DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/53**

Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark. Phase 1, report no. 2

Geological setting and structural framework of Danish onshore areas

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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.2. It presents a geological overview of the structural setting and the stratigraphic record of Danish onshore areas, and near surface geological processes.

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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. 2: Geologisk opbygning og strukturel ramme for undergrunden i det danske landområde (Geological setting and structural framework of Danish onshore areas)

Danmark er et småbakket lavland, hvor de højeste områder kun sjældent hæver sig mere end 150 meter over havoverfladen. Landoverfladen er formet dels af gletsjere, som bevægede sig hen over landet under perioder med nedisning, og dels af havet, som dækkede dele af landet i mellemistiderne og efter den seneste istid. De øverste geologiske lag består hovedsageligt af istidsaflejringer i form at moræneler og smeltevandssand- og grus, samt sand og ler der er aflejret i mellemistiderne. Stedvis har gletsjerne presset ældre aflejringer fra Kridt- og Tertiærtiden op i store flager, som især kan ses i kystklinterne - f.eks. omkring Fur, ved Møns Klint og ved Stevns Klint. Afstrømning af regnvand til åer, søer og andre vådområder har medvirket til dannelse af landets nuværende overfladekarakterer.

I den danske undergrund findes der i dybder omkring 500 meter hovedsageligt lersten, sandsten, kalksten og mergel af Mesozoisk til Palæogen alder. De sedimentære bjergarter kendes hovedsageligt fra dybe boringer og seismiske data, og lokalt ses kalksten blotlagt i kystklinter og råstofgrave. De overliggende formationer er hovedsageligt tertiære, marine lersten og stedvis sandsten. På store dele af Bornholm findes der, som det eneste sted i landet, prækambrisk, krystallinsk grundfjeld nær eller i terrænoverfladen. Kvartære glaciale aflejringer af grus, sand og ler findes i det meste af landet i den øverste del af den geologiske lagserie, lokalt med tykkelser på op til 400 meter.

For at kunne identificere områder, der kan være egnede til slutdeponering af radioaktivt affald, er det vigtigt at kunne kortlægge udbredelsen af de egnede værtsbjergarter i undergrunden og indsamle viden om bjergarternes egenskaber. Lige så vigtigt er det at have kendskab til de overliggende bjergarter (barrierebjergarterne), da de skal bidrage til den samlede geologiske barriere.

Overordnet geologisk-strukturel opbygning

Sedimentære og krystalline bjergarter i den danske undergrund repræsenterer det samlede produkt af den geologiske udvikling, som har fundet sted siden dannelsen af det krystallinske grundfjeld for ca. 1,4 milliarder år siden. Danmark er placeret i et tektonisk stabilt område langt fra tektoniske pladegrænser, og derfor er det danske område ikke udsat for hverken vulkansk aktivitet, bjergkædedannelse eller større jordskælv.

Den geologiske ramme for undergrunden er relateret til den tektoniske udvikling og de største strukturelle elementer, der inkluderer Sorgenfrei-Tornquist Zonen, det Danske Bassin og Ringkøbing-Fyn Højderyggen.

Sorgenfrei-Tornquist Zonen udgør en nordvest-sydøst orienteret forkastningszone, som strækker sig fra det nordlige Jylland til området sydøst for Bornholm. Forkastningszonen var aktiv hovedsageligt i Devon- og Permtiden og i mindre grad i senere tidsperioder. Zonen afgrænser det skandinaviske, krystallinske grundfjeldsskjold mod nordøst fra det Danske Bassin mod syd. Seismisk kortlægning af de geologiske formationer og forkastninger viser, at større forkastninger har været aktive indtil sent i Kridttiden, og at der i nyere geologisk tid kun har været små forsætninger langs forkastningerne. En kortlægning af registrerede jordskælv i Danmark viser, at de fleste jordskælv har en størrelse (intensitet), der er så lille, at det normalt ikke er muligt for mennesker at mærke bevægelserne. En betydelig del af de registrerede jordskælv ses at forekomme i Vendsyssel og i Vesterhavet ud for kysten, samt i Nordsjælland og Kattegat i områder nær den underliggende Sorgenfrei-Tornquist Zone.

I det Danske Bassin findes varierende formationer af sedimentære bjergarter, der repræsenterer de geologiske tidsperioder fra Palæozoikum (540 mio. år) til nutid (Holocæn) med tykkelser på 8000 meter eller mere.

Det Danske Bassin er afgrænset mod syd af den vestnordvest – østsydøst orienterede Ringkøbing-Fyn Højderyg. På højderyggen findes det krystallinske grundfjeld i dybder på 800 meter eller mere under terræn, mens grundfjeldet i de øvrige områder findes på langt større dybder. Syd for Ringkøbing-Fyn Højderyggen findes det Tyske Bassin.

Prækambrisk grundfjeld bestående af krystallinske bjergarter findes generelt i den danske undergrund på dybder større end 800 meter, med undtagelse af Bornholm, hvor forskellige typer af gnejs og granit findes på store dele af øen i terrænoverfladen eller lige under et tyndt dække af kvartære sedimenter.

Kambriske sandsten udgør de ældste sedimenter, og de er overlejret af siltsten efterfulgt af lerskifre og tynde kalksten fra Ordovium og Silur. Devone bjergarter kendes ikke fra det danske område, og sedimenter fra Karbontiden er observeret i nogle få dybe boringer. Aflejringer fra Permtiden findes på dybder ned til 6000 meter, hvor de dybeste lag består af sandsten og lersten, der er overlejret af tykke saltformationer, som blev dannet i et udbredt havområde i Zechstein tidsperioden. Lokalt har saltet bevæget sig op mod terrænoverfladen og dannet saltdiapirer og saltpuder, der har skubbet de overliggende lag opad eller har gennembrudt lagene.

Mesozoiske aflejringer kendes fra en lang række dybe boringer, der har boret ned i, eller gennemboret hele mægtigheden af sedimenter fra Trias-, Jura- og Kridttiderne. Trias lagserien er domineret af kontinentale aflejringer af sandsten, konglomerater og lersten samt tynde lag af stensalt. Sedimenter fra Jura veksler mellem tykke, marine leraflejringer og sandaflejringer dannet i kystnære miljøer. Den nederste del af Kridt-lagserien er domineret af vekslende marine lersten, siltsten og sandsten, mens den øvre del består af skrivekridt med flintlag og lerede intervaller (mergel), der er aflejret i et vidt udstrakt havområde. På Bornholm indeholder Jura lagserien kystnære aflejringer af sand, ler og kul. Nede Kridt lagserien på Bornholm består af sand og lersten. Øvre Kridt består hovedsageligt af kalksten og grønsand.

De tertiære aflejringer fra Kænozoikum kendes fra mere end 200.000 overfladenære boringer. Den nederste del af lagserien fra Paleocæn består af marine kalksten og udgør den øvre del af Kalkgruppen. Eocæn og Oligocæn tidsafsnittene indeholder plastiske grønne og røde lerformationer, der overlejres af siltede, glimmerholdige og brune lerformationer. I Miocæn tidsperioden ændredes aflejringsforholdene til fluviale og deltaiske, hvilket resulterede i aflejringen af vekslende lag af glimmerler, glimmersand, kvartssand, brunkul og marint ler.

Sedimenter aflejret i Pleistocæn tidsperioden (2,6 mio. år til 11.700 år) er aflejret under skiftende perioder med istider og mellemistider. Sedimenterne består af moræneler og smeltevandssand og -grus aflejret af gletsjere, vekslende med lag af marine leraflejringer og søaflejringer bestående af sand, tørv, gytje og ler fra mellemistiderne. Moræneaflejringer af ler og sand samt smeltevandssand og -grus er de mest udbredte og udgør den største del af overfladelagene. Tykkelsen varierer fra 0 meter på dele af Bornholm til omkring 400 meter i det nordlige Jylland.

De yngste aflejringer er fra Holocæn tidsperioden, der dækker de seneste 11.700 år, og består af marine aflejringer af ler og sand vekslende med tynde søaflejringer af ler, sand, tørv og gytje, samt flyvesand.

Naturlige processer der påvirker de geologiske formationer i dybder ned til 500 meter

De naturlige processer, som i fremtiden kan påvirke den danske landoverflade og undergrunden ned til dybder på flere hundrede meter inden for de næste 10.000 til 500.000 år, er hovedsageligt relateret til klimaændringer, glaciationer og associerede havniveauændringer. Processerne inkluderer fluvial erosion, glacialtektonisk deformation, indsynkning og oversvømmelse såvel som opløft af landområder og mindre forsætninger ved reaktivering af gamle forkastninger. Baseret på geologiske observationer ses det, at disse processer typisk påvirker formationer i undergrunden ned til dybder omkring 200 meter under terrænoverfladen, men lokalt er der observeret erosion til dybder på 400 meter under terræn. De naturlige processer og deres mulige fremtidige påvirkning af de øvre dele af undergrunden, herunder grundvandet, er yderligere beskrevet i Rapport nr. 7 (jf. reference i Kapitel 8.1).

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 km^2) 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

The 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. Geological setting of Denmark

Denmark is a lowland with gentle slopes and hills generally less than 150 meters high (Figure 1). The morphology of the land surface is formed largely from erosion and deposition during several episodes of glaciations in the Quaternary time. Sediments and crystalline rocks occurring below the Quaternary and Holocene cover represent the cumulative results of the geological development that has taken place since formation of the crystalline basement 1.4 billion years ago. Denmark is situated in a tectonically stable area away from plate boundaries, without volcanic activity and rising mountains, and without major earthquakes.

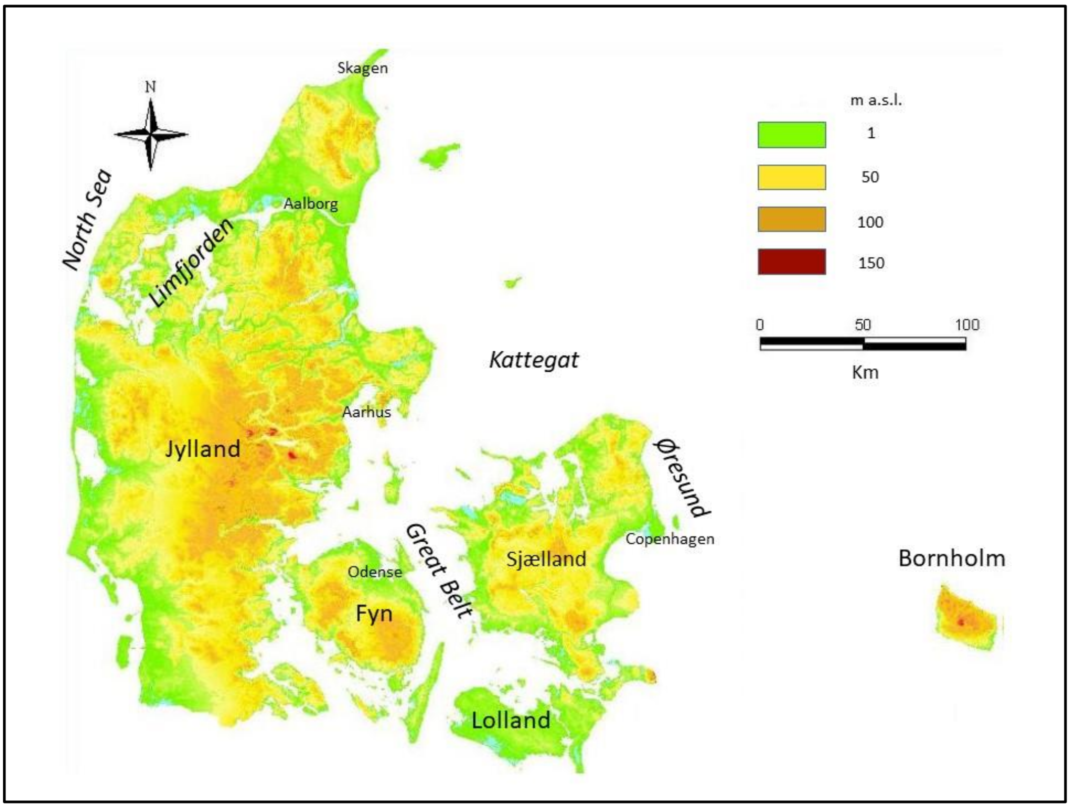

Figure 1. *Topographic map of Denmark showing the general low relief landscape with the highest elevations being less than 200meterabove mean sea level. The highest areas are found in the central part of Sjælland, the central part of Fyn, the central part of Bornholm and the central part of Jylland.*

Figur 1. *Topografisk kort over Danmark. De højeste områder findes hovedsageligt midt på Sjælland, midt på Fyn, i den centrale del af Jylland samt på Bornholm.*

The geological subsurface setting of Denmark is related to the tectonic development of the main structural elements including the Danish Basin, the Ringkøbing-Fyn High and the Sorgenfrei-Tornquist zone (Figure 2). Deposition in the Danish Basin was initiated in the late Paleozoic when the basin formed as a result crustal extension. The basin is bounded to the northeast by the Sorgenfrei–Tornquist Zone, which is a NW-striking fault zone separating the

Scandinavian basement to the north and east from the up to 10 thick deposits in the Danish Basin to the south and west (Liboriussen et al., 1987, Michelsen & Nielsen, 1993) (Figure 3).

The main fault activity in the Sorgenfrei–Tornquist Zone took place about 70 million years ago, but minor earthquakes occur occasionally along this zone. Towards the south, the Ringkøbing–Fyn High forms a basement high, separating the Danish Basin from the North German Basin (Nielsen, 2003).

The general geological development of the Danish onshore area is in the following described for the major time-stratigraphic sequences beginning with the oldest rocks of crystalline basement and ending with the glacial deposits and postglacial processes influencing the present landscape. An overview of the main geological time periods is given in Figure 4.

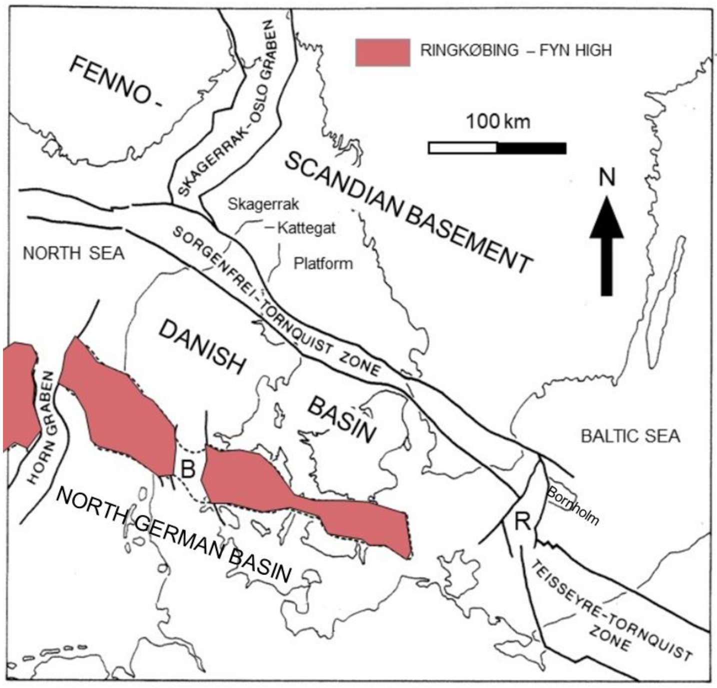

Figure 2. *The structural elements of the Danish subsurface, which is governed by the position of the Ringkøbing–Fyn High. B is the location of the Brande Through, and R indicates the Rønne Graben, which forms the western boundary of the basement horst comprising the main part of the island Bornholm.*

Figur 2. *Geologisk strukturel opbygning af det danske område. To hovedelementer styrer den danske undergrund: 1) Den ØSØ–VNV strygende Ringkøbing–Fyn grundfjeldsryg; og 2) Den langstrakte Sorgenfrei–Tornquist forkastningszone, som strækker sig fra Polen mod NV via Østersøen vest om Bornholm, NV–på gennem Sydsverige til Kattegat og forbi det østlige Limfjorden til Jammerbugten.*

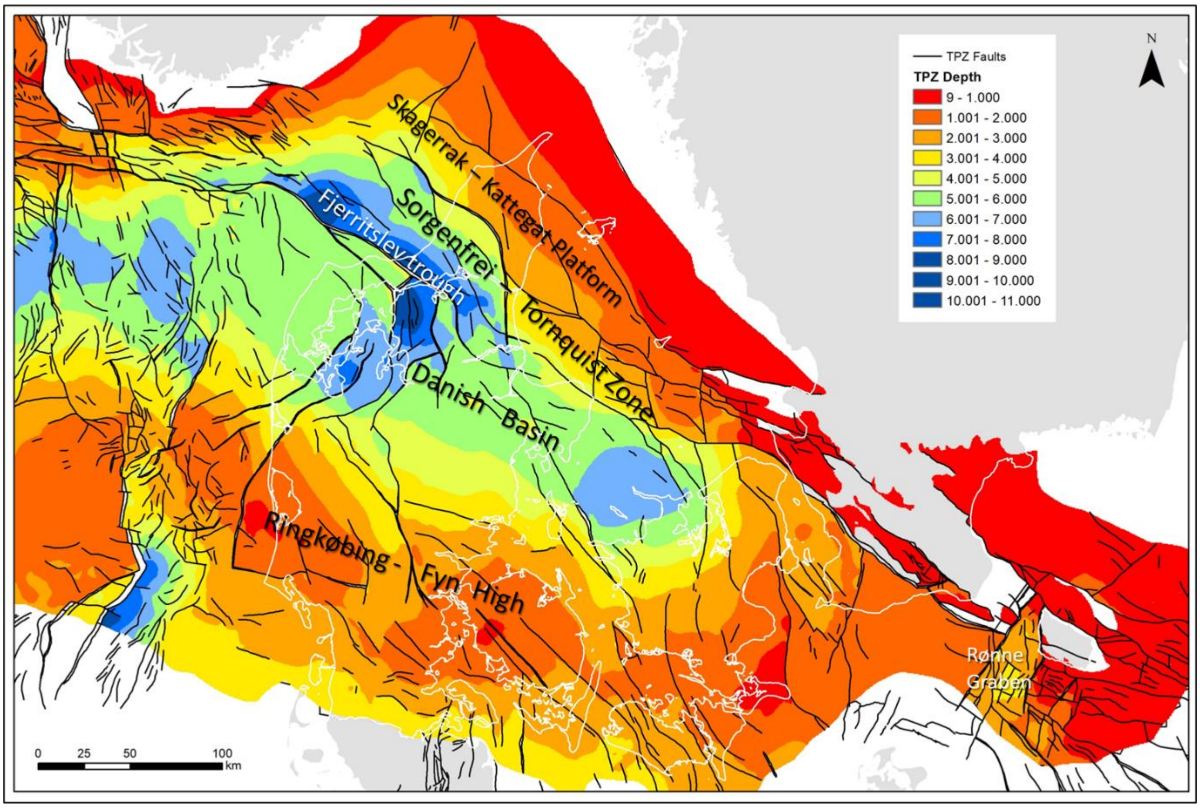

Figure 2. *Depth structure map at Top Pre-Zechstein illustrating the setting of the Danish Basin depocenter bounded by the Sorgenfrei-Tornquist Zone to the north and the Ringkøbing – Fyn High to the south. The Rønne Graben is situated in the southeasternmost part of the Sorgenfrei-Tornquist Zone.*

Figur 3. *Strukturkort over det danske område ved dybden til Top Præ-Zechstein. Det Danske Bassin er afgrænset af mod nord af Sorgenfrei-Tornquist Zonen og Ringkøbing – Fyn Højderyggen mod syd. Rønne Graven udgør den sydøstligste del af Sorgenfrei-Tornquist Zonen.*

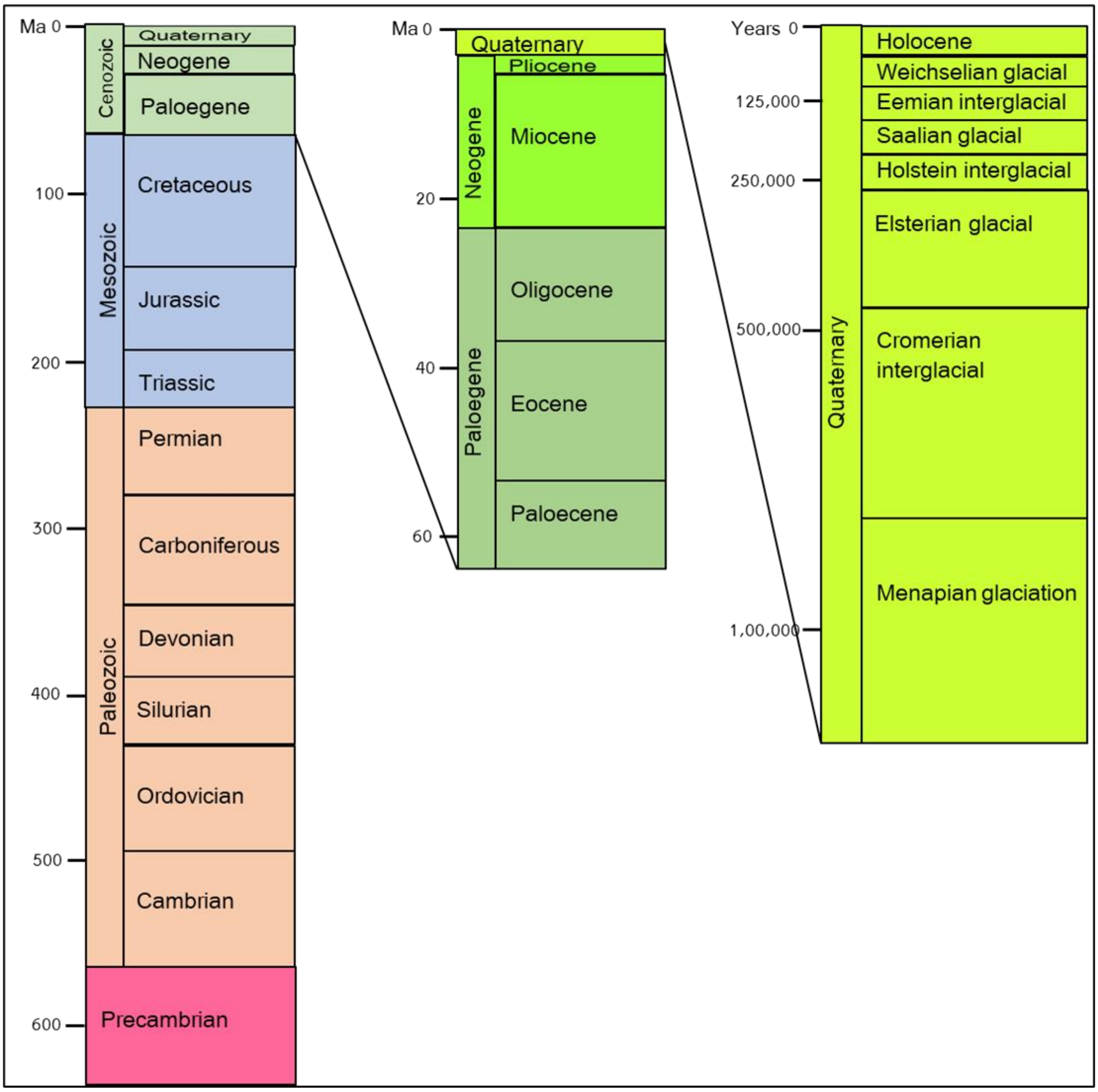

Figure 4. *Geological time periods overview referred in this report*

Figur 4. *Oversigt over geologiske tidsperioder der er refereret til i denne rapport.*

3. Structural framework

In the subsurface, the Precambrian basement forms a distinct WNW-ESE trending high, the Ringkøbing–Fyn High, which separates Denmark into the Danish Basin towards north and the North German Basin towards south (Figs. 2, 3 & 5) (Michelsen & Nielsen, 1993). The basement swell, known from the deep wells in Denmark with the shallowest depth of ca. 800meteron Fyn (in the Glamsbjerg well) and ca. 1500meterin the well at Grindsted in central Jylland, is separated by a few minor N-S trending grabens, Horn Graben to the west and the Brande Trough in central part of Jylland (Figure 5). The Ringkøbing–Fyn High fades out in the subsurface of the Baltic between Møn and Bornholm.

The tectonic development of the Danish Basin is closely related to the Sorgenfrei-Tornquist Zone. This zone extends from the Baltic Sea, where it includes the island of Bornholm and the Rønne Graben, crosses the south-western corner of Sweden, from where it trends up through the Kattegat and further up towards the eastern part of Limfjorden (Liboriussen et al., 1987). One of the prominent faults in the Sorgenfrei-Tornquist Zone is the Fjerritslev Fault (Figure 5) which strikes to the NW from Fjerritslev and continues into the Jammerbugt and further to the North Sea, where it links up with the fault complex in the Egernsund Basin off the south coast of Norway.

Northeast of the Sorgenfrei-Tornquist Zone, Precambrian basement crops out in Sweden and Norway. The Børglum Fault, crossing Vendsyssel SE–NW, comprises the northern limit of the Sorgenfrei-Tornquist Zone (Figure 2). North of the Sorgenfrei-Tornquist Zone, a platform area mainly covered by Upper Cretaceous chalk, Lower Cretaceous and Jurassic sandstones is referred to as the Skagerrak-Kattegat Platform. The platform was separated from the Sorgenfrei-Tornquest Zone during the Mesozoic. This platform area extends to the southern part of the Oslo Graben (Figure 2), which is characterised by syenitic plutonic intrusions and lava successions, the rhomb porphyries, a well know source province for erratics, distributed throughout the Quaternary deposits in western part of the Denmark.

The Danish Basin formed due to 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 kilometers thick sedimentary record, which in many places is bounded by NW–SE trending faults (Figs. 3, 5 & 6). 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 (Figs. 2, 3 & 7). To the north and northeast, the bedrock/basement occurs at shallow depths at the Skagerrak–Kattegat Platform, forming a transition from the deep Danish Basin to the bedrock in Norway and Sweden.

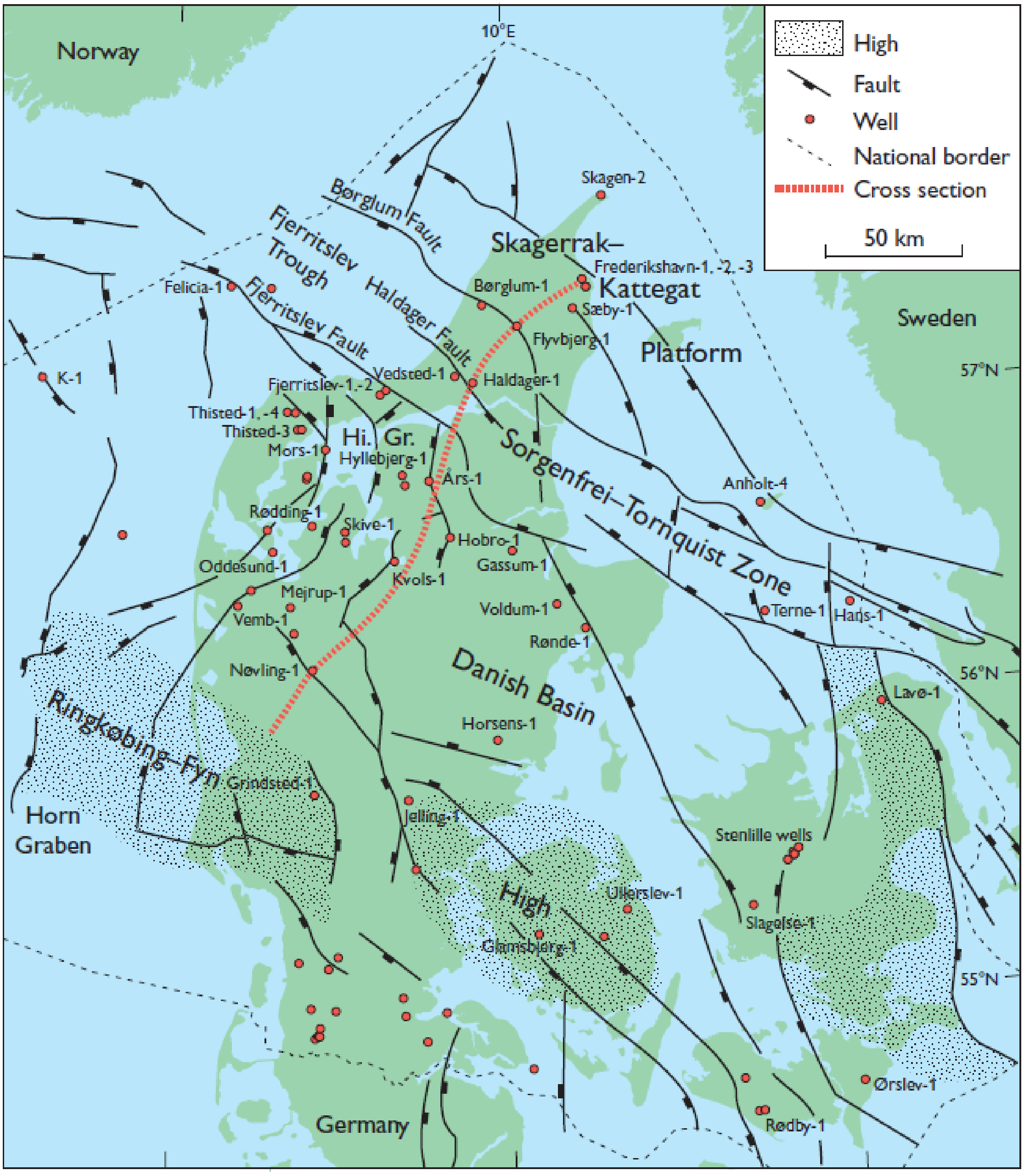

***Figure 5**. Map of the geological structural framework of Denmark including the Sorgenfrei-Tornquist Zone, the Ringkøbing-Fyn High, the Skagerrak-Kattegat Platform, the Danish and German Basins and several associated faults. Deep wells are located with red dots. For Bornholm, see the map in Figure 7 (from Nielsen, 2003).*

***Figur 5.** Kort over den geologiske strukturelle opbygning af Danmark med Sorgenfrei-Tornquist Zonen, Ringkøbing-Fyn Højderyggen, Skagerrak-Kattegat Platformen, de Danske og Tyske bassiner og adskillige forkastninger. Dybe boringer er markeret med røde prikker. Bornholm er ikke medtaget på dette kort (se Figur 15) (fra Nielsen, 2003).*

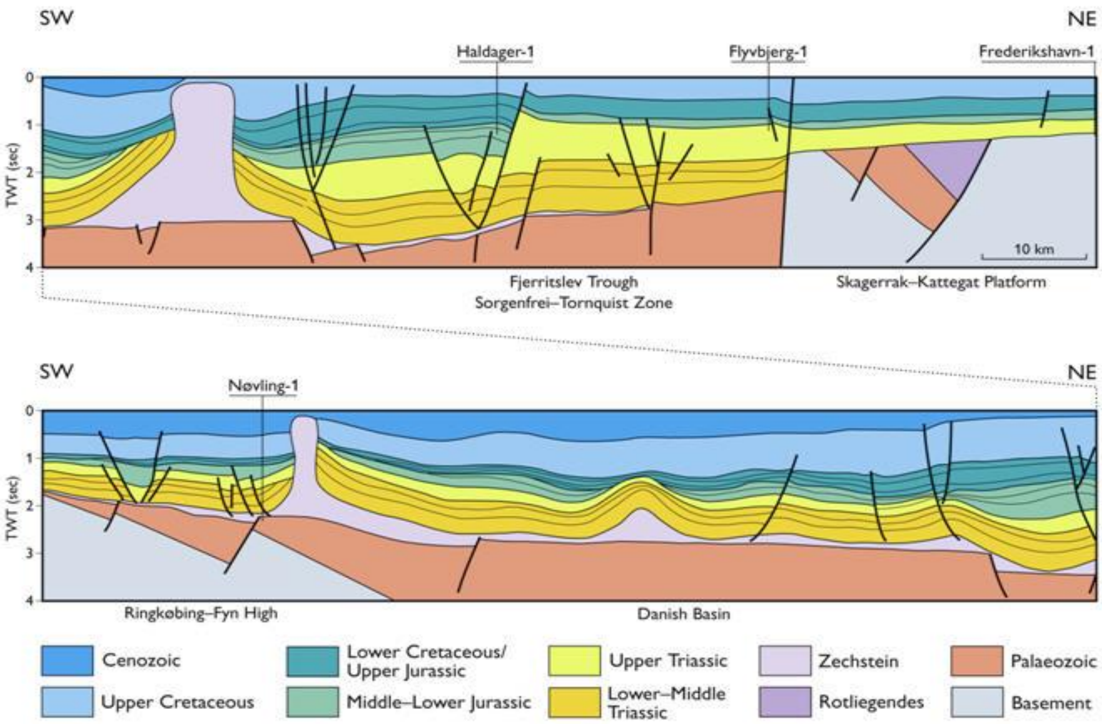

Figure 6. Geological cross section from the Frederikshavn-1 Well, Northern Jylland (NE) to the Nøvling-1 Well, central Jylland (SW) (for location see Figure 5). The section displays about 8 kilometres of section and crosses the Skagerrak- Kattegat Platform, the Sorgenfrei-Tornquist Zone, the Danish Basin and The Ringkøbing-Fyn High (from Nielsen, 2003).

Figur 6. *Et geologisk profil fra Frederikshavn-1 boringen, Nordjylland (NE) til Nøvling-1 boringen, Midt Jylland (SW) (se beliggenheden på Figur 3). Profilet krydser Skager-rak-Kattegat Platformen, Sorgenfrei-Tornquist Zonen, det Danske Basin og Ringkøbing-Fyn Højderyggen (Fra Nielsen, 2003). Profilet viser intervallet fra terræn til ca. 8 kilometers dybde.*

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 kilometre due to limited deposition on the structural high and erosion on the flanks (Figure 6). 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 (Figure 2), where the sedimentary section is up to 4 kilometres thick. South of the Ringkøbing-Fyn High the successions of Palaeozoic and Mesozoic sediments increase in thickness until they are met with the front of the concealed front of the Caledonian Fold Belt.

Regional uplift in the Middle Jurassic time led to significant erosion, especially on the Ringkøbing–Fyn High. A major hiatus in the Mesozoic includes most of the Triassic and Jurassic sections on the Ringkøbing-Fyn High (Figure 6) and was formed during the late Caledonian Orogeny and the Hercynian Orogeny. The Sorgenfrei-Tornquist Zone was activated several times during the Mesozoic rift phase (Triassic–Jurassic). This rifting resulted in differential subsidence of the Rønne Graben, which in combination with eustatic sea-level changes had

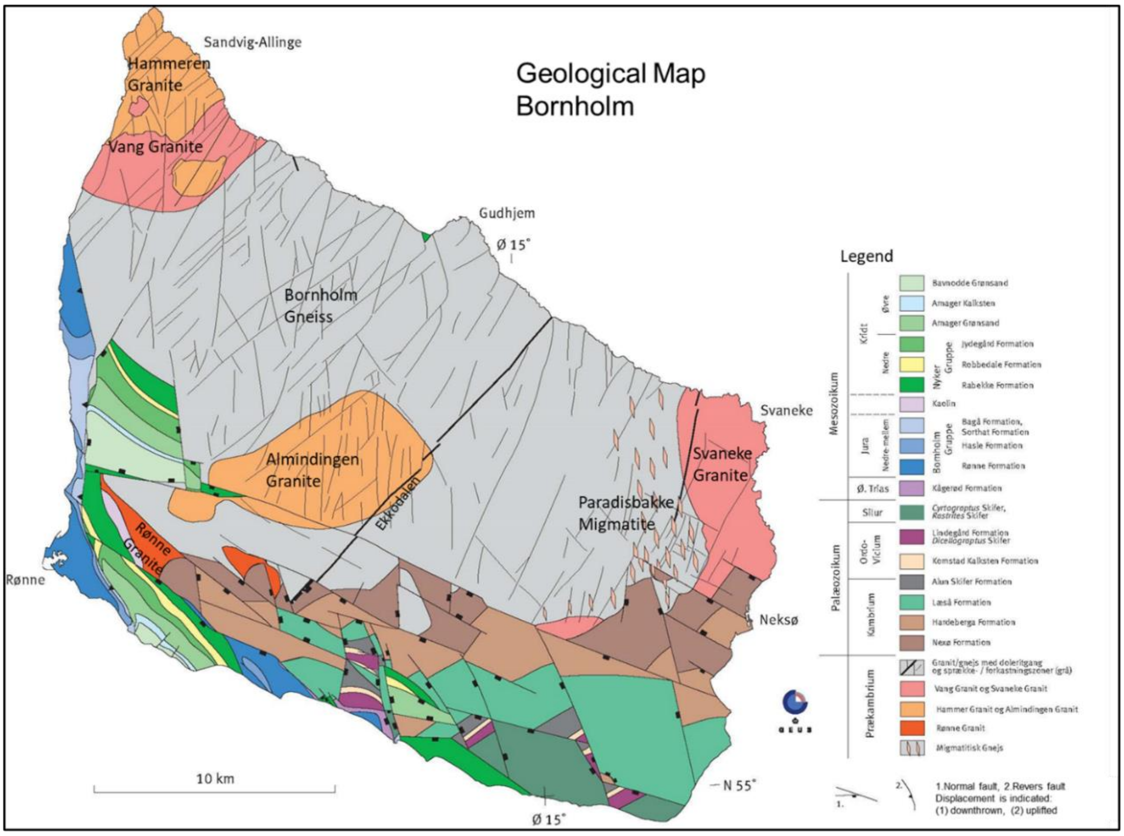

Figure 7. *Geological map of Bornholm*

Figur 7. *Geologisk kort over Bornholm*

a major control on the depositional environments on Bornholm and adjacent areas, during this period (Gravesen et al., 1982, Gry, 1969, Nielsen, 2003).

Fault-related subsidence continued in the Sorgenfrei–Tornquist Zone, associated with deposition of sand and mud. Regional subsidence was recurring 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 tectonic activity in the Danish Basin was very intensive in the late Cretaceous–early Paleocene time, which caused inversion of fault blocks as well as syntectonic deposition in subsiding segments (Japsen, 1992). Particularly the eastern part of the basin was affected by subsidence in smaller elongated basins along the Sorgenfrei-Tornquist Zone. These basins were subsequently subjected to inversion in the Paleocene along the former active faults. This tectonic event was dominantly affecting the area around Anholt and the Rønne Graben west of Bornholm (Vejbæk, 1997). During the Late Cenozoic time the inversion continued with uplift in Fennoscandia, which resulted in significant erosion (Japsen & Bidstrup, 1999, Japsen, 1992).

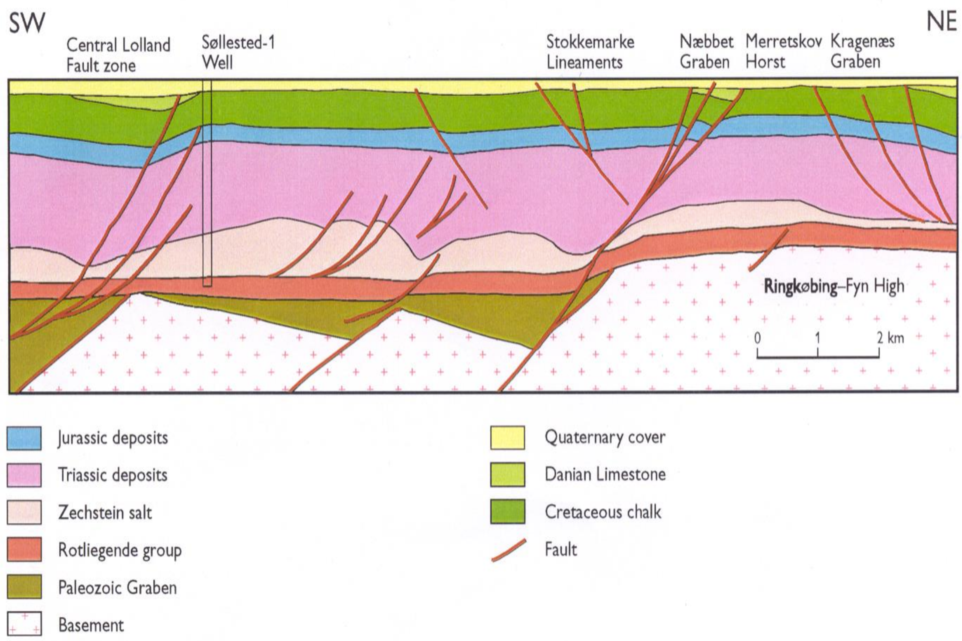

Figure 8. *Geological cross section from the northern part of Lolland showing the fault patterns extending from the basement up into the Danian sediments and perhaps also extending into the Quaternary sediments (from Pedersen et al., 2015).*

Figur 8*. Geologisk profil fra den nordlige del af Lolland, som viser forkastningsmønsteret fra grundfjeldet op til Danien aflejringerne og muligvis op i de kvartære aflejringer (fra Pedersen et al., 2015).*

Very few faults are observed to extend across the pre-Quaternary surface into the Quaternary sediments (Figure 8). This could partly be due to scarcity of detailed geophysical seismic data and detailed geophysical surveys and borehole data may reveal a more complex picture of the distribution of the sedimentary deposits and the fault pattern. An example of detailed mapping and investigations from the Roskilde area illustrates that small-scale faults can be mapped when detailed data is available (Figure 9).

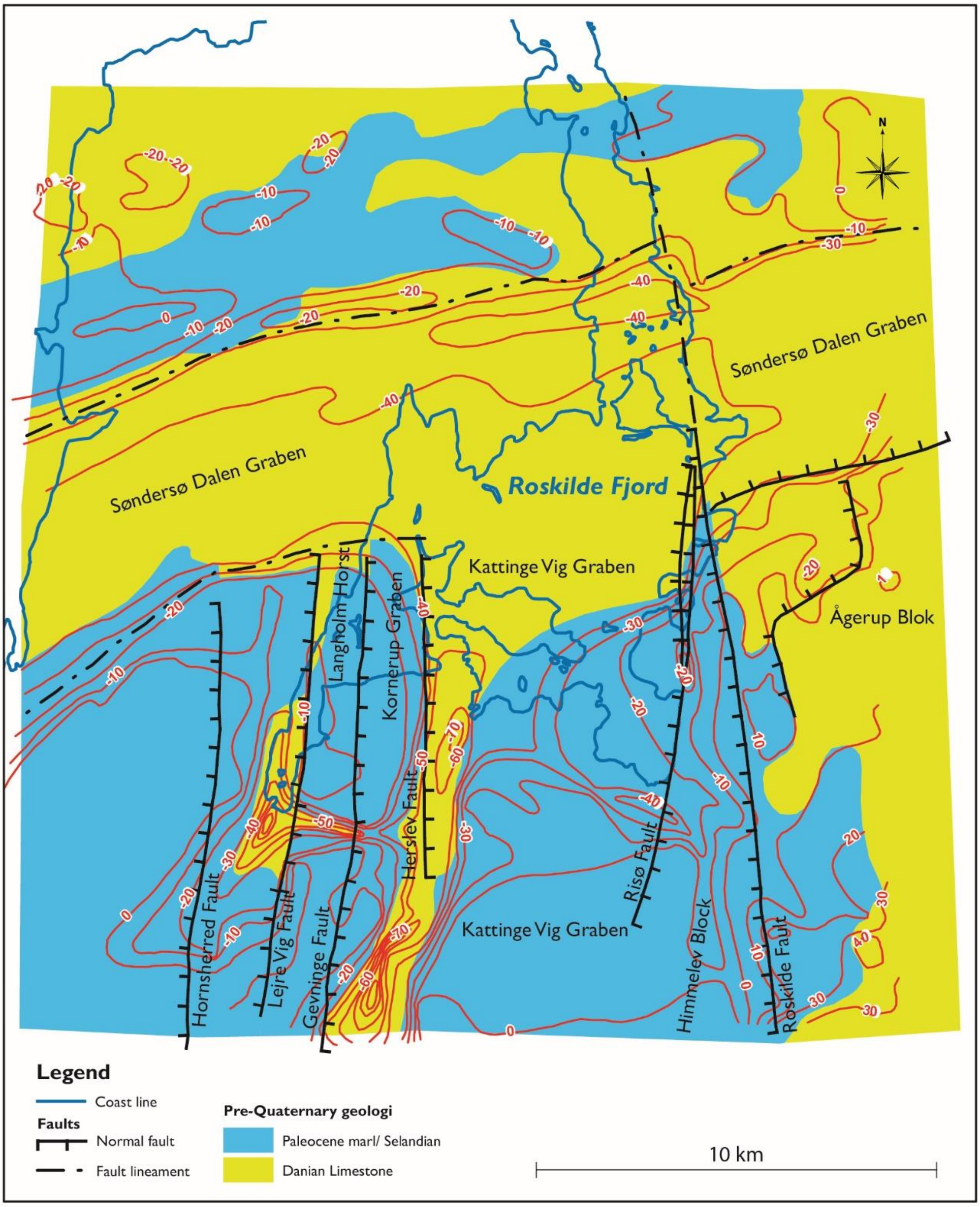

Figure 9. *Map of the pre-Quaternary surface in the Roskilde Fjord area showing that several small faults and graben systems are recognized. The contour lines outline the topography of the pre-Quaternary surface (meters below mean sea level). (From Gravesen & Pedersen, 2005).*

Figur 9. *Prækvartær overfladekort fra Roskilde Fjord området der viser, at adskillige små forkastninger og graben strukturer er kortlagt. De røde højdekurver angiver prækvartær overfladens dybde i meter i relation til havniveau. (Fra Gravesen & Pedersen, 2005).*

4. Overview of the stratigraphic record

In the following section, an overview of the rock types occurring in the Danish subsurface and their depositional environments and formation processes is presented.

4.1 Precambrian crystalline basement

Crystalline basement rocks occur in the Danish subsurface at highly varying depths from more than 10 kilometers in the deep basins to land surface on the island of Bornholm. In the subsurface the crystalline basement is known from seismic data and deep wells to occur at relatively shallow depths on the Ringkøbing-Fyn High where it was encountered at the shallowest depth of ca. 800meteron Fyn (in the Glamsbjerg well) and ca. 1500 meters in the well at Grindsted in central Jylland (Figure 5).

The basement rocks are located at relatively shallow depth under the Kattegat-Skagerrak Platform (Figs. 5 & 6). Here the north-eastern boundary fault of the Sorgenfrei-Tornquist Zone is represented by the Børglum Fault, along which the Precambrian rocks are normally displaced down to the SW in the order of a kilometre (Vejbæk, 1997).

Bornholm is the only place in Denmark where Precambrian crystalline basement outcrops. The island constitutes a horst, with basement rocks form the northern half and central part of the island at ground level and sedimentary basins in the southern part (Figure 7). The crystalline rock is composed of seven different types of granite and gneiss all formed from magma that intruded and cooled deep in the subsurface around 1450 million years ago (Gravesen et al., 2021). The formation of these rocks is generally correlated to the formation of similar crystalline basement rocks in southern Sweden.

4.2 Palaeozoic platform sediments

In the Danish Basin, the oldest known sediments are from the Early Cambrian (Figure 4). Generally, the Lower Palaeozoic sediments are poorly known from the subsurface of Denmark, but seismic mapping shows the sediments occur in small Palaeozoic grabens in the Danish Basin whereas they are thinner or absent on the Ringkøbing-Fyn High and the Skagerak-Frederikshavn Platform (Figs. 5 & 8). Cambrian sandstone, Cambrian alum shale and Ordovicium-Silurian limestones and shales were reached in the Slagelse-1 well at 2 kilometers depth and in Jylland in the Rønde-1 and Nøvling-1 wells, Silurian shales and pre-Permian rocks were encountered at 3500-4960 m´s depth (Sorgenfrei & Buch, 1964, Nielsen & Japsen, 1991).

On Bornholm, Cambrian, Ordovician and Silurian sediments are locally exposed in outcrops on southern Bornholm and occur in the subsurface as well with a total thickness around 600 m. The sediments are dominated by sandstone and shale, and minor limestone. Deposition of red fluvial and aeolian sand (Nexø sandstone) began in the Early Cambrian succeeded by deposition of quartz-rich, glauconitic marine sand (Balka sandstone) deposited in a shallow shelf environment close to a tidal-dominated shoreline. During the remaining part of the Cambrian, the Ordovician and the Silurian times, the sediments were dominated by dark, organic rich marine clay and limestone deposited in a fully marine environment (Pedersen, 1989). There are several hiati in the succession indicating periods of tectonic movements, uplift, and erosion. The shales and limestones were deposited in an epicontinental sea under low-energy and anoxic conditions (Pedersen, 1989). The Upper Ordovicium and Silurian successions comprise bentonites and tuffaceous sand layers indicating contemporaneous volcanic activity. Upper Silurian, Devonian, Carboniferous, and Permian deposits are absent on Bornholm, and Devonian sediments seems generally to be absent in the Danish subsurface.

Carboniferous deposits are recognized from a few wells drilled in Kattegat, Falster and southern Jylland including the Ørslev-1 well drilled south of the Ringkøbing – Fyn High (Figure 5) where Carboniferous sediments were encountered at a depth of 2 kilometres. The Carboniferous section is up to 500 meters thick. The Early Carboniferous section comprises grey mudstone and limestone and the Late Carboniferous comprises red and green claystone, and limestones. Redeposited Carboniferous palynomorphs are recognized in Jurassic sediments on Bornholm indicating that thicker sections of Carboniferous sediments were deposited and subsequently removed due to erosion and redeposited during the Jurassic time.

The Permian section is dominated by Rotliegendes coarse grained terrestrial sediments and thick deposits of Zechstein evaporites and is known from numerous wells. The Rotliegendes section comprises aeolian desert and lake deposits of red sand, gravel and clay reaching a thickness of 100-250meterin most of the Danish basin area. The thickness increases to more than 600meterin the Sorgenfrei-Tornquist zone. The Zechstein section thickness exceeds 1000meterand comprises evaporite deposits of halite and potassium-salt, and associated clay and limestone. The sediments are widespread within the Danish subsurface (Figs. 5). They were deposited in shallow seas that developed in large depressions both north and south of the Ringkøbing-Fyn High as the result of a major transgression. Due to the warm and arid climate thick successions of halite and associated evaporites and sediments accumulated in the basins.

In northern Denmark, the depth to the Zechstein salt is more than 6000 meters. From this depth, the salt has migrated upwards into numerous diapirs and some are situated only a few hundred meters below the present surface (Figure 6). Remobilisation of salt into diapirs and salt pillows was initiated during the Triassic time and as a result the depth to top Zechstein salt varies significantly. The salt structures occur predominantly in two provinces: the western Limfjorden region and the North German Salt Province (Figure 10). Moreover, scattered occurrences of individual salt pillows are present locally in the central part of Denmark north of the Ringkøbing-Fyn High and southeast of the Sorgenfrei-Tornquist Zone.

A common indication of the presence of salt structures occurring in the Limfjorden region is the presence of Upper Cretaceous Chalk or Danian limestone below a thin cover of Quaternary deposits or even exposed at the surface (Madirazza, 1968). On the north side of the Ringkøbing–Fyn High, salt is known from the Hvornum structure near Hobro, which is excavated by ex-solution caverning for salt production. Southeast of Hobro are the Gassum and Voldum structures. The two salt pillows at Hvalsø and Stenlille are the most prominent salt structures on Sjælland (Figure 10).

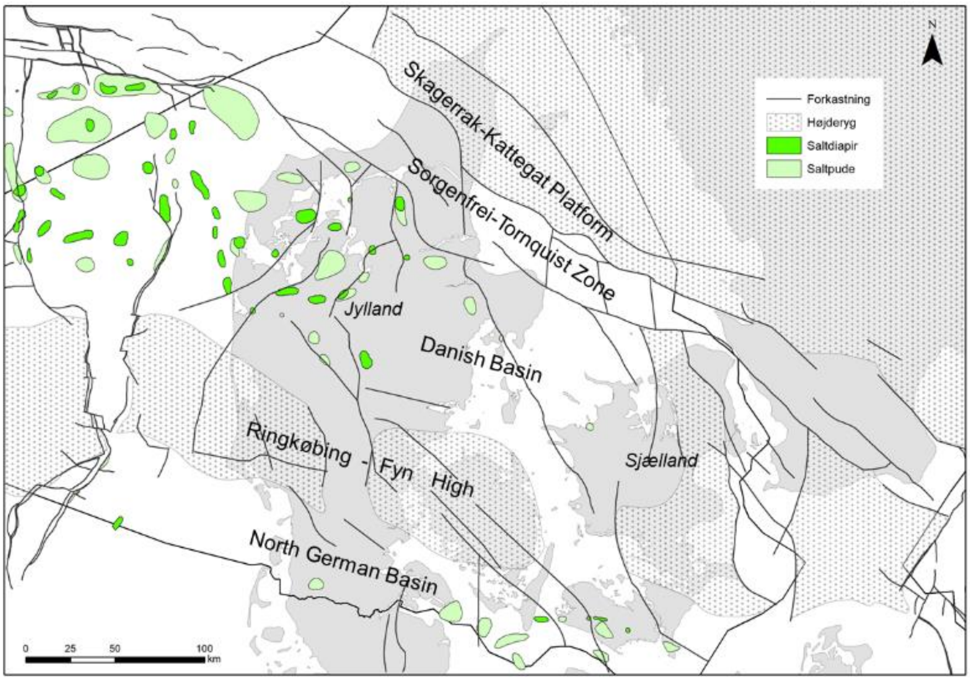

Figure 10. *Map showing the occurrence of Zechstein salt pillows and diapirs.*

Figur 10. *Kort der viser forekomsten af Zechstein saltstrukturer.*

4.3 Mesozoic rift basins

An overview of the Mesozoic lithostratigraphy is given in Figure 11. The sediments are known from deep wells onshore and offshore Denmark, from small local outcrops on Bornholm and the chalk is known also from cliffs and quarries across the country. The geometry of the major structural elements of basins and highs in the subsurface is illustrated in the geological cross-section in Figure 6.

On the Ringkøbing-Fyn High a major hiatus in the Mesozoic includes most of the Triassic and Jurassic sections. The Sorgenfrei-Tornquist Zone was activated several times during the Mesozoic rift phase (Triassic–Jurassic) with associated uplift and especially the Middle Jurassic was a period with significant erosion of older sequences. This rifting resulted in differential subsidence of the Rønne Graben, which in combination with eustatic sea-level changes had a major control on the depositional environments on Bornholm and adjacent areas, during this period (Gravesen et al., 1982, Gry, 1969, Nielsen, 2003). At the same time subsidence continued in the Sorgenfrei–Tornquist Zone, associated with deposition of sand and mud. Regional subsidence recurred 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.

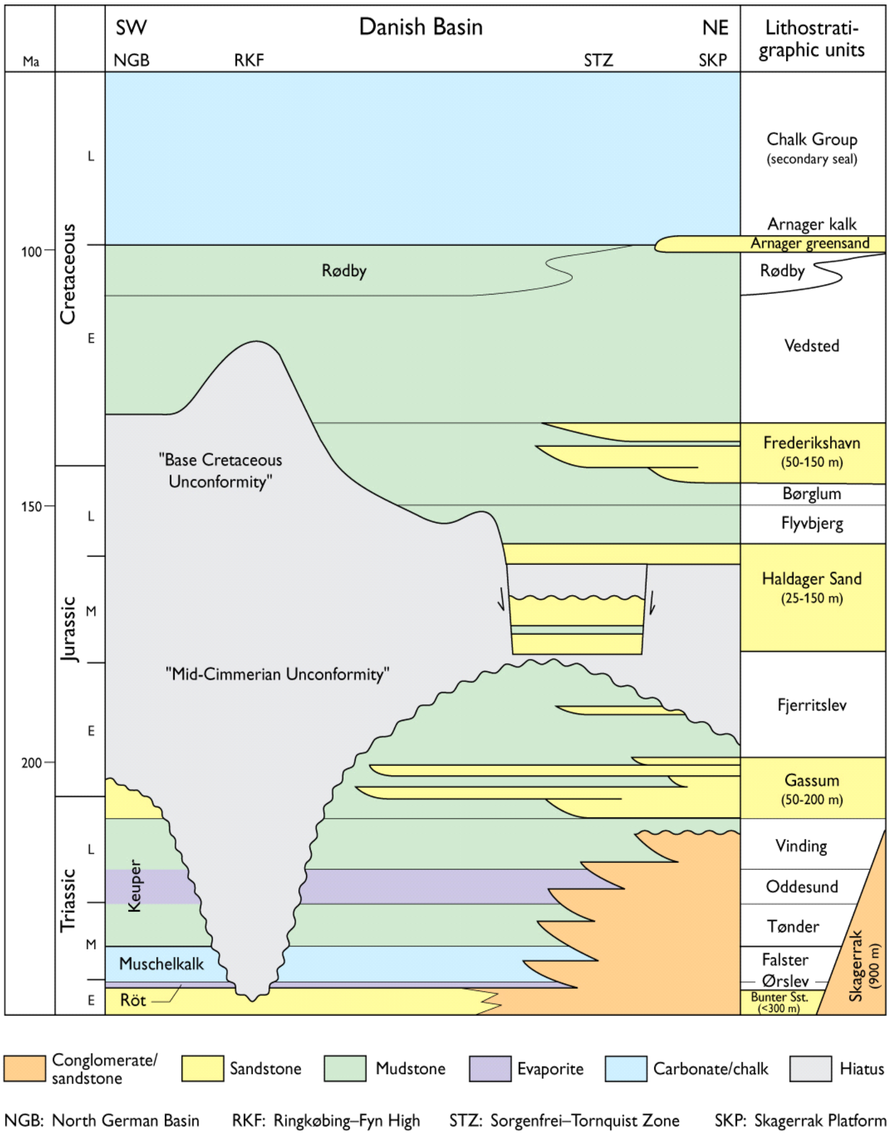

***Figure 11**. Stratigraphic scheme of the Mesozoic deposits in the Danish and North German Basins (From Nielsen, 2003).*

***Figur 11.** Stratigrafisk skema over de mesozoiske aflejringer i det Danske Bassin og det Nordtyske Bassin (Fra Nielsen, 2003).*

The deposition of thick sedimentary sequences in the basin centres during the Mesozoic and active faulting along the basin margins led to remobilisation of the underlying less dense salt layers. The salt layers were plastically deformed and locally rising to form salt pillows and eventually also salt diapirs that may reach to, or near ground level.

Where sediments overlie rising salt, the layers were moved upwards, or alternatively pierced by the rising salt. One example is the southern margin of the Sorgenfrei-Tornquist zone (see Figure 10) towards the Danish Basin, where a large salt diapir dissects through all the overlying sections except for the uppermost part of the Chalk Group. Increased subsidence at the flanks of the salt structures (in the rim synclines) caused a local thickening of layers deposited contemporaneously with the main phases of salt remobilisation.

4.4 Mesozoic sediments

The Triassic section comprise terrestrial sediments of red and green clay, sandstone and conglomerates forming a more than 3 kilometers thick sequence. The sediments comprise mainly red conglomeratic to coarse grained sandstones deposited on huge fluvial plains intercalated with aeolian dunes and claystones from ephemeral lakes in an arid environment. Towards the south intercalated green and grey marine claystone, limestone and marl with anhydrite occur with increasing frequency. The considerable thickness and relative fast deposition of the Triassic deposits contributed to the subsequent remobilisation of the Zechstein salt into salt pillows and diapirs as seen in Figure 10.

The overlying Jurassic deposits mirrors a major marine transgression in Northern Europe during the onset and development of rifting in the North Atlantic (Surlyk & Ineson, 2003). The early Jurassic transgression formed a deep-sea environment where fine-grained, dark grey, and black mudstones and shales were deposited. In the Danish Basin the thickness exceeds 1000meterin the depressions related to the Fjerritslev Fault Zone (trending SE–NW across northern Denmark, Figure 4 & 5) and in the Central Graben in the North Sea (Vejbæk, 1997). In the Danish Basin the Lower Jurassic section comprises marine mudstone referred to the Fjerritslev Formation which has an increasing content of sand beds in the upper part of the section (Nielsen, 2003). On the Ringkøbing-Fyn structural high shallow marine sandstones of the Gassum Formation occur (Figure 11).

The Jurassic sediments crop out on the pre-Quaternary surface in the Rønne Graben and along the inversion swell in the Sorgenfrei-Tornquist Zone in the Kattegat Sea, from where they can be traced along strike to outcrops in southwestern Sweden (Vejbæk & Andersen, 2002, Gravesen 1996).

On Bornholm in easternmost part of Denmark the Lower Jurassic deposits are exposed in fault blocks along the west and south-west coast of Bornholm (Figure 7). Here shallow marine claystone, sandstone and interbedded coal beds represent tidal and deltaic depositional environments. The Early Jurassic was dominated by deposition of sand, clay, and coal in deltas,

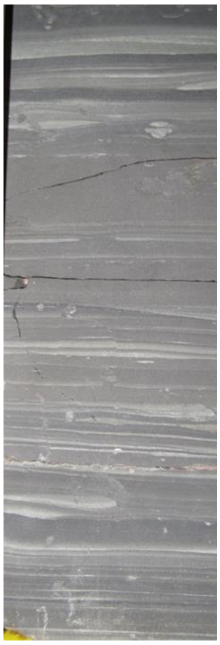

Figure 12. *Sediment core (50 cm long) from the Stenlille-1 well, Fjerritslev Formationen, Lower Jurassic. The mudstone is horizontally laminated with thin streaks of fine-grained grey silt stone. Bioturbation is rare.*

Figur 12. *Borekerne (50 cm) fra Stenlille-1 boringen, Fjerritslev Formation, Nedre Jura. Mudderstenen er lamineret med finkornet, lys grå silt. Bioturbation forekommer sjældent.*

and in shallow marine, tidal and beach areas. Deposition of sand under fully marine conditions occurred close to a fault-controlled shoreline (Figure13). Conglomerates sourced from local fault scarps were deposited in the basin, as the result of tectonic activity in the Middle Jurassic time. The Jurassic succession is terminated by terrestrial sediments of clay, coal, and sand interpreted as delta plain in channels, levees, and swamp deposits.

The Middle Jurassic to Early Cretaceous was a period subjected to renewed tectonic activity with faulting, subsidence, uplift, and erosion. North of the Ringkøbing-Fyn High a transgression occurred in late Jurassic associated with deposition of shallow marine clay and sand forming the Børglum, Frederikshavn and Flyvbjerg Formations. In the Sorgenfrei-Tornquist Zone in northern Jylland sand, clay and coal were deposited in a terrestrial to shallow marine setting and now constitute up to 200meterthick sequences of Middle to Upper Jurassic sediments.

Figure 13. *Lower Jurassic fine grained, marine sandstone from the Hasle Formation, Hasle cliff, Bornholm.*

Figur 13. *Nedre Jura, finkornet marin sandsten fra Hasle Formationen, Hasle klint, Bornholm.*

During the Early Cretaceous the Danish Basin was characterized by deposition of marine sediments referred to the Vedsted Formation and the Rødby Formation (Figure 11) (Sorgenfrei & Buch, 1964, Larsen, 1966). Sandy coastline deposits from the period occur along the south coast of Bornholm and west coast of Scania. The Lower Cretaceous section comprises grey and red mudstones and siltstones forming 300 to 700meterthick sequence across most of northern Jylland. The thickness decreases significantly to the east where 70-100 meter was deposited in eastern Jylland, 50-150 meter in southern Jylland and only 10- 50 meters in Sjælland and southeasternmost parts of Denmark (Figure 12). On Bornholm three episodes of marine transgressions occurred interrupted by periods of non-deposition or erosion. The marine deposits consist of glauconitic fine-grained sand, mudstone and clayey chalk deposited in a shallow shelf environment (Figs. 15 & 16). Deposits from the late Cretaceous are not known from Bornholm suggesting it was period characterized by uplift and erosion, or at least non-deposition.

The Upper Cretaceous section consists mainly of white chalk which can reach thicknesses up to 2000 meter close to the Sorgenfrei-Tornquest Zone and ca. 1000 meter on the Skagerrak-Kattegat Platform. The thickness decreases south-eastward to less than 1000 meter in areas adjacent to the Ringkøbing-Fyn High on Fyn, on southern Sjælland and Lolland-Falster. The greatest thicknesses were deposited during the Campanian with 500 meter and the Maastrichtian with 700 meters. During the late Cretaceous and the Tertiary inversion took place along older fault lines.

Figure 14. *Drill core from the Rødby-1 well demonstrates the red, sandy, calcareous siltstone of the Rødby Formation, upper part of the Lower Cretaceous.*

Figur 14. *Borekerne fra Rødby-1 boringen, Rødby Formationen. Sandet, kalkholdig siltsten.*

Figure 15. *Lower Cretaceous black claystone with abundant plant material from the Rabække Formation, Arnager Bay cliff, Bornholm.*

Figur 15. *Nedre Kridt sort lersten med talrige planterester, Rabække Formationen, Arnager Bugt Klint, Bornholm.*

Figure 16. *Lower Cretaceous glauconitic sand from the Arnager Greensand Formation and overlying clay bearing limestone from the Arnager Limestone Formation, Arnager Cliff, Bornholm. The dark green sand layer at the base of the outcrop is ca. 1 meter thick.*

Figur 16. *Nedre Kridt glaukonitrigt sand fra Arnager Grønsand Formationen og overliggende leret kalksten fra Arnager Kalksten Formationen, Arnager Klint, Bornholm. Det mørkegrønne sand lag ved basis af blotningen er ca. 1m tykt.*

The Upper Cretaceous chalk was deposited in the northern part of the large North European carbonate platform. In the Danish Basin and the Fjerritslev Trough the chalk can reach a thickness of 2000 meters (Figure 6).

The chalk is generally a rather pure calcium carbonate rock but intervals with cyclic laminated chalk and marly (muddy limestone) are found in northern Jylland, Sjælland and southeastern islands (Figure 17) (Surlyk et al., 2013). Sequences of interbedded marl and chalk layers have also been identified from well log data and in drill cores (Nielsen et al., 2011).

Figure 17. *White chalk from the Upper Cretaceous Møns Klint Formation. The exposure is located at the northern part of Stevns Cliff.*

Figur 17. *Hvidt skrivekridt fra Møns Klint Formationen, nordlige del af Stevns Klint.*

The Upper Cretaceous Maastrichtian chalk crops out on the pre-Quaternary surface in the Kattegat Platform and in the Baltic area. The chalk is known from numerous exposures including the Portland pits at Aalborg in northern Denmark, above the centers of some of the salt-diapir produced domes, in the glaciotectonic complex at Møns Klint, and along the Stevns Klint in southeastern Denmark (Pedersen & Gravesen, 2009, Pedersen, 2000, Surlyk et al., 2006).

An example of characterization and mapping of chalk in the subsurface is presented in Figure 18. The well logs show how some intervals from the Lower Cretaceous section have highly varying physical properties indicated by the erratic log curves with varying colours. In contrast the Chalk Group in the upper part of the well logs (Blue colored interval) is very homogeneous with almost constant values for the entire interval. These different characteristics are used to identify and correlate various lithostratigraphic units and different rock types in the subsurface based on borehole data.

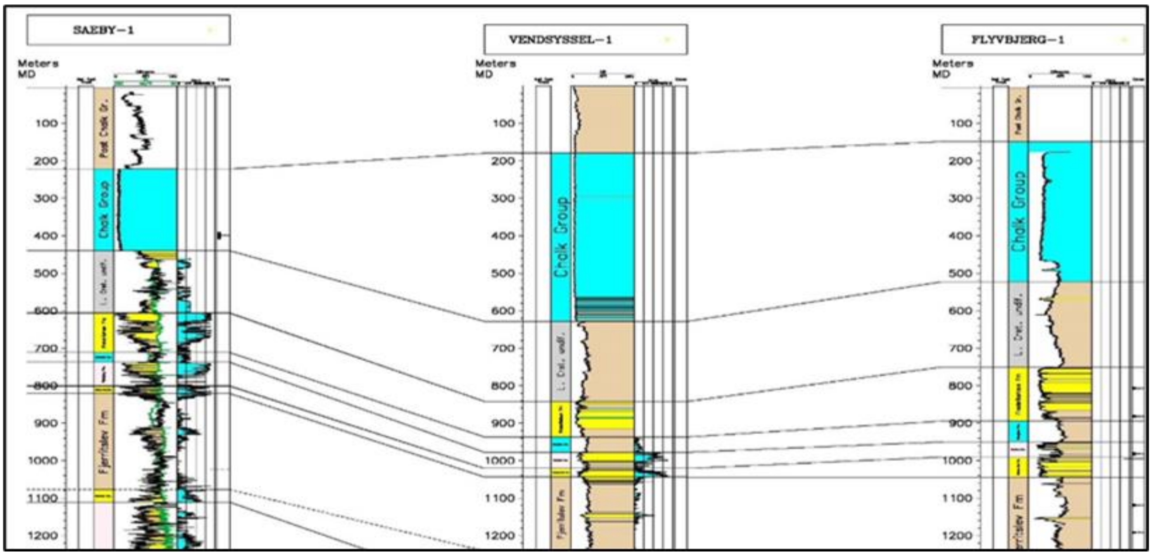

***Figure 18**. An example of well log correlation based on petrophysical logs and core descriptions: Saeby-1, Vendsyssel-1, and Flyvbjerg-1. The blue interval in the upper part is Upper Cretaceous, the underlying interval of varied colours is Lower Cretaceous (For location see Figure 3, from Nielsen, 2003).*

***Figur 18**. Et eksempel på korrelation mellem boringer baseret på borelogs og kernebeskrivelser: Sæby-1, Vendsyssel-1 og Flyvbjerg-1. Det øverste blå interval er Øvre kridt, det underliggende interval med varierende farver er Nedre Kridt (Borepositioner ses på Figur 3, efter Nielsen 2003).*

4.5 Cenozoic sediments

The prominent Cretaceous/Tertiary boundary forms the lower boundary of the Danian Limestone (Surlyk 1980). The Danian Limestone is widespread in the Danish subsurface and comprises bryozoan reef limestone interbedded with chert. The Danian section is 50 to 300 meters thick with the thickest deposits occurring in central Jylland and thinning in all directions, and it is absent on Bornholm.

Locally, choral limestone is present, and the limestone succession grades upward into a hard, massive limestone named the København Formation (Jakobsen et al., 2002). The well-known exposure for the Danian Limestone is Stevns Klint (central eastern Denmark). Here the Fish Clay with a high iridium-content, contributing to the interpretation of the “asteroid impact” hypothesis for the end Cretaceous mass extinction, is exposed (Surlyk et al. 2006) (Figure 18).

Succeeding the limestones are thick and laterally widespread clay-rich Paleogene sediments up to 260 meters thick. The clay-rich sediments were deposited on the basin floor in a marine environment. In the northern part of Denmark is a succession of interbedded clayey diatomite and volcanic ash beds which constitutes the Fur Formation (Pedersen & Surlyk 1983). The ash layers represent the volcanic activity related to the early break-up of the Laurentian continent and the formation of the North Atlantic Ocean on the Paleocene/Eocene boundary (Larsen et al, 2003).

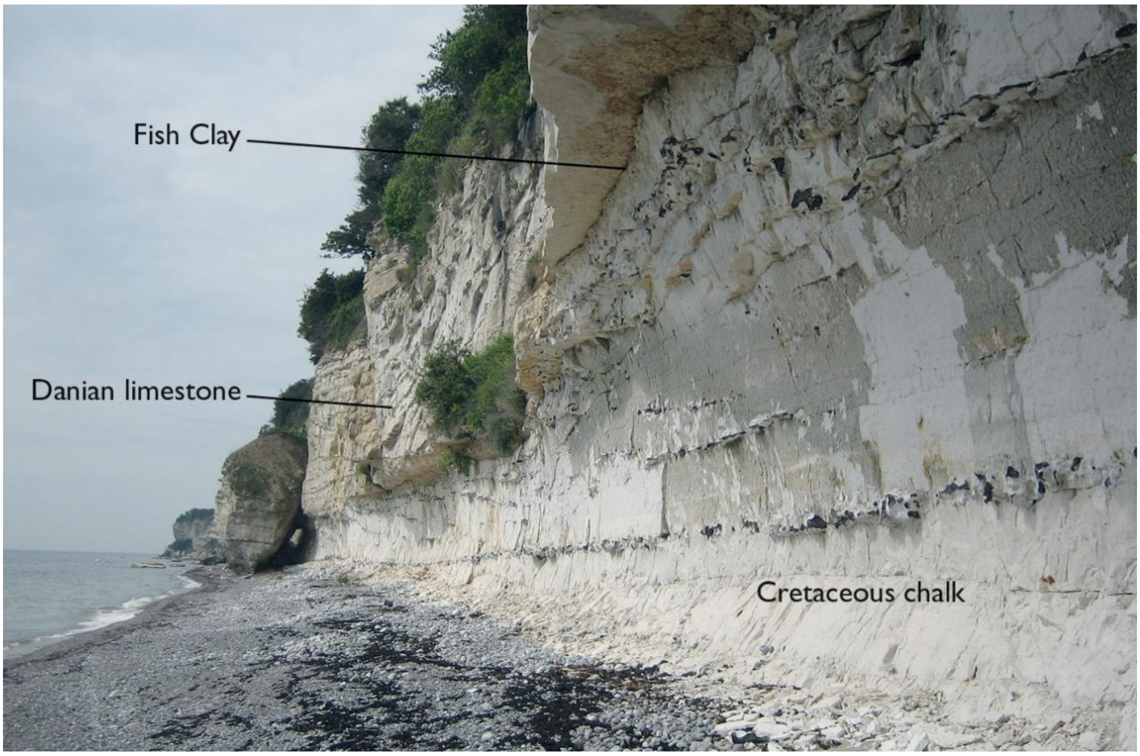

Figure 19. *Danian limestone overlying the Cretaceous chalk at the Stevns Cliff. Both types of limestone contain layers of black and grey chert. The boundary between the Cretaceous succession and the Tertiary (C-T boundary) is represented by the presence of the black Fish Clay layer (as marked at the base of the overhang).*

Figur 19. *Danien kalk som overlejrer skrivekridt fra Kridt-tiden, Stevns klint. Begge typer kalk indeholder sorte og grå lag af flint. Kridt-Tertiær grænsen (K-T Grænsen) er markeret ved det tynde lag af sort ler, også kaldet Fiskeler, der ses lige ved basis af overhænget.*

During the Eocene more than 200 meters of marine fine-grained clays in green, red, and white colours were deposited in a relatively deep-sea environment. Marine Oligocene glauconitic and micaceous clay and silt deposits are known from the eastern and central part of Denmark with thicknesses around 170 meters.

The Neogene was dominated by a large delta system building out from the North-East European–Baltic platform towards the North Sea in the Miocene time (Rasmussen, Dybkjær & Piasecki, 2010). These delta deposits dominate the western part of central Denmark, and they extend into the Danish Basin in the North Sea, where a kilometre-thick accumulation of sandy units have filled the depocentre above the Central Graben. In addition to the delta system, parts of the Miocene in central Jylland comprise thick successions with more than 200 meters of fluvial sand with scattered lignite. Towards the west, marine Miocene deposits containing clays, silts and fine-grained sands reach large thicknesses.

The Pleistocene glacial and interglacial till, clay, sand, and gravel deposits vary in thickness from 0 meters locally on top of the Precambrian basement on Bornholm to a maximum thickness of 350 to 400 meters in northernmost and southwestern Jylland (Figure 6).

4.6 Quaternary deposits

Quaternary deposits from Pleistocene and Holocene generally forms the uppermost geological layers of the geological record of Denmark. The Pleistocene time period was characterized by dramatic climate changes from cold periods dominated by widespread glaciations to time intervals with climate conditions almost as today.

4.6.1 Pleistocene

Denmark has been glaciated several times during the Menapian, Elsterian, Saalian and Weichselian ice ages (Figure 4) that advanced from north (Norway), northeast, (Norway and Sweden) and east and south east (Sweden, Finland, and the Baltic) (Figure 25).

Clayey tills from the latest Weichselian glaciation cover most of eastern Denmark. These deposits can be followed to the central part of Jylland, where the boundary between till and outwash plane sand-deposits marks the Main Stationary Line of the ice cover (Figure 24). The line was established during the Late Glacial Maximum about 23 ka BP (Houmark-Nielsen, 2003). From the Main Stationary Line, the outwash plane extends towards the south and west, where meltwater eroded the geomorphologic landscape remaining from the former (Saalian) ice age.

Between the ice ages the interglacial periods Cromerian, Holsteinian and Eemian occur (Figure 4). During these mild climate periods marine and terrestrial sediments were deposited. Remains of animals and plants found in the sediments reveal a setting varying between land and sea, influenced by sea-level and climate changes. The climate has nearly been as the present interglacial Holocene or a little bit warmer.

Most of the surface of the Danish land area is covered by Quaternary sediments deposited during the last 500.000 years. The Quaternary deposits vary in thickness from 0 meters to a few meters on e.g. Bornholm and locally in valleys thicknesses of 30 to 80 meters or more. Maximum thicknesses of 350-400 meters occur in northernmost part of Jylland and in southwest Jylland (Figure 22). The glaciers deposited clayey and sandy tills with boulders and meltwater gravel, sand, silt, and clay.

The main part of the land surface is characterized by a glacio-morphological topography with fjords situated in the former tunnel valleys incised during the Pleistocene glaciations. The main stationary line of the latest ice shield forms a characteristic feature in the landscape in central and south Jylland, west of which huge sandur plains and erosion remnants of the Saalian landscape occur (Figure 2).

Following the latest Weichselian glaciation the southern part of Denmark was subsiding and drowned by the Atlantic transgression. This resulted in the archipelago where islands constitute a drumlin dominated moraine plateau south of Fyn (Pedersen et al., 2015) (Figure 21). In contrast the latest deglaciation resulted in relative uplift of the land in central and northern Denmark with maximum values of 13 meters of uplift in northernmost Jylland (Sandersen et al., 2021).

To the north, the deeply eroded Skagerrak Seaway disconnects Norway from Denmark, and to the west, Denmark is bordered by the North Sea. Along the southern part of the Danish coastline, the Wadden Sea area is located, from where the border between Denmark and northern Germany crosses the peninsula Jylland from the North Sea to the Baltic (Figure 21). The most significant addition to the subaerial part of the land after the Weichselian glaciation is the Skagen Odde, which forms one of the biggest spit systems in the world.

The spit system (odde) started to form during a forced regression at the transition from the Pleistocene to the Holocene about 12.000 years ago (Nielsen & Johannessen, 2009). It is closely related to the main uplift of the Vendsyssel area south of the spit, which was isostatic uplifted 20–50 meters above sea level during the last 15.000 years (Mertz, 1924). South of Vendsyssel, the Limfjorden forms an inner sea area system of branching fjords formed from deep incision during the latest glaciation (Figure 23). Only 8.000 years ago Limfjorden was open to the west, where it formed an archipelago on the transition to the North Sea (Figure 21).

During the isostatic uplift and the associated formation of beach ridges along the west-coast of Jylland, the western part of Limfjorden was disconnected from the North Sea for about 1000 years and developed into a freshwater lake. A winter storm in 1823 re-established the western entrance to the Limfjorden, which since that time has remained a salt-water fjord system.

Figure 21. *Geomorphological map of Denmark with the main geological surface elements. Saalian sediments are the oldest deposits and Holocene are the youngest deposits (after Gravesen & Jakobsen, 2010).*

Figur 21. *Geomorfologisk kort over Danmark med de vigtigste overfladenære geologiske elementer (Efter Gravesen & Jakobsen, 2010).*

The features in the pre-Quaternary surface are mainly caused by glacial erosion during the last part of the Pleistocene. The pre-Quaternary surface is mapped as the boundary between the pre-Quaternary sedimentary rocks and the Quaternary sediments (Figure 22). The high laying terrain in central part of Jylland is intersected by many valleys and deeply eroded areas now filled with varying amounts of Holocene deposits (Figure 21). Towards the north and the southwest, the depth to the pre-Quaternary exceeds 250 meter below present sea level. In these areas, marine sediments were deposited during Holsteinian, Eemian and Weichselian, and the sedimentation prevailed throughout the Holocene with accumulation of both fresh-water and marine deposits. In general, the valleys were formed as tunnel valleys. However, in many cases the glacial drainage inherited underlying deep structural elements e.g. the graben structure in the Horsens valley (Lykke-Andersen, 1995).

On central and northern Bornholm, the Quaternary sediments directly overlie the crystalline basement rocks (Grönwall & Milthers, 1916). The deposits are relatively thin over much of the island, but in the valleys cut into the basement, the Quaternary deposits can locally reach a thickness of 30–80 meters or more.

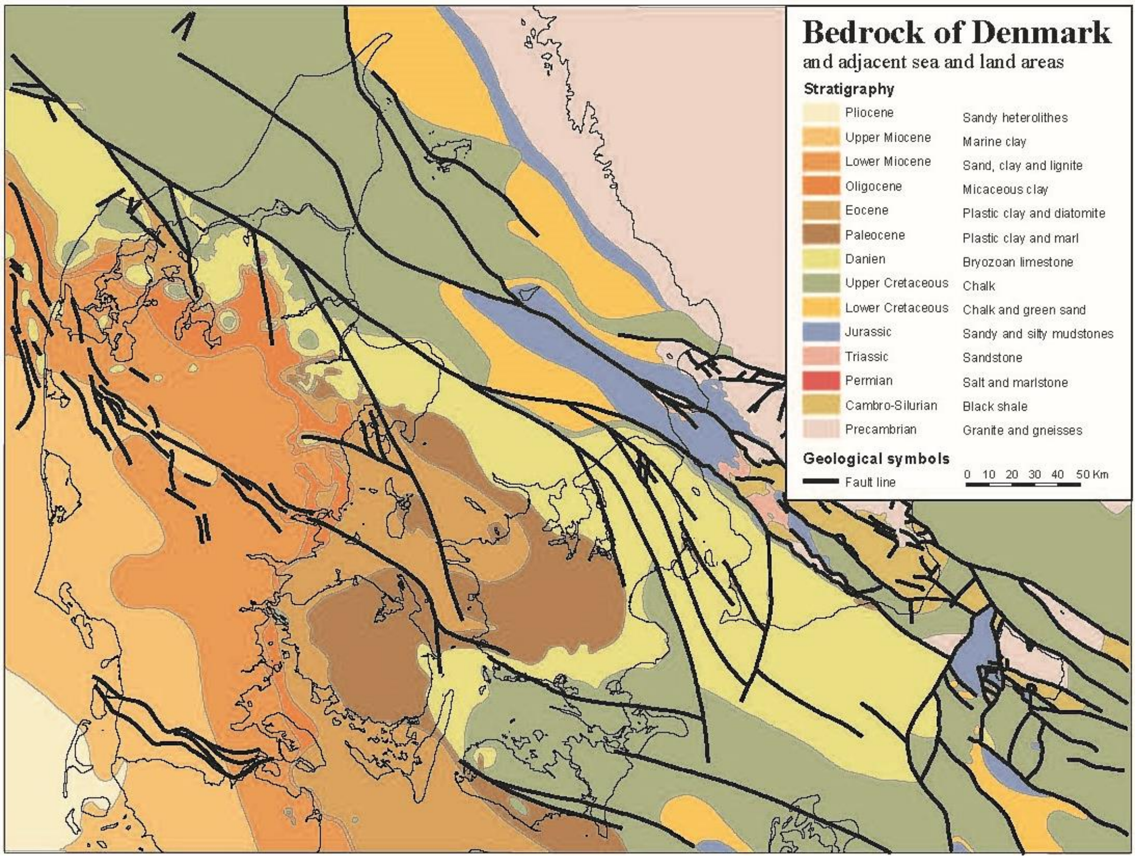

Figure 22. *Map of the geological units outcropping at the pre-Quaternary surface. A general trend is that younger units appear towards the WSW, ranging from Precambrian basement in Sweden to the Miocene/Pliocene deposits in SW Jylland. Modified after Håkansson & Pedersen, 1992.*

Figur 22. *Geologisk kort over den danske undergrund ved basis af Kvartæret. De geologiske enheder bliver yngre og yngre mod sydvest, fra det prækambriske grundfjeld i Sverige til de yngste miocæne/pliocæne aflejringer i SW Jylland og Nordsøen (Modificeret efter Håkansson & Pedersen, 1992).*

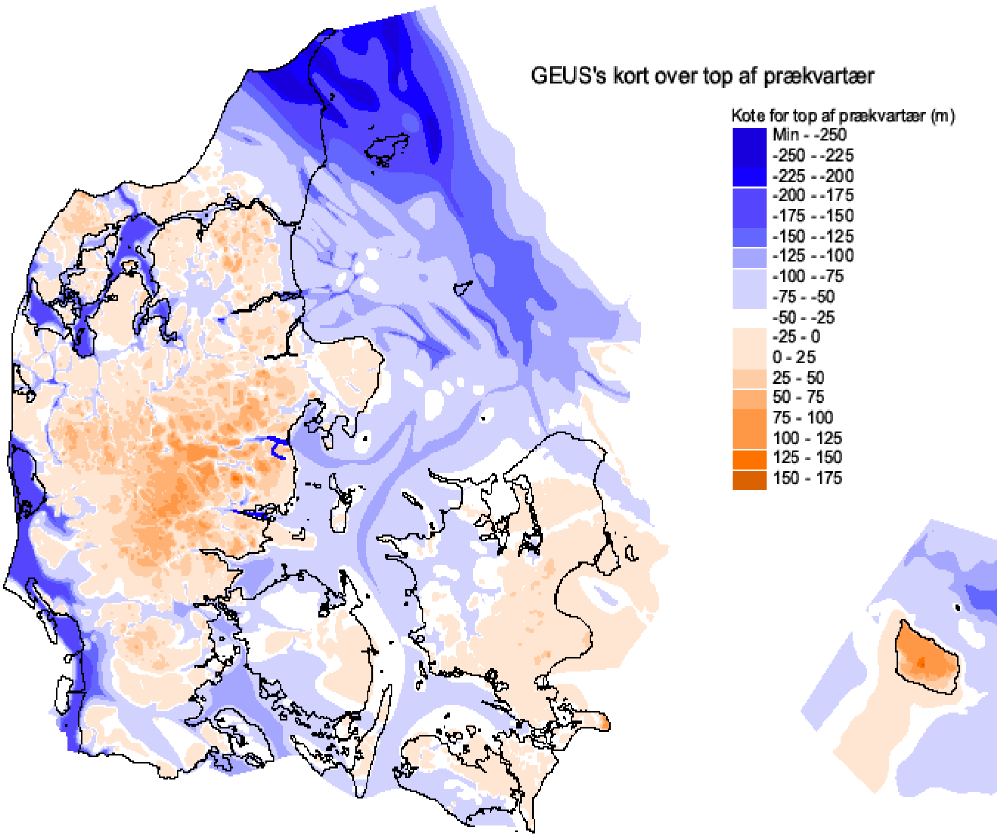

Figure 23. *Map of the pre-Quaternary surface topography in Denmark. Deepest levels are presented in blue colours (-50 meters to below -250 meters) and areas with highest elevation are orange colours (-50 meters to + 175 m) with reference to mean sea level. (Modified after Binzer & Stockmarr, 1994).*

Figur 23. *Kort over prækvartæroverfladens højdeforhold i Danmark. Signaturforklaring: Konturintervaller er 25 meter med de dybeste niveauer i blå farver (-50 meter til dybere end 250 meter under havniveau). De højest liggende områder er dem med hvide, gule og orange farver (+50 meter til + 175 meter). (Modificeret efter Binzer og Stockmarr, 1994).*

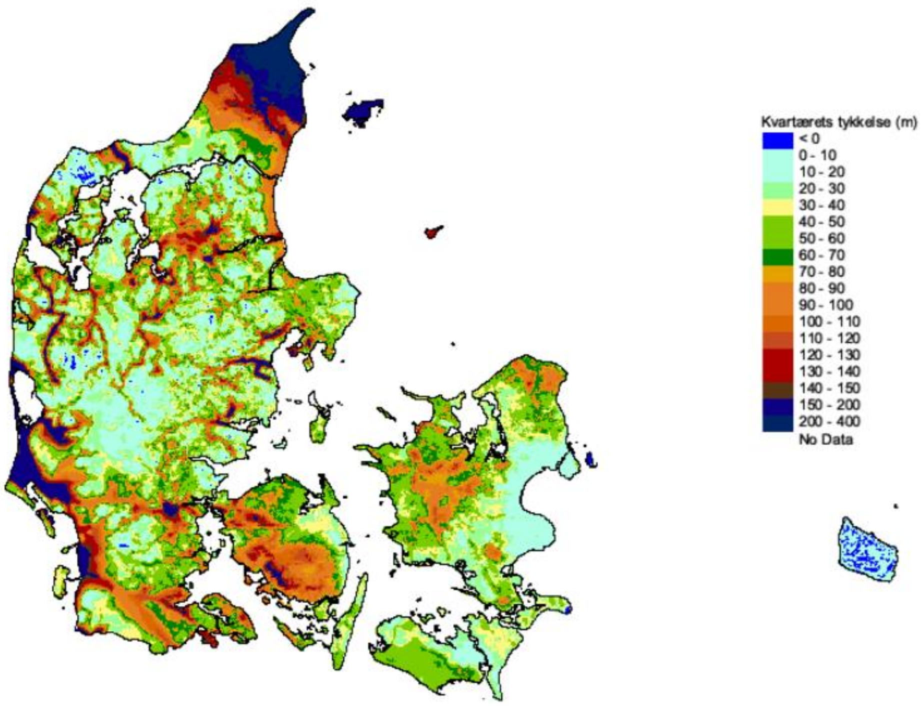

Figure 24. *Isopach map of the thickness of the Quaternary sediments (van Platen, 1995). Light greenish colours show the thinnest layers and dark brown show greatest thicknesses.*

Figur 24. *Kort der viser tykkelsen af de Kvartære aflejringer (van Platen, 1995). Områder med grønlige farver har de mindste tykkelser og de største mægtigheder findes i områder med mørkebrune farver.*

The thickness of the Quaternary deposits (Figure 24) represents the difference between the surface topographic map (Figure 1) and the base Quaternary depth map (Figure 23).

4.6.2 Holocene

After the ice cover melted during the Late Weichselian, the land began to rise due to isostatic uplift. This tectonic event occurred contemporaneously with a considerable rise of the sea level caused by the water released from melting icecaps. These events resulted in rapid changes of the coastlines and the formation of previous coastlines now present in high lying terrains in the northern parts of Denmark now forming fossil coastlines. Succeeding transgressions and uplifts changed the position of the coastline, but about 3000 years ago, the present coastline was established and has subsequently been subject only to small, local changes. The marine transgressions resulted in deposition of several layers of Holocene marine clay and sand mainly in northern Jylland and in general along the present coastline (Figure 21). Deposition of sediments occurred on land in streams, lakes, and bogs as peat, gyttja, clay and sand and aeolian sand was transported across the land surface, particularly in Jylland. The Holocene deposits of marine, aeolian and freshwater deposits rarely exceeds 20 meters.

5. Near-surface features and processes

The morphology of the present land scape and shallow geological layers is fomed from the combined influence of long-term and short-term natural processes and events. Some processes and events. Some processes cause sudden changes such as major landslides, earthquakes, and storms whereas other processes such as glacial erosion and deformation, and sea-level changes occur gradually over relatively long periods of time.

Since a final repository shall provide long-term safety it is important to identify the natural processes that may influence the geological record in the interval 0-500 meter. By identifying the recent and sub-recent processes it is assumed that processes that may affect the geological layers within the coming 100,000 to 1 mill years can be predicted.

In the following section surface and near-surface features are described as well as processes causing their formation.

5.1 Major glaciotectonic near-surface structures

The structural geology of surface-near deposits in Denmark is strongly influenced by glaciotectonic deformation. All of Denmark was covered by glaciation in the Saalian time about 300.000 years ago, and glaciotectonic structures formed during this glaciation are well known from western Jylland. During glaciations in the Weichselian, the Main Stationary Line of the Scandinavian Ice Cap was located in the northern and central part of Jylland (Figure 25). All parts of Denmark have been affected by glacial deformation, and in many places, the bedrocks have been displaced by glaciotectonic actions. Along the present Danish coastline, several exposures in cliffs reveal cross sections with instructive examples of the glaciotectonic deformation (Pedersen, 2011, 2014) (Figs. 26 and 27).

On Bornholm very few deformations of the sediments have been recognized. However, the basement rocks have suffered glacier erosion and intense horizontal and vertical fracturing of the uppermost 10-20 meters due to several events of loading and unloading of thick ice sheets. Roche moutonnes and other marks in the rocks are together with abundant subhorizontal fractures the most significant glacio-geological deformation.

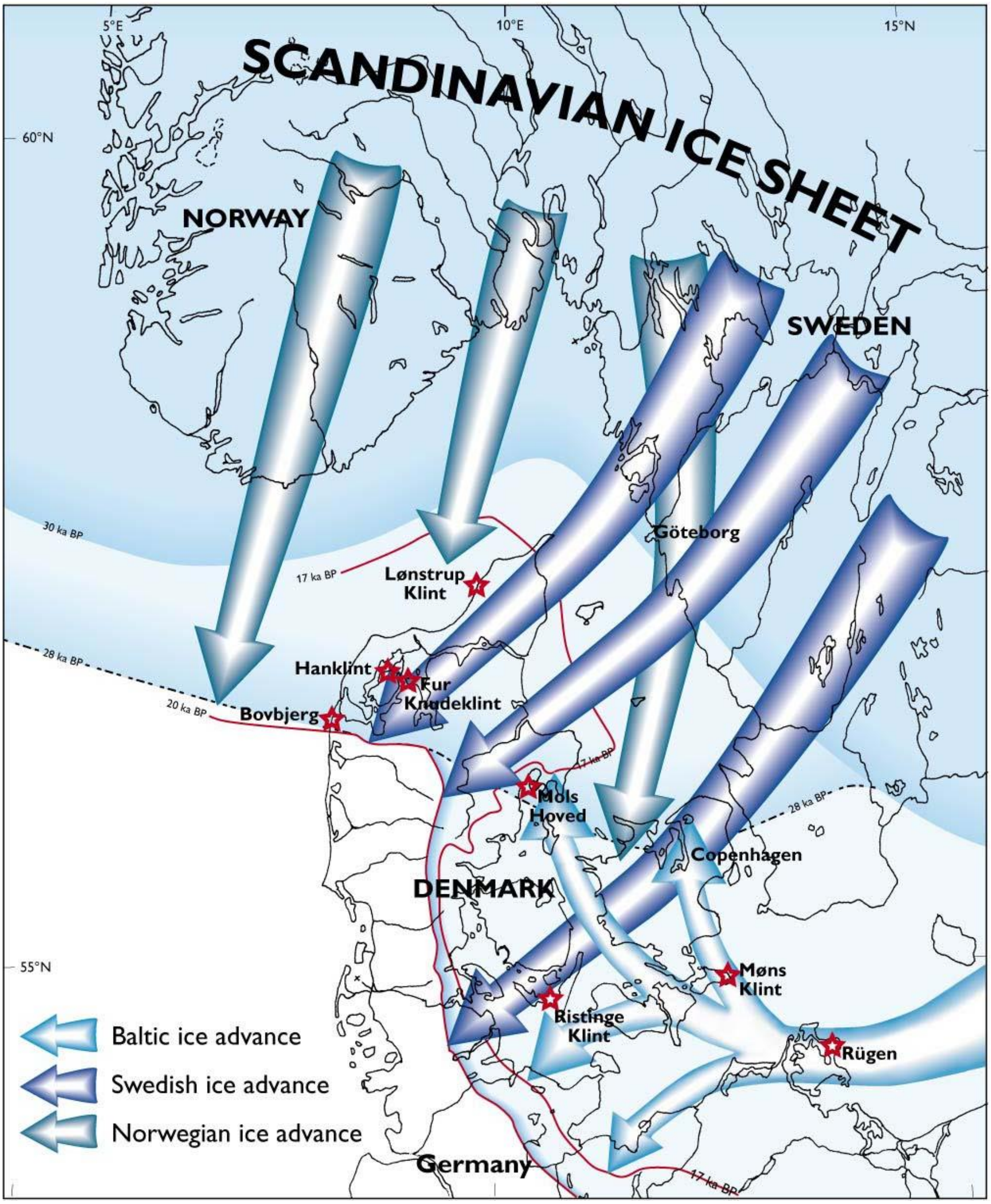

Figure 25. *The glacier advances during the Weichselian with three main courses from north, northeast, and southeast. Red asterisks mark larger glaciotectonic complexes in Denmark and on Rügen, N Germany (From Pedersen, 2005).*

Figur 25. *Isstrømsbevægelser gennem Weichsel istiden med tre hovedretninger fra nord, nordøst og sydøst. Røde stjerner: Større glacialtektoniske komplekser i Danmark og på Rügen i Nordtyskland (Efter Pedersen, 2005).*

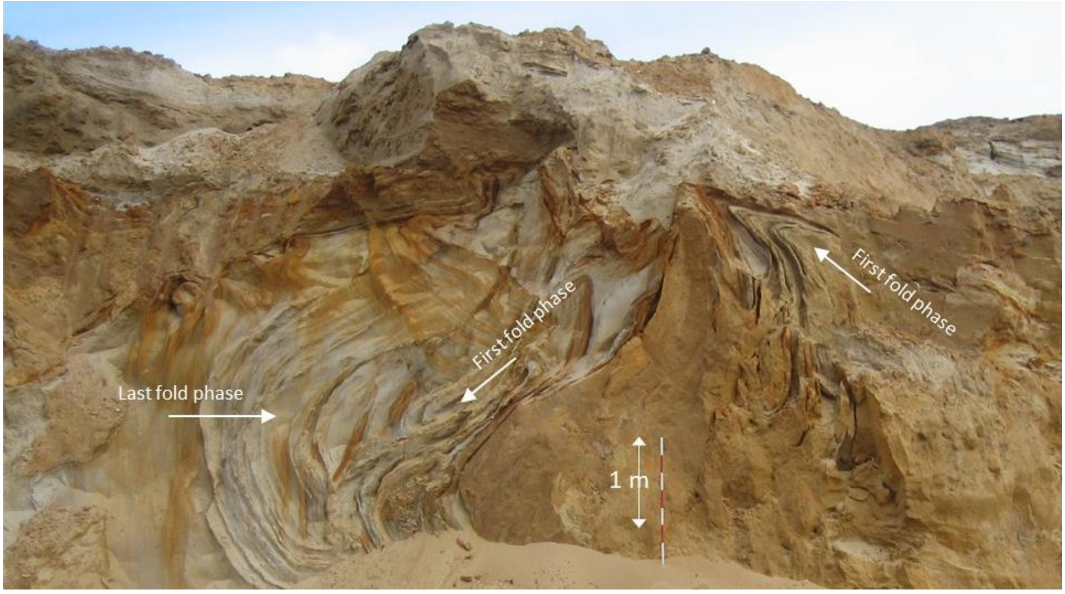

Figure 26. *An example of glaciotectonic deformation in the Saalian landscape. Superimposed folding in glaciofluvial sand, Attenager, Ringkøbing.*

Figur 26. *Et eksempel på glacialtektonisk deformation inden for Saale landskabet. Overpræget foldning i sand- og grusgraven i Attenager ved Ringkøbing.*

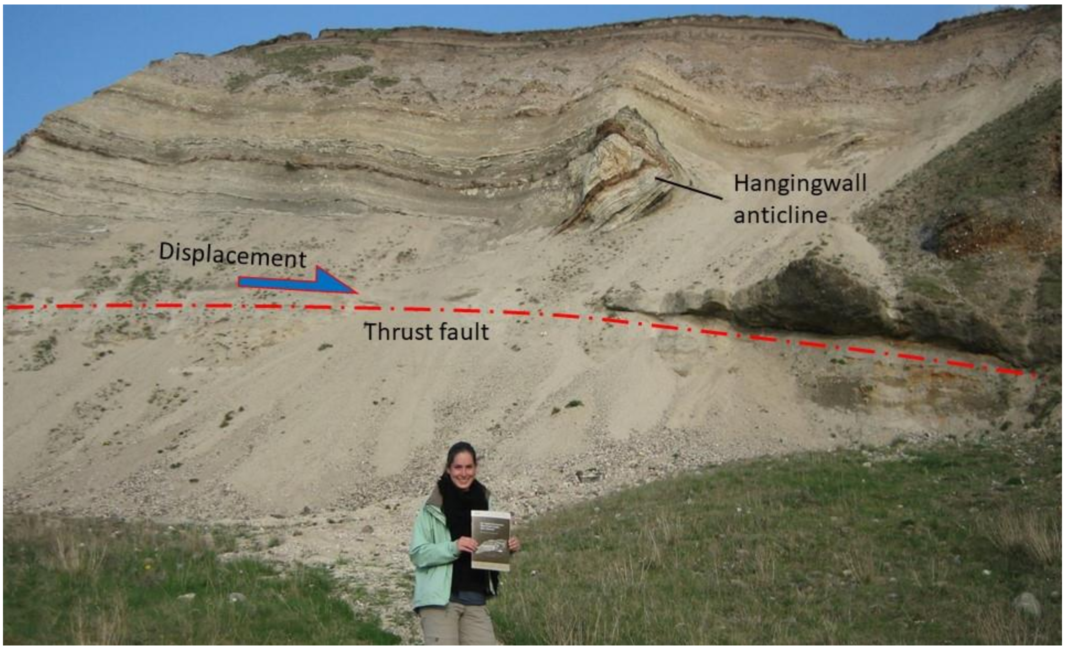

Figure 27. *An example of Weichselian glaciotectonic deformation, the Hanklit thrust sheet on northern Mors. This thrust sheet comprises Eocene clayey diatomite with volcanic ash layers, and it was laterally displaced c. 300 meters across Pleistocene outwash deposits.*

Figur 27. *Eksempel på Weichsel glacialtektonisk deformation, Hanklit overskydningens skive på Nordmors. Skiven omfatter Eocæn diatomitler med vulkanske askelag, som blev flyttet ca. 300 meter henover pleistocæne hedesletteaflejringer.*

In general, the glaciotectonic deformations created folds and thrust fault structures to shallow depths in the underlying sediments. In very clay-rich and muddy lithologies, mud diapirs may have formed (Pedersen, 2005). Often, the structures can be related to a complex consisting of a hinterland part, a central part, and a foreland part. The complexes vary in size from a few hundred meters in cross section and along strike to larger complexes covering areas of more than 25 square kilometres. The largest complex is mapped in a cross section extending 6 kilometres from south to north at Rubjerg Knude (Pedersen, 2005). The longest identified fold structure occurs in marine diatomites and volcanic ash layers and can be traced for 10 kilometres along the fold axis (Figure 28) (Klint & Pedersen,1995).

The general depth of glaciotectonic deformation is around 100 meters below surface (Pedersen,1996, 2005), and hills reaching an elevation of 130 meters above sea level are known from e.g. the Møns Klint (Pedersen, 2000). The Møns Klint glaciotectonic complex comprises displaced Maastrichtian chalk, which is the oldest bedrock known to be affected by glaciotectonics in Denmark. This complex as well as a majority of the glaciotectonic complexes form a landscape of parallel-ridges that mirrors the imbrications of thrust sheets in the subsurface, typically with the development of hanging-wall anticlines on the crest of the thrust sheets (Figure 28).

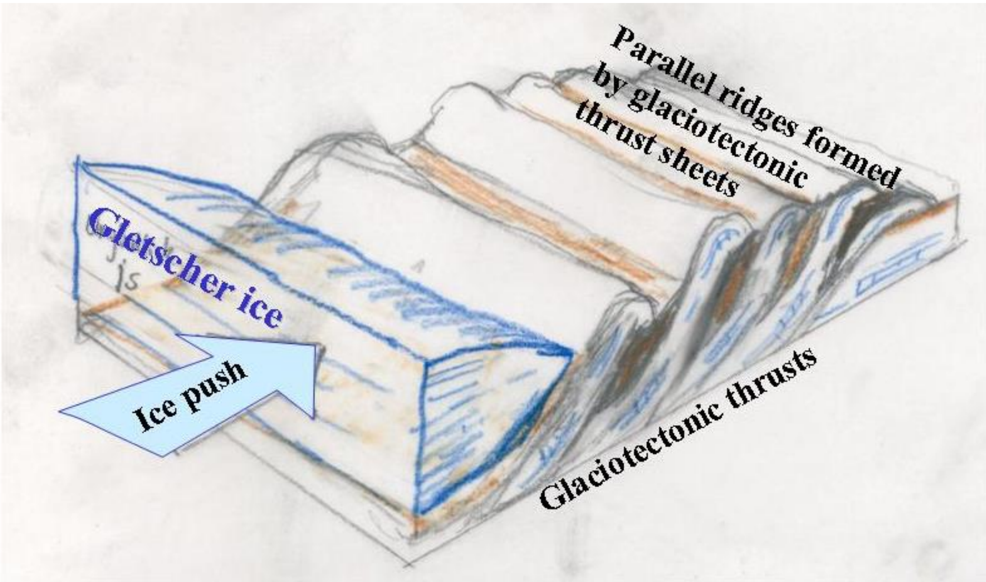

Figure 28. *Conceptual diagram illustrating a glaciotectonic complex. The glaciotectonic thrust faulting creates a landscape with parallel ridges perpendicular to the direction of the ice push. The thickness of the thrust sheets is 50–100 m, and the crests are elevated up to 100 meters above the original depositional position of the layers. Along strike, the crests may extend up to 10 kilometres.*

Figur 28*. Principskitse af et glacialtektonisk kompleks. De glacialtektoniske overskydninger danner et landskab af parallelle rygge, hvor ryggenes strygning er vinkelret på isbevægelsen. De enkelte overskydningsskiver kan være 50–100 meter tykke, og ryggene kan være løftet 100 meter op over lagenes oprindelige position. Bakkeryggene kan følges op til 10 kilometer i længderetningen.*

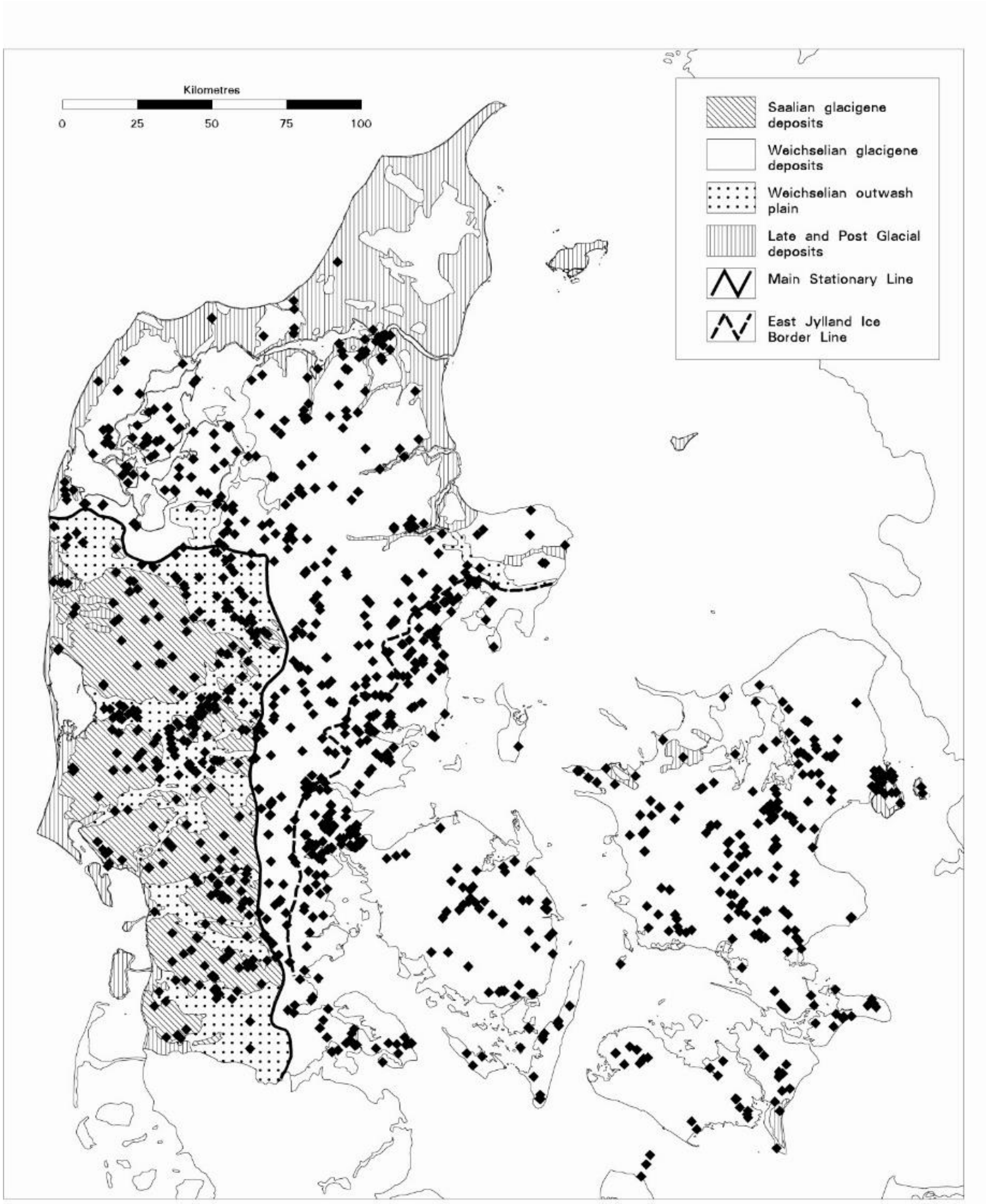

Figure 29. *Map showing the location of boreholes with borehole logs where dislocated pre-Quaternary sediments are recorded above or within the Quaternary deposits (From Jakobsen, 1996).*

Figur 29. *Kort der viser boringer hvor forstyrrede prækvartære sedimenter over eller imellem kvartære aflejringer er observeret fra borelogs (Fra Jakobsen, 1996).*

The glaciotectonic deformations and disturbances of the shallow pre-Quaternary and Quaternary deposits have also been documented from borehole data as described by Jakobsen (1996), where folds and sediment sheets of the pre-Quaternary and interglacial sediments can be identified from in the borehole logs (Figure 29). The information is based on borehole data stored in GEUS´ Jupiter Database.

5.3 Presence of erosional Quaternary valleys

Ancient valleys forming elongate, erosional features in the subsurface now filled in with Quaternary sand, gravel and muds and covered by younger sediments are referred to as buried valleys. Most of the valleys formed from meltwater erosion into the subsurface beneath the ice sheet. Numerous buried valleys have been mapped at shallow depths in the Danish subsurface (Sandersen et al., 2021). In many areas the valley fill of sand host significant groundwater resources, wherefore the knowledge about their formation and distribution is important. For the present project on deep disposal mapping of the valleys and understanding of factors controlling their formation and location is important for the potential prediction of where new valleys may be formed and to which depth they will erode during future glaciations. Further, the presence of thick sand deposits in the shallower sections is unfavorable for geotechnical feasibility and will not provide an additional seal.

Abundant geophysical surveys have recently been used for mapping of widespread systems of buried valleys in the Quaternary sediments and some valleys have been observed also to cut into the pre-Quaternary sediments (Jørgensen & Sandersen, 2009) (Figure 30). The age of the valleys is often uncertain, but most were probably formed during the Elsterian, Saalian, or Weichselian glaciations (Figure 4). The depth of the buried valleys varies, and the deepest structures are observed to exceed 400 meters. They are generally between 0.5 and 1.5 kilometres wide, but a few have widths of more than 3.5 kilometres. Their full lengths are difficult to assess because the surveyed areas are usually rather small, but some valleys are 25-30 kilometres long.

The valleys are highly irregular, with depressions and thresholds along the valley floors and they often termiate abruptly. Buried valleys appear both as single valleys and in dense cross-cutting networks. Their internal architecture is typically complex due to repeated events of erosion and deposition.

Mapping of the buried valleys is based on data available in 2015, and more valleys may be recognized as the data base is growing in the future. The maximum level of erosion reached by the deepest valleys has not been observed deeper than close to 400 meters. The establishment of a repository at depths around 500 meters will be significantly below the deepest erosional levels observed from Tertiary glaciers.

Figure 30. *Mapped buried valleys in Denmark shown with dark grey polygons. The light grey areas show the areas with data from Transient Electromagnetic surveys (TEM). Modified from Sandersen & Jørgensen (2017).*

Figur 30. *Kortlagte begravede dale i Danmark vist med mørkegrå polygoner. De lysegrå områder viser områder kortlagt med den Transient ElektroMagnetiske metode (TEM). Modificeret efter Sandersen & Jørgensen (2017).*

An example of mapping of buried valleys in Jylland using geophysical TEM data is presented in Figure 31. The N-S cross section in upper part of Figure 31 shows the presence of several buried valleys, and most of these have eroded into the Miocene and Palaeogene sections.

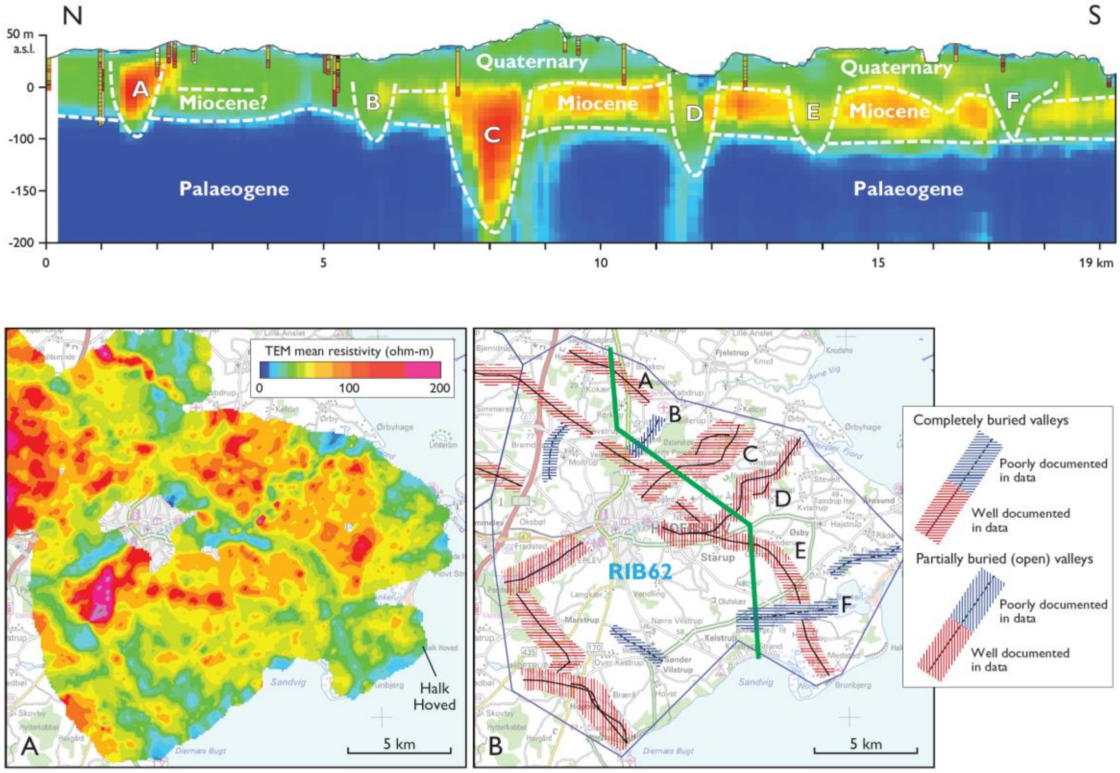

Figure 31. Example of mapping buried valleys using geophysical TEM data. A) Map of recorded resistivity. B) Interpretation of the buried valley systems from combined geophysical data and borings. The status and documentation are noted to the right. The green line in the map indicate the position of the cross section shown in the upper part of the figure. The cross-section in the upper part of the figure illustrates the buried valleys have eroded into geological formations from the Miocene and Palaeogene (from Sandersen & Jørgensen, 2017).

Figur 31. *Eksempel på kortlægning af begravede dale ved hjælp af geofysiske TEM data. A) Kort over resistivitetsresponsen. B) Tolkning af de begravede dale på baggrund af geofysiske data og boringer. Den grønne linje viser positionen af profilet øverst i figuren. På profilet øverst i figuren ses, at de begravede dale stedvis har eroderet ned i de underliggende miocæne og palæogene lag (fra Sandersen & Jørgensen, 2017).*

5.4 Late Weichselian and Holocene transgressions, elevation and subsidence

During periods of glaciations, significant changes of sea-level occurred as well as isostatic rebounds causing the position of the coastline to change laterally over long distances within short periods of time. These interacting processes have had significant influence on the present-day landscape and the sedimentary cover and will continue to gradually reshape the landscape and change the coastlines due to ongoing isostatic movements and changes of sea level.

5.5 Late Weichselian (Late Glacial) elevation

When the last glacier from the Late Weichselian glaciation melted away from the Danish territory, unloading of the thick ice cover resulted in an isostatic elevation of the land. Subsequently, the sea level began to raise because huge amounts of melt water were derived from the melting ice caps and during a long period of time the northern part of Denmark was covered by a cold arctic sea. The net result of the sea level rise and the land elevation was the formation of raised, coastal cliffs, and fossil coastal cliffs and sea-beds are now found at altitudes up to 60 meters above present sea level in northernmost Denmark. The isostatic land rise was less to the south and the paleo-shoreline at Mariager Fjord occurs at an altitude of only 5 meters above present sea level (Mertz, 1924) (Figure 32).

5.6 Holocene (Post Glacial) elevation and subsidence

During the Holocene, periods of transgressions and land elevation causing forced regressions occurred (e.g. the Littorina transgressions). The presence of inland fossil coastal cliffs is well known from the northern part of Denmark with a maximum elevation of up to 15 meters in the NW Vendsyssel (Mertz, 1924). Along the north coast of Sjælland, the elevation is about 10 meters above present sea level and decrease southwards to 0 meters in southern Sjælland, mid Fyn and Ringkøbing Fjord. South of the Ringkøbing–Fyn High, the land surface has subsided more than 4 meters (Pedersen et al., 2015).

5.7 Glacio-isostacy and sea level rise

Vertical movements of the Danish land area related to the last glacio-isostatic rebound from termination of the Weichselian glaciations are still ongoing. The relative vertical movements are very small but still measurable (Figure 32). In the northernmost part of Denmark, the current uplift is ca. 1.5 mm/year. Due to the ongoing uplift this area will probably not be flooded in case of a near-future event of sea level rise. In contrast the southern part of Denmark, where the land is currently subsiding with rates around 0.25 mm/year, present low-lying areas would be flooded if a significant sea level rise occur (Hansen et al., 2012).

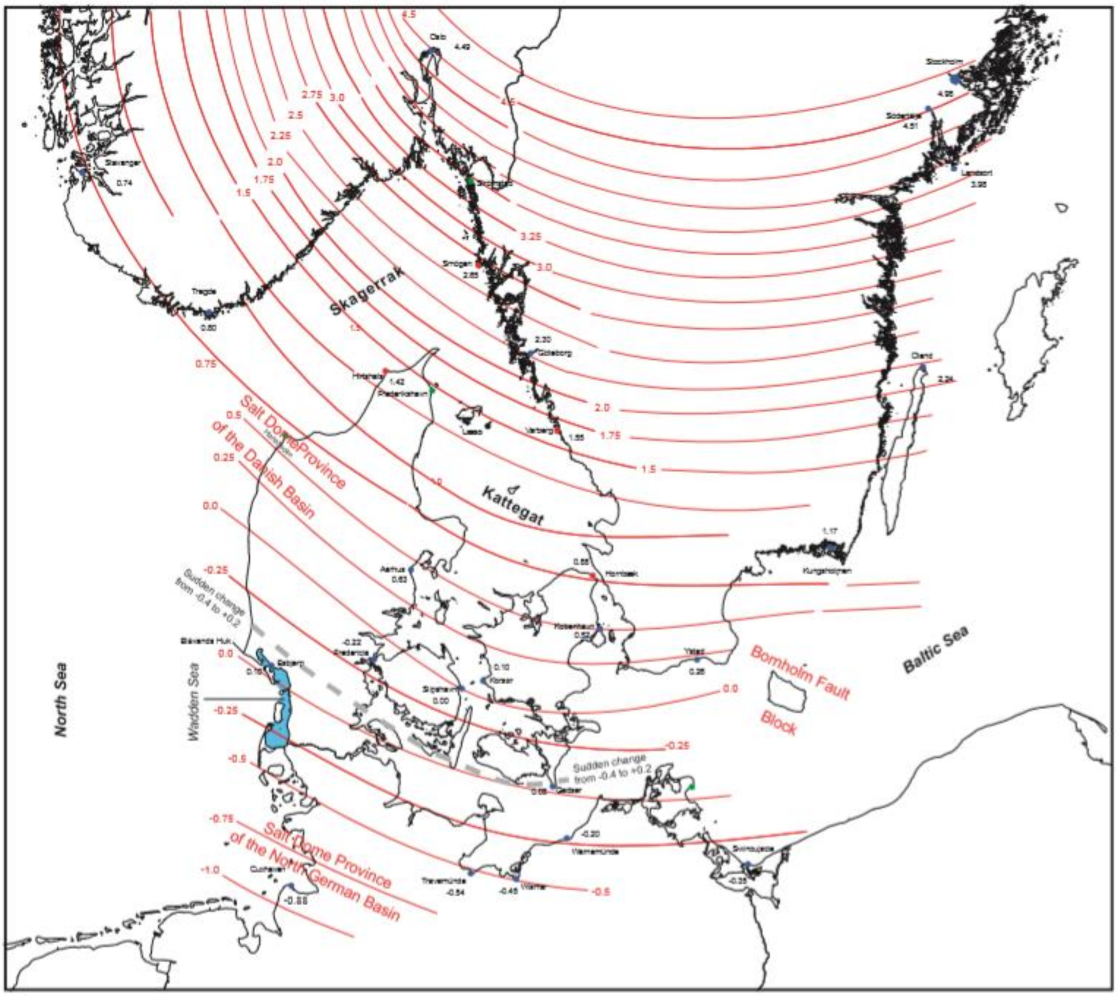

Figure 32. *Map showing the present-time isostatic uplift rates (red lines) of the Danish and surrounding areas in mm/year. The dashed, grey line shows the boundary between the northern areas that are currently being uplifted and southernmost areas where subsidence is ongoing (From Hansen et al. 2012).*

Figur 32. *Kort over de nutidige isostatiske landbevægelser (røde isobase linjer) i Danmark og omkringliggende områder i mm/ år. Den grå punkterede linje viser 0-niveauet for opløft og indsynkning (Fra Hansen et al., 2012).*

5.8 Fractures in near-surface sediments and rocks

The uppermost 0 to 20 meters, and sometimes deeper levels, of the Danish rock record usually display a dense network of horizontal and vertical fractures. Fractures occur in all rock types including crystalline basement, chalk, and Quaternary till deposits. Some of the fractures are of tectonic origin related to major faults and unloading due to tectonic uplift whereas a significant amount of the shallow fractures are related to deformation and loading/unloading of advancing and retreating glaciers and ice sheets (Gravesen 2006).

Figure 33. *Intensively fractured Precambrian Hammer Granite exposed in a granite quarry on northern Bornholm, Denmark.*

Figur 33. *Stærkt opsprækket Hammer Granit ses i granitbruddet på Nordbornholm, Danmark.*

The main part of the Danish limestone and chalk deposits are at shallow depths affected by fracturing. There seem to be a tendency of random glaciotectonic fracturing superimposed on Paleogene wrench related fractures (Jakobsen et al., 2002). However, the distribution and density of fractures varies significantly and is highly dependent on the lithological behavior and geomechanical competence of the rocks (Figure 30). The fractures are vertical and horizontal, and the uppermost layers of the limestone and chalk sections have often been crushed and fractured intensively by glaciers (Jakobsen et al., 2002).

Figure 34. Danian limestone intersected by horizontal and vertical fractures, Amager (hammer for scale).
Figur 34. *Danien kalksten gennemskåret af horisontale og vertikale sprækker, Amager.*

Mesozoic, Paleogene, and Neogene fine-grained and plastic clays occurring near surface often contain fractures of tectonic origin. In addition, thaw-freeze fractures can be found in the top layers. In many clay types, the combination of fractures and heavy rain followed by dry conditions may cause gravitational instability.

Figure 35. Outcrop of clayey till in a gravel pit, Sjælland. Sets of sub-vertical fractures can be recognized.

Figur 35*. Profil af moræneler fra en grusgrav på Sjælland. Sæt af subvertikale sprækker kan tydeligt ses.*

Fractures in clayey tills have been studied from outcrops in coastal cliffs and pits (Figure 35). Clayey tills in the Quaternary section are normally fractured within the upper 10 meters below ground level where e.g. the conjugating sub-vertical fracture sets are considered as being of tectonic origin (Klint & Gravesen, 1999). The tills may also comprise macropores in terms of biopores formed by rootlets and earth worm burrows (Figure 36).

The vertical and sub-vertical fractures in sediments and rocks facilitate the transport of surface water from the ground surface to the groundwater. The presence of horizontal fractures enhances the lateral movement of ground water over long distances.

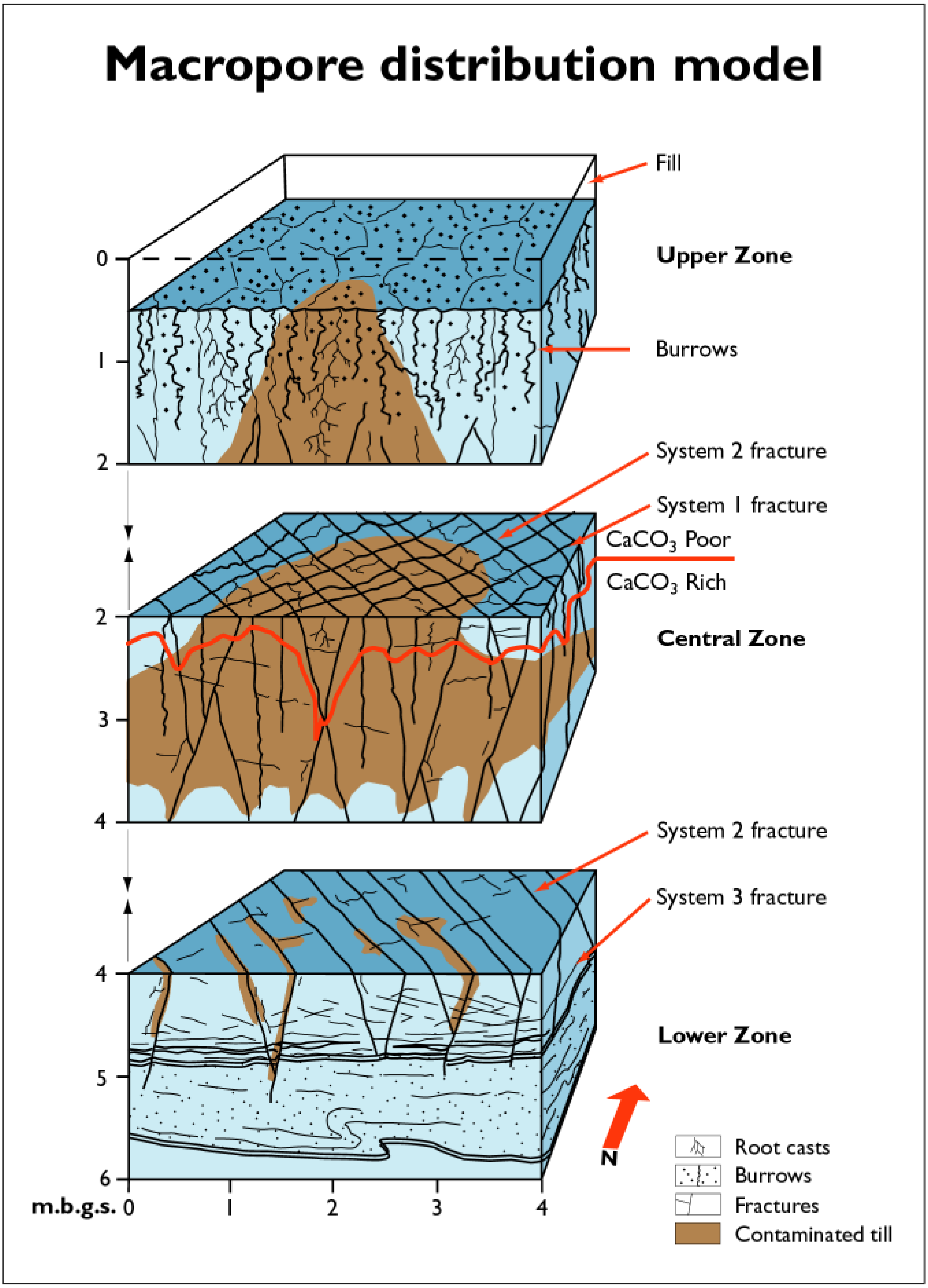

Figure 36. *Model of the macropore/fracture systems in a clayey till, Flakkebjerg. (From Klint & Gravesen, 1999).*

Figur 36. *Model for makropore/sprække system in moræneler, Flakkebjerg. (Efter Klint & Gravesen, 1999).*

5.9 Landslides

Landslides may occur as sudden events where a steep cliff collapse, or they may occur gradually where the presence of soft clay or other incompetent soft rock may cause the layers to slide due to gravitational forces.

Landslides occur frequently along the coastal cliffs dominated by clayey lithologies and limestone due to gravitational instability (Figure 37). Cliff collapses with dramatic rock falls occur occasionally, where Upper Cretaceous chalk and/or Danian limestone are exposed. The most hazardous cliff collapses occur along Møns Klint (Figure 38). Major cliff collapses have a typical frequency of one per every 3–5 years. The last dramatic major rock fall appeared in January 2007 (Pedersen & Gravesen, 2009). At this rock fall, the supply of a huge amount of chalk material from the Store Taler caused the formation of a new coastal area, with a peninsula extending 300 meters into the sea from the main coastline. At the less tall cliff Stevns Klint rock fall also occur, but usually with less volume of rock (Pedersen & Gravesen, 2016).

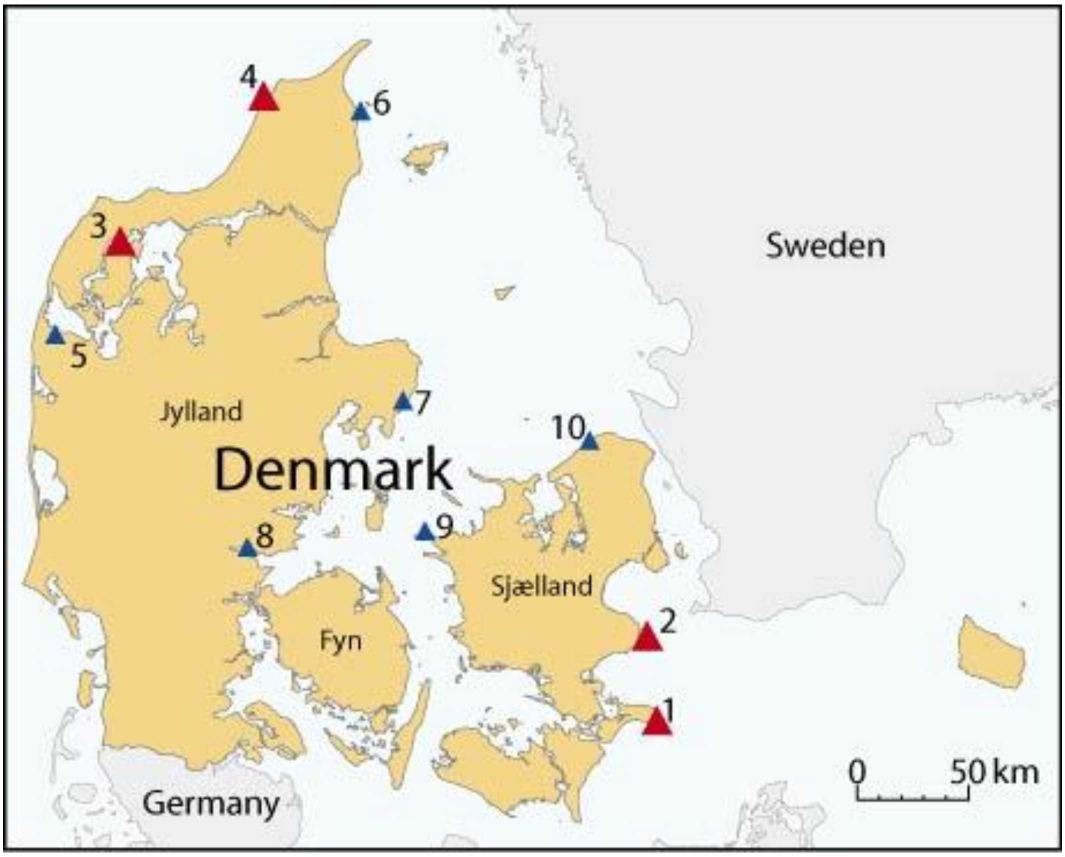

Figure 37. Map showing areas with risk of landslide geohazards. Legend: Red triangles: High-risk areas, Blue triangles: Low-risk areas (From Nadim et al., 2008). Note that all areas with risk are located where high and steep coastal cliffs occur.

Figur 37. *Kort over lokaliteter med risiko for jord- og klintskred (geohazards). Røde trekanter: Højrisiko områder, blå trekanter: Lavrisiko områder (Fra Nadim et al., 2008). Bemærk at alle områder med risiko for store skred findes, hvor der er høje og stejle kystklinter.*

Figure 38. *Example of landslide at Møns Klint, the Store Taler slide January 2007. More than 100.000 m^3 of chalk were displaced up to 300 meters away from the coastline.*

Figur 38. *Klintskred ved Møns Klint, Store Taler skreddet, januar 2007. Mere end 100.000 m^3 skrivekridt blev flyttet mere end 300 meter væk fra kysten.*

Initiation of the landslides is caused by weather conditions changing between precipitation and freeze and thaw processes. A high porewater content will facilitate the formation of fractures in the areas behind the cliffs during freeze, which facilitates sliding and collapses due to lose of strength during the subsequent period of thaw.

In general, the landslide hazards in clayey lithologies are not very sudden and dramatic and they usually occur gradually over longer time periods. A structural model for the main landslides and their mechanic development is illustrated in Figure 39, and the typical terrace morphology of coastal areas affected by landslides is shown in Figure 40.

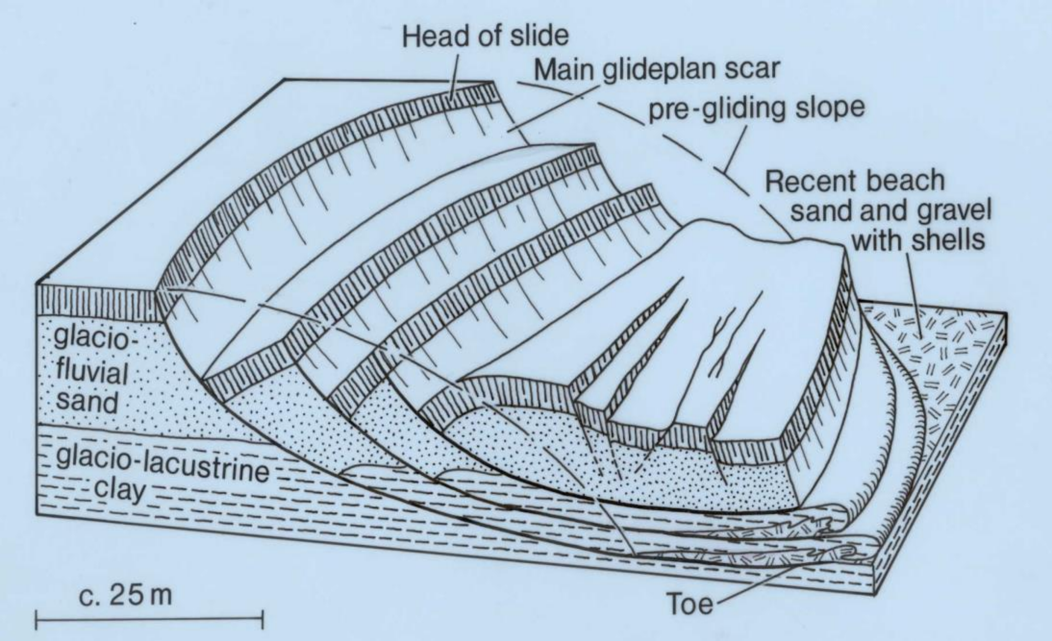

Figure 39. *A model of the structural elements of the landslide (after Pedersen 1987).*

Figur 39. *En generel model for jordskreds struktur og udvikling (efter Pedersen 1987).*

Figure 40. *An example of normal extensional imbrications of the head of a landslide from Sundby Bakker, Mors. The displacement along each escarpment is approx. 1 m/year, and the sliding layers comprise Paleogene plastic clay.*

Figur 40. *Eksempel på normale ekstensionelle forsætninger ved toppen af et jordskred, Sundby Bakker på Mors. Bevægelsen langs forsætnings-planerne er ca. 1m/år, og de ned-forkastede lag består af palæogent plastisk ler.*

5.10 Neotectonic features

Neotectonic features are tectonic structures penetrating the Neogene deposits and eventually also the Quaternary sediments. The tectonic activity forming these structures occurred within the last 10 million years. Usually, the deformation occur as displacements along older re-activated, deeper-seated faults.

In Denmark, a few examples of neotectonic activities are documented based on surface structures and sometimes confirmed by seismic data. An example of fault planes and fracture valleys that were formed due to tectonic activity in the Weichselian have been described from Hvorslev in Jylland (Jakobsen & Pedersen, 2009) (Figure 41). Another example is from areas near and above the deep-seated Thisted salt dome in Jylland, where uplift has taking place during the last 4000 years (Hansen & Håkansson, 1980).

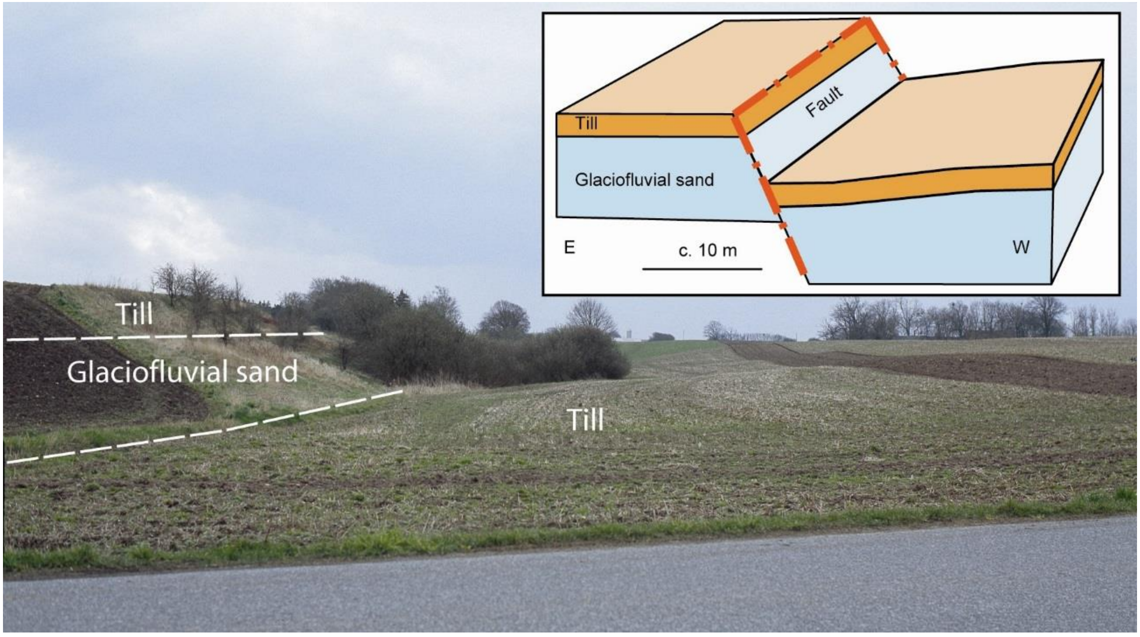

Figure 41. *Neotectonic fault plane at Hvorslev in central Jylland. The top till and the underlying Quaternary sediments are down thrown to the west (right side of the photo) with a displacement of approx. 8 meters (From Jakobsen & Pedersen, 2009).*

Figur 41. *Neotektonisk forkastningsplan ved Hvorslev i Midtjylland. Det øverste morænelers-lag og de underliggende kvartære aflejringer er nedforkastet mod vest med en forsætning på ca. 8 meter (Fa Jakobsen & Pedersen, 2009).*

In Kattegat, the Late Weichselian clayey sediments have been displaced along old faults that were reactivated along the Sorgenfrei-Tornquist Zone as the result of glacio-isostatic rebound. The faulted marine clayey sediments are referred to the Vendsyssel Formation, which was deposited during the late glacial eustatic sea level rise about 15,000 years ago (Jensen et al., 2002)

Finally, a well-dated example of neotectonic displacement is recorded above the Børglum Fault Zone on the west coast of Vendsyssel, Nordjylland. Here, the 15–17,000 years old deposits in the Vendsyssel Formation were faulted and show a vertical displacement of approx. 25 meters. Subsequently, sediments deposited 12,000 years ago in a bog truncate the structure (Lykke-Andersen, 1992).

6. Seismic activity since 1930

Seismic activity in Denmark is of low magnitude and unevenly distributed as seen in Figure 42 and they are usually not registered by people. Earthquakes registered recently over a 38-year period in Denmark have magnitudes between 1.5 and 4.8 on the Richter scale (Gregersen et al., 1998, Larsen et al., 2008).

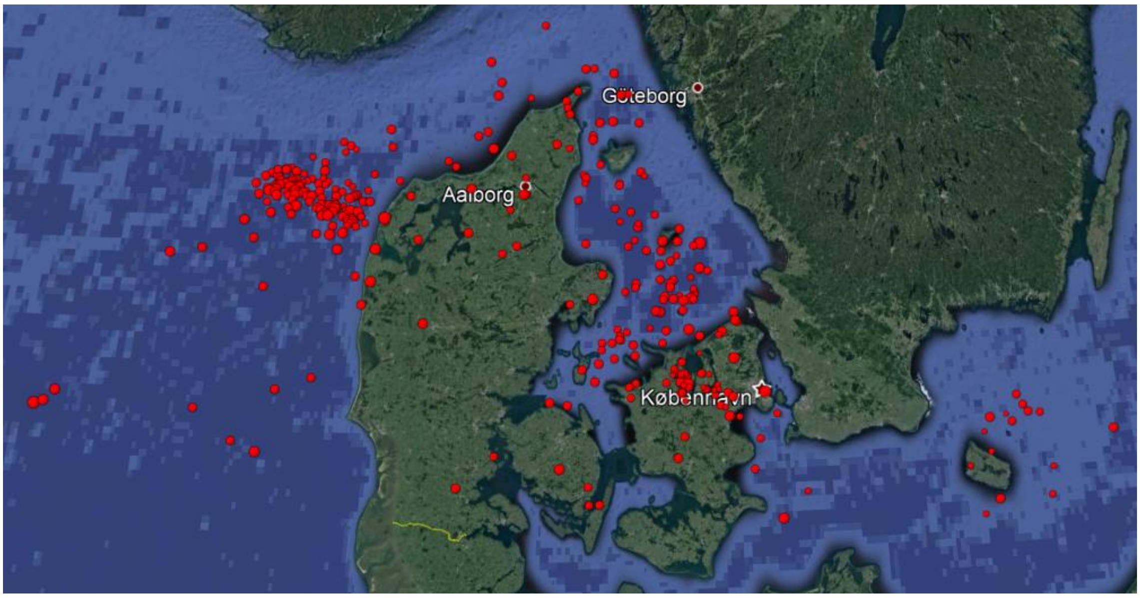

Figure 42: *Instrumentally recorded seismicity in Denmark for the period 1930 – 2018. Epicenters (red dots) are from GEUS earthquake database, and all epicenters are determined using data from a minimum of three stations. In addition to earthquakes the map may show data related to explosions which have not yet been screened out (GEUS, 2018).*

Figur 42: *Instrumentelt registreret jordrystelser i Danmark i perioden 1930 – 2018. Epicentrene (røde prikker) er fra GEUS´ jordskælvsdatabase. For lokalisering af epicentre er der brugt data fra mindst tre stationer. Kortet kan indeholde epicentre relateret til eksplosioner, hvor data endnu ikke er blevet identificeret og sorteret fra i databasen (GEUS, 2018).*

Large areas have not experienced any earthquake activity within the 38 years observation period (Figure 42). Seismic activity has been registered back to 1677 (with some indications of events as early as 1073) as written communications (Abrahamsen, 1967). The most active earthquake area is the Sorgenfrei-Tornquist-Border Zone, the North Sea and Kattegat and, with slightly less activity, the Roskilde Fjord area in northern Sjælland (Gregersen et al., 2005, Voss et al., 2009). The earthquake in Scania in 2008 had a magnitude of 4.8 ML and was sensed in large areas of eastern Denmark (Figure 44).

A correlation of registered earthquakes to known shallow or deep-seated fault zones is not straightforward. In general, there is no direct indication of seismic activity such as lateral or vertical displacement along recognized and mapped faults and fault zones in Denmark. One reason is that the earthquake focus points are situated at several kilometres depth where the formations may be brittle or at least rather competent. In contrast soft, uncompacted Quaternary sediments will usually be able to accommodate the displacement, such that only very subtle impact is observed at the ground level, if any. However, seismic activity has been registered in the Roskilde Fjord area, which is an area where abundant faults, both major and minor, have been mapped thus suggesting some relationship between presence of faults in cutting the surface layers and earthquake activity (see Figure 9) (Larsen et al., 2008). Also, the high frequency of earthquakes in parts of the Sorgenfrei-Tornquist Zone suggest that parts of the large fault zone are still active (Gregersen, et al., 1996).

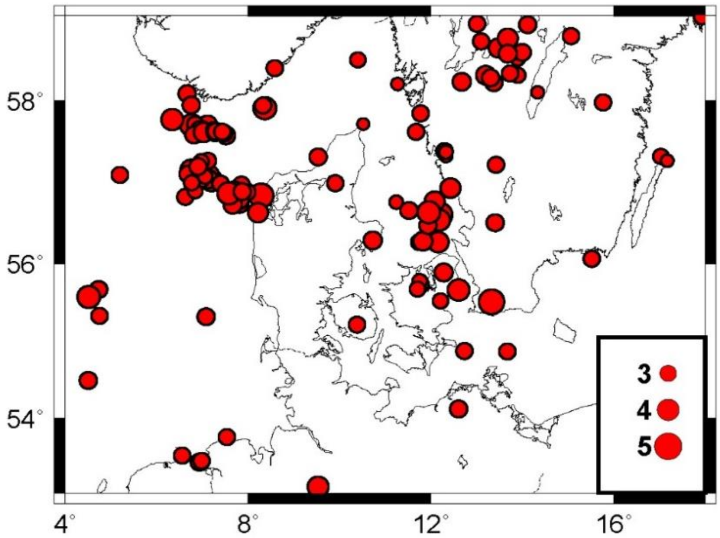

Figure 43. *Map showing the location of the largest earthquakes registered in Denmark with magnitudes from 3 to just below 5 on the Richter scale.*

Figur 43. *Kort med de største jordskælv i Danmark med størrelser på fra 3 til lige under 5 på Richter skalaen.*

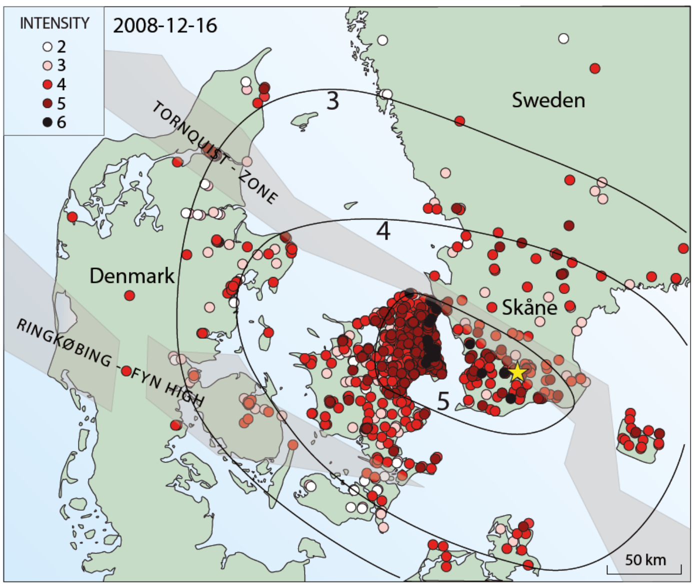

Figure 44. *The earthquake in Scania (Skåne) in 2008 was registered in many areas in eastern Denmark as shown on the Intensity map from Voss et al., (2009).*

Figur 44. *Jordskælvet i Skåne i 2008 kunne mærkes i store dele af Østdanmark, som vist på intensitetskortet (Voss et al. 2009).*
Richter skalaen.

7. Summary

Denmark is located within a geological setting of general tectonic quiescence, although some activity along the Sorgenfrei-Tornquist Zone is recognised. Occasional earthquakes of low magnitude occur most frequently in northern parts of Jylland and northern Sjælland. The geology of the Danish subsurface and surface layers is the combined result of long-term tectonic processes and sedimentary processes filling in the basins, as well as relatively short-term events and processes influencing the shallow layers. The main structural elements in the subsurface include the Sorgenfrei-Tornquist Zone, the Danish Basin, Ringkøbing-Fyn High, and the North German Basin.

In most areas, the formations occurring at 500 meters depth are Mesozoic mudstone, sandstone, chalk, and marl. Sand layers are common in the Jurassic and Lower Cretaceous sections and detailed local analyses have to be made to identify areas where sand is absent in order to fulfil the requirements and criteria for a suitable disposal site (as described in Midtgaard et. al, 2021). The sediments are known from deep wells and seismic, however, locally chalk is exposed in cliffs and quarries. Overlying formations include Tertiary chalk and claystones, and Quaternary sandstones and mudstones with thicknesses locally up to 400 meters. Crystalline basement rock occurs at 500 meters depth only on the island of Bornholm.

The identified natural processes that may influence the Danish land surface and shallow subsurface layers in the near-future time are related mainly to climate changes, glaciations, and associated sea-level changes. The processes include glacio-fluvial erosion, glaciotectonic deformation, subsidence and uplift, and small-scale re-activation of old faults. These processes are observed to influence most commonly the upper 0-200 meters but locally erosion to depths of 400 meters below the ground level has been observed. Thus, a repository situated at 500 meters depth is highly unlikely to be directly influenced by future fluvio-glacial erosion. In the report of Sandersen et al. (2021) (cf. Chapter 8.1 for reference) all these processes and their potential future impact are described with the aim to evaluate the long-term natural stability.

The geology and the properties known from the potential repository rocks are presented in more detail in the reports on mudstone (Pedersen et al., 2021), crystalline basement (Gravesen et al., 2021), and chalk (Jakobsen et al., 2021). Seismic mapping of the sedimentary rocks is presented in Mathiesen et al., (2021).

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