport nr. 1. Område Østermarie-Paradisbakkerne, Bornholms Regionskommune, GEUS Rapport 2012/123, 100 pages.

Rapport nr. 2. Gravesen, P., Nilsson, B., Binderup, M. Larsen, T. & Pedersen, S.A.S., 2012: Lav- og mellem radioaktivt affald fra Risø, Danmark. Omegnsstudier. Rapport nr. 2. Område Rødbyhavn, Lolland Kommune, GEUS Rapport 2012/124, 55 pages.

Rapport nr. 3. Gravesen, P., Nilsson, B., Binderup, M. Larsen, T. & Pedersen, S.A.S., 2012: Lav- og mellem radioaktivt affald fra Risø, Danmark. Omegnsstudier. Rapport nr. 3. Område Kertinge Mark, Kerteminde Kommune, GEUS Rapport 2012/125, 68 pages.

Rapport nr. 4. Gravesen, P., Nilsson, B., Binderup, M. Larsen, T. & Pedersen, S.A.S., 2012: Lav- og mellem radioaktivt affald fra Risø, Danmark. Omegnsstudier. Rapport nr. 4. Område Hvidbjerg, Thyholm, Struer Kommune, GEUS Rapport 2012/126, 61 pages.

Rapport nr. 5. Gravesen, P., Nilsson, B., Binderup, M. Larsen, T. & Pedersen, S.A.S., 2012: Lav- og mellem radioaktivt affald fra Risø, Danmark. Omegnsstudier. Rapport nr. 5. Område Thise, Skive Kommune, GEUS Rapport 2012/127, 83 pages.

Rapport nr. 6. Gravesen, P., Nilsson, B., Binderup, M. Larsen, T. & Pedersen, S.A.S., 2012: Lav- og mellem radioaktivt affald fra Risø, Danmark. Omegnsstudier. Rapport nr. 6. Område Skive vest, Skive Kommune, GEUS Rapport 2012/128, 91 pages.

Low- and intermediate level radioactive waste from Risø, Denmark. Studies of interim storage (Mellemlagerstudier).

DD & GEUS, 2016: Supplerende mellemlagerstudier-sammenfatning. Udarbejdet af Dansk Dekommissionering og de Nationale Geologiske Undersøgelser for Danmark og Grønland for en tværministeriel arbejdsgruppe under Uddannelses- og Forsknings-ministeriet, 30 pages.

GEUS og DD, 2015: BESLUTNINGSGRUNDLAG for et dansk mellemlager for lav- og mellemaktivt affald. Udarbejdet af GEUS og DD for en Tværministeriel arbejdsgruppe under Ministeriet for Sundhed og Forebyggelse, februar 2015, 128 pages.

Gravesen, P., Binderup, M., Nilsson, B. & Pedersen, S.A.S., 2016: Kriterier og proces for lokalisering af et mellemlager for det lav – og mellemaktive affald fra Risø. De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS), 99 pages.

Low- and intermediate level radioactive waste from Risø, Denmark. Deep final repository in 500 m´s depth

Danish Parliament, 2018: Parliamentary resolution B90. Proposal for parliamentary resolution on a long-term solution for Denmark´s radioactive waste, 11 pages

Gravesen, P., 2016: De geologiske forhold i ca. 500 m´s dybde. Foreløbig redegørelse udarbejdet på eksisterende data. GEUS-NOTAT nr. 05-VA-16-08. Til: Uddannelses- og Forskningsministeriet V/ Merete Storr-Hansen og Ole Kastbjerg Nielsen, 24 pages.

Uddannelses- og forskningsministeren, 2018: Betænkning over Forslag til folketingsbeslutning om en langsigtet løsning for Danmarks radioaktive affald. Beslutningsforslag B90, 11 pages.

9.3 Other publications

Dansk Dekommisionering (DD), 2011: Pre-feasibility study for final disposal of radioactive waste. Disposal concepts. Main Report. Prepared by Cowi A/S for DD, 404 pages.

Dansk Dekommissionering (DD), De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS) & Sundhedsstyrelsen, Statens Institut for strålebeskyttelse (SIS), 2011: Forstudier til slutdepot for lav – og mellemaktivt affald – sammendrag indeholdende hovedkonklusionerne og anbefalinger fra tre parallelle studier. Rapport til den tværministerielle arbejdsgruppe vedr. udarbejdelse af beslutningsgrundlag med henblik på etablering af et dansk slutdepot for lav – og mellemaktivt affald, 44 pages.

Gravesen, P. & Jakobsen, P.R., 2010: Radon content in Danish till deposits: relationship with redox condition and age. Geological Survey of Denmark and Greenland Bulletin 20, 39-42.

Gravesen, P., Ulbak, K. & Jakobsen, P.R., 2010: Radon og radioaktivitet i danske bjergarter og sedimenter. GeoViden. Geologi og geografi nr. 4, 2-17.

Gravesen, P., Nilsson, B., Binderup, M. & Pedersen, S.A.S, 2011a: Forstudier: regional kortlægning. Kriterier og metoder til udvælgelse af 6 områder ud af 22 områder, som kan anvendes til et potentielt slutdepot for Risø´s lav- og mellemaktive radioaktive affald. Notat til den Tværministerielle arbejdsgruppe under Indenrigs og Sundhedsministeriet. GEUS-NOTAT nr. 08-EN2011-28, 12 pages.

Gravesen, P., Binderup, M., Nilsson, B. & Petersen, S.A.S, 2011b: Geological Characterisation of potential disposal areas for radioactive waste from Risø, Denmark. Geological Survey of Denmark and Greenland Bulletin 23, 21-24.

Gravesen, P., Binderup, M., Nilsson, B., Pedersen, S.A.S., Thomsen, H.S., Sørensen, A., Nielsen, O.K., Hannesson, H., Breddam, K. & Ulbak, K., 2011c: Slutdepot for Risø´s radioaktive affald. Geoviden, geologi og geografi nr.2, 19 pages.

Gravesen, P., Nilsson, B., Binderup, M. & Pedersen, S.A.S., 2012: Risøområdet: Geologi og grundvand vurderet i forbindelse med slutdepotprojektet. Udarbejdet til Ministeriet for Sundhed og Forebyggelse. GEUS-NOTAT nr.: 05-VA-12-06. 18 pages.

Gravesen, P., 2012: De geologiske forhold ved Risø. Notat til Den Tværministerielle Arbejdsgruppe angående deponering af atomaffald fra Risø under Ministeriet for Sundhed og Forebyggelse. GEUS NOTAT nr. 05-VA-12-03, 14 pages.

Gravesen, P. & Nilsson, B., 2013: Borehulslogging i 8 boringer i Østermarie-Paradisbakkerne området udført i forbindelse med undersøgelse af mulighederne for lokalisering af et slutdepot for radioaktivt affald fra Risø (Omegnsstudier). Notat til Bornholm Regionskommune. GEUS-NOTAT nr.: 05-VA-13-02, 27 pages.

Gravesen, P., Nilsson, B., Binderup, M., Larsen, T.B., & Pedersen, S.A.S., 2013: Geology, seismic activity and groundwater conditions at six potential disposal sites for radioactive waste from Risø, Denmark. Geological Survey of Denmark and Greenland Bulletin 28, 13-16.

Gravesen, P., Nilsson, B., Rasmussen, P. & Pedersen, S.A.S.,2014: Borehole logs from the Precambrian basement on Bornholm, eastern Denmark: geology and groundwater flow. Geological Survey of Denmark and Greenland Bulletin 31, 15-18.

Gravesen, P., Nilsson, B., Petersen, S.A.S. & Binderup, M. 2015: Final repository for Denmarks´s low- and intermediate level radioactive waste. Abstract and Poster. Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. 6th International Clay Conference, Brussels March 23-26, 2015, p. 299.

Gravesen, P., Jakobsen, R. & Nilsson, B., 2015: Relationship between groundwater chemistry and the Precambrian basement rocks on eastern Bornholm, Denmark. Geological Survey of Denmark and Greenland Bulletin 33, 33-36.

Gravesen, P. & Jakobsen, P. R., 2016: Pre-Quaternary rocks and sediments with a high level of radioactivity in Denmark. Geological Survey of Denmark and Greenland Bulletin 35, 31-34.

Gravesen, P., Pedersen, S.A.S, Nilsson, B. & Binderup, M., 2016, 2017: An assessment of Palaeogene and Neogene clay deposits in Denmark as possible host rocks for final disposal of low-and intermediate-level radioactive waste. I: Norris, S., Bruno, J. Van Geet, E. & Verhoef, E. (eds.): Radioactive Waste Confinement: Clays in Natural and Engineered Barriers, Geological Society, London, Special Publications, 443, 29-38, www. sp.lyellcollection. org.

Indenrigs- og Sundhedsministeriet, 2005: Slutdepot for radioaktivt affald i Danmark. Hvorfor? Hvordan? Hvor? Juni 2005, 18 pp.

Indenrigs- og Sundhedsministeriet, 2007: Beslutningsgrundlag for et dansk slutdepot for lav – og mellemaktivt affald. Udarbejdet af en arbejdsgruppe under Indenrigs – og Sundhedsministeriet, april 2007, 47 pp.

Ministeren for Sundhed og Forebyggelse, 2009: Redegørelse om Beslutningsgrundlag for et dansk slutdepot for lav- og mellemaktivt affald. Præsenteret for Folketinget. Januar 2009, 13 pages.

Nilsson, B., Gravesen, P., Pedersen, S.A.S. & Binderup, M., 2012: Final repository for Denmark´s low- and intermediate level radioactive waste. AGU Fall Meeting 3-7 December 2012 San Francisco, USA, (Poster).

Nilsson B., Gravesen, P., Pedersen S.A.S. & Binderup, M., 2017: Investigations of clay deposits as barrier for a final repository for Denmark´s low- and intermediate level radioactive waste. Abstract 7th the International Conference on Clays in Natural and Engineered Barriers fir Radioactive Waste Confinement. + Poster Davos, Switzerland, Sept. 24.-27, 2017.

Sundhedsstyrelsen, Statens Institut for Strålebeskyttelse (SIS), 2011: Radiation doses from transport of radioactive waste to a future repository in Denmark – A model study, 50 pages.

Hjemmesider

www.dd.dk
www.dmi.dk
www.geus.dk
www.ufm.dk