DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/58**

Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark. Phase 1, report no. 7

Evaluation of long-term stability related to glaciations, climate and sea level, groundwater, and earthquakes

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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.7. It describes how glaciations, earthquakes and climate changes may influence geological formations occurring at ground level and to depths of more than 500 meters.

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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 slutdepotprojekt. 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. 7: Evaluering af stabilitet relateret til glaciationer, klima og havniveau, grundvand og jordskælv (Evaluation of long-term stability related to glaciations, climate and sea level, groundwater, and earthquakes).

Denne rapport præsenterer i fire kapitler den eksisterende viden om de naturlige processer, som har påvirket de øverste lag i den geologiske lagserie indenfor de seneste 500.000 år og frem til i dag. Påvirkningerne er i høj grad foregået under de seneste istider (glaciationer), som har formet det eksisterende landskab med aflejring af sedimenter, deformation af undergrunden og lokalt dyb erosion. Andre processer, der påvirker såvel terrænoverfladen som undergrunden, omfatter jordskælv, klimaforandringer og havniveauændringer samt dannelse af grundvand. Kendskabet til processerne og deres indvirken på terrænoverfladen og de geologiske formationer i dybder ned til 500 meter er vigtigt for at kunne vurdere den mulige påvirkning af de geologiske barrierer ved et geologisk slutdepot i 500 meters dybde - og dermed den naturlige stabilitet og sikkerhed på både kort og lang sigt.

Kapitel 2. Fremtidige glaciationer i Danmark: mulige implikationer for den øvre del af undergrunden

I løbet af Kvartær tidsperioden blev det danske område flere gange overskredet af iskapper. Isens tyngde og bevægelser, samt smeltevand fra isen, har resulteret i dybe deformationer og erosion af landoverfladen samt ændringer af den hydrologiske cyklus under og foran isen. Subglacial smeltevandserosion og glacialtektoniske deformationer kan lokalt forstyrre sedimentære aflejringer til en dybde af flere hundrede meter under terrænoverfladen. Hertil kommer stress-påvirkningen af skorpen ned til den øvre kappe på dybder ned til omkring 100 km ved belastning og efterfølgende aflastning af isens vægt. Stress-ændringerne i forbindelse med deglaciationen kan reaktivere eksisterende inaktive forkastningszoner i det danske område. De hydrologiske og geologiske hændelser, der er knyttet til istiderne, kan således påvirke de geologiske egenskaber ved lokaliteten for et fremtidigt dybt slutdepot.

Klimaændringer og glaciale cykler

Undergrundens overfladenære geologi og de morfologiske træk i terrænet er et resultat af en vekslen mellem istider og isfri perioder, der har påvirket det danske område i løbet af

Kvartær tidsperioden (de seneste 2,6 mio. år). I løbet af de seneste 800-900.000 år er istiderne optrådt med en cyklicitet på ca. 100.000 år. Baseret på resultater fra klimamodeller forventes det, at der indenfor de næste 500.000 år vil optræde 1-4 nye istider i Skandinavien, hvor også det danske område vil blive dækket af iskapper. Modellerne forudsiger også, at den tidligere cyklicitet vil blive ændret pga. den stigende mængde drivhusgasser i atmosfæren, og at det forventede tidspunkt for den næste glaciation derfor vil blive udsat. Klimamodellerne forudser, at effekten på undergrunden af fremtidige istider formentlig vil være sammenlignelig med de tidligere istider. Det er derfor relevant at se på effekterne af tidligere istider for at forudsige mulige påvirkninger af undergrunden ved fremtidige istider i Danmark.

Kvartære glaciationer i Skandinavien

De seneste istider Sen Saale og Weichsel er de bedst kendte i Danmark, og deres aflejringer kan studeres i f.eks. kystklinter, mens deres aftryk ses i geomorfologien. Vores forståelse af de kvartære iskappers dynamik i Danmark bygger på forskning, som primært dækker de seneste 150.000 års geologiske udvikling. Den maksimale istykkelse i Weichsel blev nået for ca. 20.000 år siden med en tykkelse i det danske område på op til 2500 meter, mens tykkelser på 1000 – 2000 meter forekom under Saale istiden for ca. 140.000 år siden. Hver gang ismasserne byggede op, resulterede det i en sænkning af det globale havspejlsniveau på omkring 150 meter, hvilket betyder, at erosionsbasis blev sænket i samme størrelsesorden. Iskapperne kan både erodere og deformere de underliggende lag samt optage og transportere materialer over store afstande og aflejre dem andre steder. Den glaciale erosion under iskapperne er maksimalt 20-30 meter i løbet af en enkel glaciation.

Subglacial smeltevandserosion – tunneldale

Smeltevand, der forekommer mellem gletsjersålen og underlaget under højt tryk, kan erodere kanaler, kaldet tunneldale, dybt ned i underlaget. Tunneldale er almindeligt forekommende i Danmark, hvoraf størstedelen nu er fyldt med senere aflejrede sedimenter, og derfor beskrives som begravede dale. Dalene er typisk 500-1500 (op til 3.500) meter brede; 25-400 meter dybe, og længden kan overstige 25-30 kilometer. Geofysiske elektromagnetiske data (TEM) og seismiske data viser, at enkelte dale er mere end 400 meter dybe, og at de ofte har en kompleks historie med flere faser af erosion og opfyldning indenfor perioder af få hundrede år. Dalenes orientering indikerer et genbrug af gamle dalsystemer, formentlig betinget af præ-eksisterende lavninger i terrænet, som er styret af dybereliggende strukturer og forkastninger i undergrunden.

Glacialtektonisk deformation

Glacialtektonisk deformation kan finde sted foran og under isranden, samt under den centrale del af en tyk iskappe. Deformationsgraden afhænger af isens vægt og bevægelse, karakteren af underlaget og porevandstrykket nær isranden. Deformationen påvirker normalt de øverste 20-50 meter af jordoverfladen, men går lokalt ned til 300 meter. De øverste få hundrede meter af den danske undergrund er domineret af ukonsoliderede aflejringer, som let deformeres. De deformerede (foldede, forkastede, stablede osv.) lag er synlige i klinter og ses som bakkerygge i landskabet. Det klassiske glacialtektoniske kompleks forbindes typisk med deformationer i form af foldede og stablede lag, der ses i Møns Klint, men findes også i den øvrige del af Danmark med varierende tæthed. Det største, kendte glacialtektoniske kompleks i Danmark er Jammerbugt-komplekset fra Saale, som dækker et areal på mere end 300 km^2 og deformationerne når mere end 400 meter ned under havbunden.

Påvirkning af grundvandet i løbet af en glacial cyklus

Grundvandets hydrologi påvirkes af bl.a. smeltevandsproduktionen, isens temperatur, belastningen fra istrykket, underlagets sammensætning, permafrost og ændringerne i havniveau. I relation til et dybt geologisk slutdepot er de vigtigste ændringer af det hydrologiske system cirkulationsdybden, saliniteten samt iltindholdet af smeltevandet. Europæiske og nordamerikanske undersøgelser tyder på, at smeltevandet i løbet af de kvartære nedisninger trængte 300 - 1000 meter ned under terræn, hvor det fortrænger saltholdigt grundvand.

Muligheden, for at subglacialt smeltevand drænerer ned til dybereliggende lag under en kommende glaciation, afhænger af mægtigheden af de kvartære aflejringer, af karakteren af de underliggende prækvartære lag, samt regionale strukturer i undergrunden. I områder med høj-permeable prækvartære lag, vil der være stor sandsynlighed for en dyb påvirkning, mens en dyb påvirkning er mindre sandsynlig, hvor underlaget består af tykke lerformationer eller krystallinsk grundfjeld.

Glacialt inducerede reaktivering af forkastninger

Vægten af tykke iskapper resulterer i, at der sker en horisontal massebevægelse i den øvre del af kappen væk fra belastningen ved isskjoldets opbygning, og omvendt under afsmeltningen. Store dele af Danmark er dækket af flere hundrede meter tykke lag af ukonsoliderede prækvartære og kvartære sedimenter, og glacialt inducerede forkastninger er generelt vanskeligere at erkende i Danmark, bortset fra på Bornholm, hvor grundfjeldet ligger tæt på terrænoverfladen. Eksempler på sen- og postglaciale tektoniske hændelser er beskrevet fra bl.a. Nr. Lyngby i Nordjylland, hvor forkastninger med forsætninger på flere meter blev dannet under Senglacial tid ved reaktivering af Børglum forkastningen.

Et andet eksempel er fra Tinglev Hedeslette i Sydjylland, der blev skabt foran isranden for mellem 25.000 og 18.000 år siden. Områder af den ellers plane, svagt hældende hedeslette, som ligger over flanken af Tønder Graben-strukturen, er deformerede. Deformationerne af hedesletten er sandsynligvis et resultat af forkastningsbevægelser langs graben-strukturen i begyndelsen af Holocæn forårsaget af trykaflastning ved afsmeltning af isen.

I et studie af begravede tunneldale er der fundet en tæt korrelation mellem orienteringen af de begravede dale, dybtliggende forkastninger og erosionsdale i det nutidige terræn i store dele af Danmark. Den foretrukne orientering af både de begravede dale og erosionsdalene i det nutidige terræn er i stor udstrækning sammenfaldende med forkastninger i undergrunden, hvilket viser, at de dybe tektoniske strukturer har indflydelse på topografien i terrænoverfladen, og dermed har en stor indflydelse på dræneringsmønsteret i Senglacial og Postglacial tid. Det danske område bliver normalt betragtet som værende tektonisk stabilt, men de ovennævnte eksempler viser, at stressændringer, der relaterer sig til glaciationer/deglaciationer, kan skabe geologisk set kortvarig tektonisk ustabilitet.

Vurdering af mulige fremtidige påvirkninger af undergrunden

Den vigtigste hydrologiske faktor under en istid er cirkulationsdybden af smeltevandet, idet strukturer i undergrunden kan ændre de hydrauliske rammer og skabe nye korridorer for dannelse og cirkulation af dybt, ferskt grundvand.

Processer så som dalerosion og reaktivering af forkastningszoner ses i høj grad at være betinget af dybe strukturer i undergrunden og relaterede svaghedszoner. Tunneldalserosion forekommer ofte i præ-eksisterende lavninger, hvorfor eksisterende dale og strukturelt betingede lavninger over forkastningszoner vil være mest udsat for erosion under kommende glaciationer. Kendskab til placeringen af forkastningerne og deres aktivitetshistorie er således vigtig for at kunne forudsige en mulig glacialt betinget tektonisk re-aktivering. Glacialtektoniske deformationer derimod er betingede af faktorer som isens maksimale udbredelse, placering af isranden, og isens maksimale tykkelse.

I relation til et dybt geologisk slutdepot er det vigtigt at vurdere den maksimale dybde for mulige glacialt betingede processer inklusivt glacialtektonisk deformation, erosion af smeltevand, reaktivering af dybe forkastninger og ændringer i den dybe grundvandscirkulation. Den samlede mulige påvirkning bør evalueres ved de specifikke lokaliteter for et muligt depot, idet processerne i kombination kan resultere i en større påvirkning af undergrunden, end de enkelte faktorer kan alene. For eksempel kan reaktivering af forkastninger fremme en lokal subglacial erosion, som kan skabe kontakt mellem oprindeligt adskilte grundvandsmagasiner og derved resultere i cirkulation af det dybe grundvand. Detaljeret kortlægning og efterfølgende geologisk og hydrologisk modellering af udvalgte lokaliteter vil gøre det muligt at adressere og evaluere den mulige effekt af fremtidige glaciationer.

Kapitel 3. Jordskælvsforhold i Danmark

I Danmark er den seismiske aktivitet kun lav til moderat, fordi vi befinder os langt fra de nærmeste pladegrænser. Så selv om der hvert år registreres mange jordskælv, er der flere år mellem skælv, der er store nok til, at de kan mærkes. De fleste danske jordskælv forekommer under Kattegat, Skagerrak og den nordlige del af Nordsøen. På land er det Midtsjælland og Nordvestjylland, der er de mest aktive regioner. I resten af landet forekommer der også jordskælv, men de er sjældne. Nogle gange optræder jordskælv uventede steder, fx i Holstebro d. 16. sept. 2018. Jordskælvet er beregnet til styrke 3,5 på Richter-skalaen, og det fandt sted i et område, hvorfra der ikke tidligere er registreret jordskælv.

Seismisk aktivitet kendes både fra instrumentelle målinger og historiske kilder. Instrumentelle målinger er blevet indsamlet siden 1930, mens de historiske data rækker flere århundreder tilbage. Der er fundamentale forskelle mellem de to typer data. De instrumentelt målte data indeholder informationer om jordskælvsbølgerne, som gør det muligt at beregne jordskælvets epicenter (det sted på jordens overflade, der ligger vinkelret over skælvets oprindelse) og størrelse på Richter-skalaen. De historiske data indeholder typisk informationer om, hvordan jordskælvet blev følt, og hvornår det fandt sted. Den følte intensitet kan tilknyttes en værdi på Mercalli-skalaen, hvis 12 niveauer (I – XII) beskriver effekten af jordskælvet på mennesker, natur og konstruktioner. De to forskellige skalaer er uafhængige og usammenlignelige. Det kan dog i enkelte tilfælde være muligt at indplacere et historisk jordskælv på Richter-skalaen.

Muligheden for at registrere små jordskælv er gradvist blevet bedre i takt med udviklingen af måleinstrumenter. Således registrerede man i perioden mellem 1960 og 2000 alle skælv, der var mindst 3 på Richter-skalaen (logaritmisk skala uden nedre og øvre grænse), mens man nu registrerer alle skælv, der er mindst 2,5. De danske jordskælv måles af det danske net af seismografer (pt 7 stk., der vedligeholdes af GEUS), suppleret med data fra nabolandenes net. Datakvaliteten tjekkes og lokalisering af epicenter og beregning af størrelse af skælvet udføres manuelt.

Intensiteten af de rystelser, der genereres ved et jordskælv, er lige så vigtig som størrelsen på Richter-skalaen. Hvor størrelsen vedrører forskydningerne i undergrunden ved jordskælvets oprindelse, er intensiteten et mål for rystelsen følt på jordoverfladen. Geologiske forhold kan dæmpe eller øge den lokale jordbevægelse. Jordskælv så små som 2,7 på Richter-skalaen har skabt rystelser, der var store nok til, at folk lokalt i Danmark kunne mærke dem.

Usikkerheden ved beregningen af et epicenter afhænger af, hvor mange seismografer, der registrerer skælvet og af seismografernes geografiske fordeling omkring epicenteret. Beregningen af større jordskælvs epicentre sker med større præcision, end de mindre, og epicenteret for ældre jordskælv er typisk mere usikkert end for de yngre. Det skønnes, at usikkerheden på lokaliseringen af et dansk jordskælv, der indtraf før år 2000, er op til 50 kilometer i alle retninger, mens den for nutidige jordskælv er 20 kilometer – og altså stadig for stor til at knytte hændelserne til kendte forkastninger.

Risikoen for jordskælv i Danmark

Seismiske risikoanalyser baseret på Cornells (1968) metode er almindeligvis brugt i risikoanalyser verden over. Basis-idéen er at kvantificere rystelserne fra forventelige, fremtidige jordskælv baseret på alle tilgængelige jordskælvsdata fra regionen. Disse data kombineres med matematiske modeller for jordbevægelser og jordskælvs-lokalisering. De resulterende data skal behandles med stor omhu, fordi de bygger på en række antagelser. Data bliver også mere troværdige, desto flere jordskælvsdata, der indgår i modellen. Det er en udfordring for et lav-seismisk område som det danske. En anden udfordring er at estimere den maksimale størrelse af et fremtidigt skælv, fordi observationsperioden er meget kort, kun få hundrede år, sammenlignet med tidsskalaen for de styrende kræfter, som f.eks. er 10.000 år for de isostatiske bevægelser, der følger med aflastningen af jordskorpen, efter isen er smeltet væk, eller millioner af år for de tektoniske kræfter.

I Danmark inkluderer risikoanalyserne både instrumentelle og historiske data samt data fra nabolandene. Beregningerne er kun valide for landområderne og inkluderer ikke de skælv, der knytter sig til mulige fremtidige nedisninger og den efterfølgende aflastning, når isen smelter væk igen. Fra Sverige er der eksempler på, at aflastningen kan skabe store jordskælv. Ved Forsmark, Sverige, har man modelleret jordskælv ved 'slut-glaciale stress-forhold', som giver en størrelse på 5,6 på Richter-skalaen, og som skulle resultere i et 14 km^2 stort brudområde.

Den beregnede jordskælvsrisiko for Danmark er lav og sammenlignelig med de sydsvenske forhold. Den største risiko er fundet i det nordvestlige Jylland og i Nordsjælland. Beregningen er baseret på alle tilgængelige data, både de, der er målt ved instrumenter såvel som historiske kilder. Risiko-beregningen reflekterer den kendte seismicitet med den største jordbevægelse i Nordvestjylland og det centrale Sjælland. Eftersom mængden af tilgængelige data stiger år for år, er det relevant at gentage risikoberegningerne mindst hvert 10. år.

Selv om den seismiske aktivitet er lav i Danmark, er den ikke ubetydelig. En gang imellem optræder et stort jordskælv uventet et sted på jorden. Det uventede er begrundet i forskellen mellem den korte historiske tidsserie sammenlignet med længden af den geologiske skala, hvori drivkræfterne virker. De største 'overraskelses-skælv' tæt på Danmark i moderne tid fandt sted i 2004 i Kaliningrad og målte hhv. 5,2 og 5,0 på Richterskalaen.

Postglaciale hændelser

For at kunne vurdere jordskælvsrisikoen over lange tidsperioder, kan det være relevant at overveje effekten af fremtidige glaciationer og deglaciationer. Det nordlige Skandinavien har flere store forkastninger, som resulterede i store jordskælv i tiden efter den sidste deglaciation. Den største forsætning i Pärvie-forkastningen svarer til et styrke 8 jordskælv.

Risikoen for større jordskælv, både tektoniske og postglaciale, vil være størst i områder nær eksisterende forkastninger, aktive som inaktive, da forkastningerne udgør svaghedszoner i undergrunden.

Kapitel 4. Klimaændringer og havspejlsudvikling.

Kapitlet fokuserer på danske forhold og mulige forudsigelser af ændringer baseret på viden om historiske og nutidige forhold.

Under Weichsel istiden overskred isranden Danmark fra nord, nordøst og sydøst, og isens vægt tyngede landet ned. Ved begyndelsen af Holocæn (11.700 år før nu) medførte en markant temperaturstigning en stor afsmeltning af isskjoldet og en global havspejlsstigning. Afsmeltningen betød, at landet begyndte at hæve sig (isostatisk), mest i de nordøstlige områder, hvor den største tykkelse af is forekom. Havspejlsudviklingen og landbevægelserne i løbet af Holocæn har betydet, at Danmarks kystlinje konstant har flyttet sig. Således lå vestkysten langt ude i Nordsøen i Fastlandstiden, mens store dele af (især) Nordjylland blev oversvømmet ved Littorinatransgressionerne. Havspejlet nåede et maksimum for 2.000 år siden. Den isostatiske landhævning finder stadig sted, dog med aftagende hastighed. På grund af landhævningen findes kystaflejringerne, der markerer Holocæns højeste marine niveau, Littorinakysten, i dag langt inde i land i Nordjylland. Igennem Holocæn tid har klimaet ændret sig signifikant og over korte tidsperioder fra tørt og koldt til varmt og mere fugtigt end i dag.

Klimaændringer og havspejlsudvikling frem til 2073

Afsnittet fokuserer på de emner, som kan have en effekt på det danske landområde, inkl. kystzonen, i fremtiden. De igangværende klimaændringer, der bl.a. udmønter sig i ændrede temperatur-, nedbørs- og vindforhold vil også berøre parametre, der er afledt heraf, bl.a. havspejlsniveauet.

Det er vigtigt at forholde sig til risikoen for, at der sker en oversvømmelse af indgangen til depotet, mens depotet konstrueres og er taget i brug senest i 2073. Der er to hovedårsager til oversvømmelse: at den igangværende havspejlsstigning når en kritisk højde – eller ved en stormflod, forårsaget af vind og tidevand.

På basis af IPCC's seneste 'vurderingsrapport' skønnes havspejlet i år 2073 at være 23 – 57 cm højere end '1986-2005-niveauet' eller 15 – 49 cm højere end 2019-niveauet. IPCC´s skøn ændres lidt fra rapport til rapport, ligesom andre kilders skøn på den fremtidige havspejlsstigning udviser en vis spredning (Tabel 4.1). Den fremtidige havspejlsstigning vil påvirke de danske kyster; mindst i Nordjylland og mest i Syddanmark alene pga. forskelle i den relative landhævning.

Stormflodsrisici fordelt på regioner

Risikoen for, størrelsen af, og årsagen til, stormfloder er forskellig fra region til region.

Nordsøkysten er eksponeret for stormfloder fra de stærke vestenstorme. Syd for Blåvands Huk er de lavvandede kyststrækninger tillige udsat for det astronomiske tidevand, som kan enten øge eller mindske højden af en given stormflod. Vadehavskysten har i historisk tid været udsat for talrige stormfloder, f.eks. de 'store mandedræbere' i 1362 (10.000 druknede) og 1634 (vandet nåede op i +6,3 meter). I 1981 nåede vandstanden i Esbjerg 4,3 meter og i 1999 forårsagede en orkan en vandstand på >5,1 meter i Ribe (Figur 4.7).

Limfjorden. Særligt bredningerne og byerne Løgstør og Lemvig i den vestlige ende er udsat for stormfloder, når vandet presses gennem Thyborøn Kanal og ikke kan passere de smalle passager ved Aggersund og Aalborg tilstrækkeligt hurtigt. Under en meget kraftig storm i 2005 nåede vandstanden i Løgstør og Skive rekordhøjde (>2,26 meter), og dele af byerne måtte evakueres.

Kattegats sydlige del (Randers Fjord, Odense Fjord, Isefjord, Roskilde Fjord, Øresund inkl. København) er udsat for stormfloder ved storme fra nordvest og vestlige retninger. Storme fra disse vindretninger er mindre hyppige end storme fra vest, og i denne region af landet er det astronomiske tidevand mindre end 50 cm. Alligevel sker det, at regionen bliver alvorligt ramt, f.eks. under stormen Bodil (dec. 2013), hvor vandstanden nåede 2,06 meter i bunden af Roskilde Fjord; 1,96 meter i Hornbæk og 1,65 meter i Nordhavn, som er ny rekord.

Syddanmark, syd for bælterne er udsat for stormfloder pga. 'flaskehalsproblemer' ved vandudveksling mellem Nordsøen og Østersøen under storme fra enten vestlige eller østlige retninger, når vandet ikke kan passere bælterne tilstrækkeligt hurtigt. I denne region er det astronomiske tidevand mindre end 15 cm.

Fremadrettet

Klimaændringerne i nærmeste fremtid vil højst sandsynligt forårsage ændringer i vindmønsteret, inkl. vindretning, styrke og frekvens af storme og dermed øge risikoen for oversvømmelser. Ved identificeringen af en lokalitet for geologisk slutdeponering er det vigtigt at vurdere risikoen for oversvømmelser ved lokaliteten bl.a. baseret på de nyeste stormflodsmodeller, som er udviklet af Kystdirektoratet og Danmarks Meteorologiske Institut.

Kapitel 5. Grundvandsforhold i Danmark

I Danmark udgør grundvand 99,4% af kilderne til drikkevand, mad og industriel produktion. Grundvand betegner her alt vand, der befinder sig i porer og hulrum i undergrunden, uanset om det er ferskt eller salt vand. Grundvandet, der bliver indvundet, findes i tre forskellige typer af bjergarter: kridt/kalksten, sand/grus og grundfjeld afhængigt af geologien i de forskellige dele af landet. Den landsdækkende og offentligt tilgængelige database Jupiter (ved

GEUS) indeholder oplysninger om mere end 280.000 boringer og mere end 35.000 vandværker, der ligger til grund for vurderinger af mængden og kvaliteten af tilgængeligt grundvand, herunder den geokemiske status af grundvandsressourcerne.

En grundvandsforekomst er en vandressource, som rummer én eller flere hydraulisk indbyrdes forbundne grundvandsmagasiner. Forekomster inddeles i tre kategorier baseret på udbredelsen, hvor de overfladenære findes fra 0 meter til 25 meter under terræn (og horisontal udbredelse mindre end 250 km^2) og de regionale er dybere end 25 meter under terræn (horisontal udbredelse mere end 250 km^2). De dybe forekomster findes dybere end 25 meter under terræn og er hydraulisk set isolerede fra grundvand i overfladen og de regionale forekomster. I Danmark indvindes grundvand typisk fra de øverste 0-200 meter af undergrunden, bl.a. fordi dybere grundvand er saltholdigt.

I kystnære områder er de ferske grundvandsmagasiner i direkte kontakt med det salte og tungere havvand, der som en kile trænger ind under kysten og resulterer i, at saltvand her findes nær terrænoverfladen. Kontakten kaldes saltvands-/ferskvandsgrænsefladen (SFG). Dybden til SFG afhænger af tilstrømningen af det ferske vand og bevæger sig havværts, når den hydrauliske gradient øges ved stigende tilførsel af ferskvand fra nedbør og landværts, når gradienten svækkes. Grundvandsindvinding i kystnære områder og dræning af lavtliggende områder kan påvirke den naturlige balance mellem ferskt og salt vand.

Transportmekanismer under saltvands-/ferskvandsgrænsefladen

Transportmekanismerne for stoftransport i kalksten i intervallet fra 500 til 300 meter forventes domineret af diffusionsprocesser med en dominans af vertikal bevægelse, da det er i den vertikale retning, at de diffusionsdrivende koncentrationsforskelle findes. En undersøgelse i en boring på Stevns antyder, at diffusiv transport (af saltvand) er den dominerende transportmekanisme i 500 meters dybde, og at vertikale advektive grundvandsstrømme er begrænset til de øvre, opsprækkede dele af kalken.

Tidsskalaer for ændringer i grundvandssystemet

Forståelse af hydrologiske ændringer, der er foregået igennem de seneste 100.000 år, er essentiel for at kunne forudsige den mulige fremtidige indvirkninger af klima- og miljøændringer på grundvandsressourcerne. I den sammenhæng er datering af grundvandet vigtig, dels for at forstå grundvandets bevægelser, herunder at estimere hvor lang tid vand har ligget i uberørte magasiner siden deres opfyldning, og dels for at vurdere hvor lang tid magasinerne, der pumpes fra, er om at blive genopfyldt. Denne viden kan hjælpe til at belyse, hvordan kommende klimaændringer kan ændre grundvandsforholdene.

Grundvand der er yngre end 200 år kaldes det moderne grundvand, og det er dannet i en tid med antropogen påvirkning (forurening, indvinding). Det førindustrielle grundvand (de seneste 7.000 år) er fra en hydrologisk cyklus uden antropogen påvirkning og med et havspejl beliggende omtrent i samme niveau som nu. I perioden fra 18.000 til 7.000 år undergik grundvandet signifikante ændringer efter istidens afslutning og i relation til at havniveauet steg med 120 meter. Det høje havniveau havde stor indflydelse på den hydrologiske cyklus, herunder en markant hævning og position af grænsen mellem det salte og ferske grundvand.

Vandværker og overvågning af grundvandsstanden

De grundvandsforhold, som eksisterede før den industrielle periode, blev forstyrret omkring 1850, da man begyndte at indvinde grundvand. I 1894 havde 27 byer eget vandværk. I de tidlige 1970'ere var der omkring 6.000 kommunale vandværker og ca. 200.000 individuelle husholdningsbrønde på landet. Grundvandsstanden er blevet målt i de enkelte brønde, siden man overgik fra at bruge overfladevand til at indvinde grundvand, men først i 1989 blev et nationalt overvågningsprogram påbegyndt. Hvert år udgiver GEUS en rapport om både den kvalitative og den kvantitative status af grundvandet, men da informationerne er baseret på indvinding fra magasiner med ferskvand, er der ingen informationer fra dybder på 500 meters dybde, hvor grundvandet er saltholdigt.

Karakterisering af dybt grundvand

Det er kun få studier af det dybe grundvand i Danmark, da vand i 500 meters dybde generelt indeholder høje koncentrationer af klorid, og derfor er uegnet som drikkevand. I en stor del af landet findes tætte bjergarter i den dybere del af undergrunden. I Jylland er der udbredte lag af miocænt ler i få hundrede meters dybde og i det centrale Jylland og store dele af Sjælland findes tætte kridt- og kalkstensformationer, som kun indeholder begrænsede mængder af grundvands-ressourcer.

Nyere undersøgelser af miocænt sand i Sydvestjylland har vist, at sandet generelt indeholder ferskt grundvand af høj kvalitet på dybder ned til ca. 350 meter, at vandet akkumulerede i Holocæn tid, og,at det indtil nu ikke har været influeret af menneskelig påvirkning.

En anden mulig grundvands-ressource findes i dybder på 200-400 meter under terræn i sandfyldte, begravede kvartære dale. I det centrale Jylland findes dale, der er eroderet ned i prækvartære sedimenter. Vandindvinding fra disse dale kan berøre grundvandets strømning til større dybder og vil muligvis resultere i opadgående vandbevægelser, afhængigt af den hydrauliske konduktivitet, og hvorvidt de enkelte vandmagasiner er direkte forbundne.

Omkring 1/3 af Danmarks drikkevand kommer fra de øvre 50-100 meter af kridt- og kalkstenslag, hvor de er opsprækkede som et resultat af glacialtektonisk deformation. Tilstedeværelsen af sprækker er en betingelse for advektiv grundvandsstrømning, som gør det muligt at indvinde store mængder drikkevand. I de dybere dele af kalken, der ikke er opsprækket, kan bjergarten være meget tæt. Lokalt, hvor kalken ligger i eller nær terrænoverfladen, kan der muligvis være karst, der kan fungere som strømningsveje for grundvandet.

I det krystallinske grundfjeld på Bornholm findes grundvandsmagasiner i opsprækket grundfjeld og i sprækkedale udfyldt af kvartære sand- og grus-aflejringer. Det meste vand indvindes fra dybdeintervallet 0 til 100 meter. I et enkelt studie med målinger i 8 brønde er det påvist, at der foregår strømning af grundvand i dybder omkring 100 meter. Der findes ingen information om grundvandet i større dybder af grundfjeldet.

De hydrauliske forhold i prækvartære leraflejringer 500 meter under terræn er ikke undersøgt i Danmark, og der mangler således basal viden om strømning og stoftransport i det dybe grundvand. Konceptuel 1D numerisk modellering for indledende undersøgelser af stoftransport i dybder til 500 meter er præsenteret i Rapport nr. 8 (jf. Kapitel 6.1 for reference). Undersøgelser af egenskaberne af ler og lersten for karakterisering af dybe grundvandsforhold i relation til mulig deponering af radioaktivt affald findes fra internationale projekter (fx Belgien, Schweiz, Frankrig, Holland, Canada og Japan). Højporøse formationer, der strækker sig flere hundrede meter under terrænoverfladen, kan indeholde ferskvand og dermed udgøre vigtige grundvandsforekomster. De findes typisk i sandfyldte kvartære dale og i sprækkesystemer. En detaljeret kortlægning af de overfladenære formationer vil derfor være en vigtig del af projektets næste fase med detaljerede geologiske undersøgelser på to lokaliteter, idet sådanne forekomster kan have en betydelig grundvandsstrømning i flere hundrede meters dybde.

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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, Belgium, Holland, Germany, Switzerland, Sweden, Norway, and Finland (ANDRA, 2005; ONDRAF/NIRAS & ANDRA, 2015; Nagra, 2017; COVRA, 2017; SKB, 2007; 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 these experiences and cooperate with these and other countries' radioactive waste disposal organisations (SKB-Sweden, POSIVA-Finland, IFE-Norway).

Furthermore, the project will follow guidelines from IAEA (2011; 2018 a, b), the Nuclear Energy Agency (NEA (OECD), 2005, 2006, 2008, 2012) and the EU directive regarding this field (EU, 2011).

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

1.2 The deep geological repository project

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

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

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

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

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

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

2. Future glaciations in Denmark: Possible implications for the upper part of the subsurface

Peter Sandersen

2.1 Introduction

Climate change is truly not a modern phenomenon – climate perturbations have been occurring through all of Earth's history. During the 2.6 Ma years of the Quaternary period, in which we live now, the earth's climate has varied up to forty times – from warm interglacial periods to cold glacial periods, resulting in the waxing and waning of ice sheets in the northern hemisphere (e.g. Lindborg et al. 2013; Benn & Evans 2010; Fischer et al. 2015; Liljedahl et al. 2016). The causes of climate change are complex, but scientific knowledge about past climatic variations using chemical, biological, or physical indicators enable us to describe possible future climate change scenarios – including the occurrence of future glaciations.

The present chapter is a part of the preliminary investigations for siting a possible nuclear waste repository in Denmark, by means of reviewing existing literature on subjects related to the effects of climate change during the Quaternary. The purpose of the review is to form an input for later risk assessments related to future nuclear waste repository facilities. A preliminary focus for the investigations has been set to a depth of 500 meters below terrain. The aim is to evaluate if hydrologic and geologic events related to glaciations will be able to expose or in other ways impact the nuclear disposal facilities, and to further address the potential risk. The review will focus on possible impacts of future glacial cycles potentially occurring within the next five hundred thousand of years on the uppermost 500 meters of the subsurface.

Geographically, the review will concentrate on scientific literature and reports from Scandinavia and the rest of northern Europe, Greenland and North America, and will, in relation to assessments of consequences of future glaciations, focus on the region of Denmark.

2.2 Glacial cycles during the Quaternary

2.2.1 Climate change and glacial cycles

The periodic glaciation-deglaciation cycles (Figure 2.1) are generally attributed to the climatic response to external and internal forcing mechanisms outside or inside the climate system. External forcing mechanisms are for example tectonic activity, orbital forcing and variations in solar energy, whereas internal forcing mechanisms could be oceanic circulation as well as atmospheric circulation and composition (Fall & Nasir 2011; van Geet et al. 2012, Tzedakis et al. 2012). The interactions between the mechanisms are complex but there seems to be close to a 100-ka cyclicity during the last 800-900,000 years. An extrapolation of the known cyclic occurrence of the Pleistocene glaciations therefore seems to be a viable forecast for future glaciations. However, some climate models produce scenarios that differ from the known cyclicity. Simulations performed by Loutre & Berger (2000) showed that the next glaciation would not start 50 ka into the future, but rather 100 ka from now. The difference in the modelled onset of the next glaciation was primarily explained as the consequence of using CO_2-values at a pre-industrial and an industrial level, respectively.

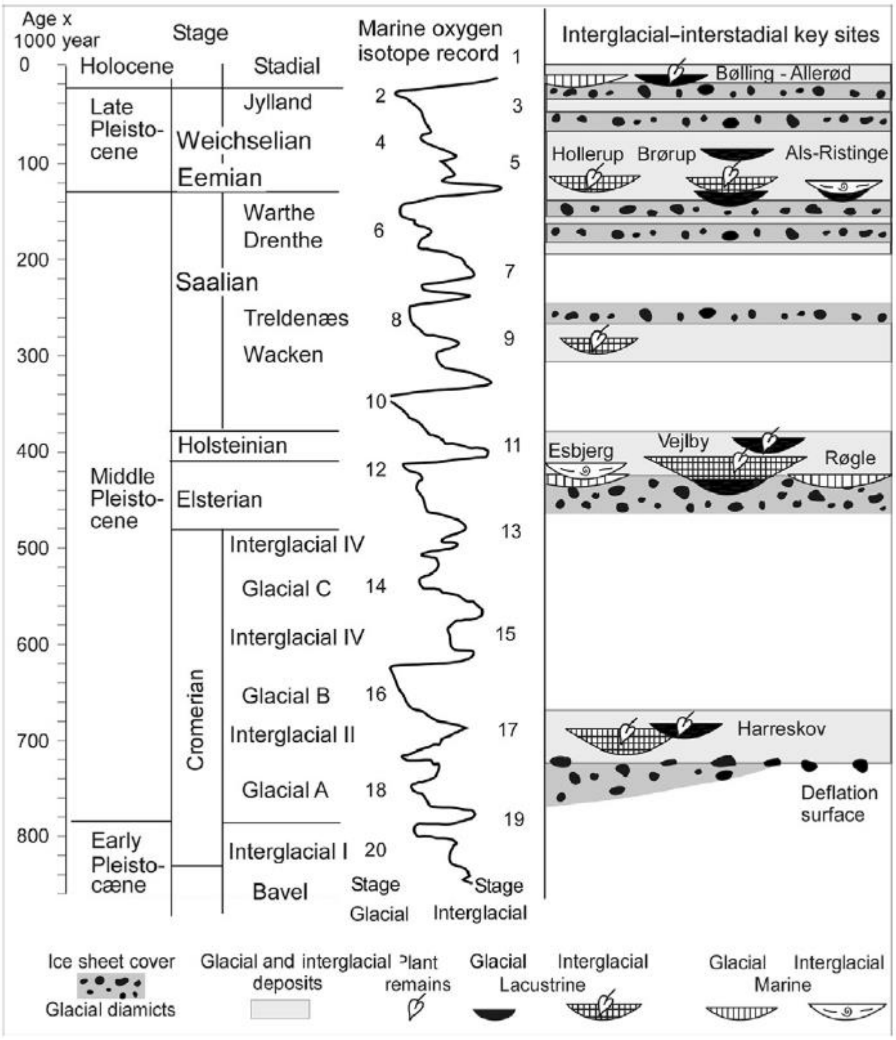


Figure 2.1. *Event–stratigraphical chart for the Middle and Late Pleistocene, Marine oxygen Isotope Stages (MIS) and chronology of Danish interglacial and glacial deposits. From Houmark-Nielsen (2011). Marine oxygen isotope stages are alternating warm and cool periods in the paleoclimate as interpreted from oxygen isotope data reflecting changes in temperature (data collected from deep-sea drill cores).*

Figur 2.1. *Hændelses-stratigrafisk diagram for Mellem og Sen Pleistocæn, marine ilt-isotopstadier (MIS) og kronologi af danske interglaciale og glaciale aflejringer. Fra Houmark-Nielsen (2011). Marine ilt-isotopstadier er skiftende varme og kolde perioder tolket ud fra ilt-isotopdata, som reflekterer temperaturen (data indsamlet fra dybhavsboringer).*

Other model scenarios infer even longer postponements of the next glaciation, using higher atmospheric CO_2-values than the present values. Some models even suggest that if, in the near future, all fossil carbon were to be released into the atmosphere, the inception of the next glaciation would be postponed for approximately 500 ka (Fischer et al. 2015). Climate models covering time spans of hundreds of thousands of years are inherently uncertain, and because the concentrations of greenhouse gases have such a large impact on the model results, various model scenarios are expected (e.g. van Geet et al. 2012).

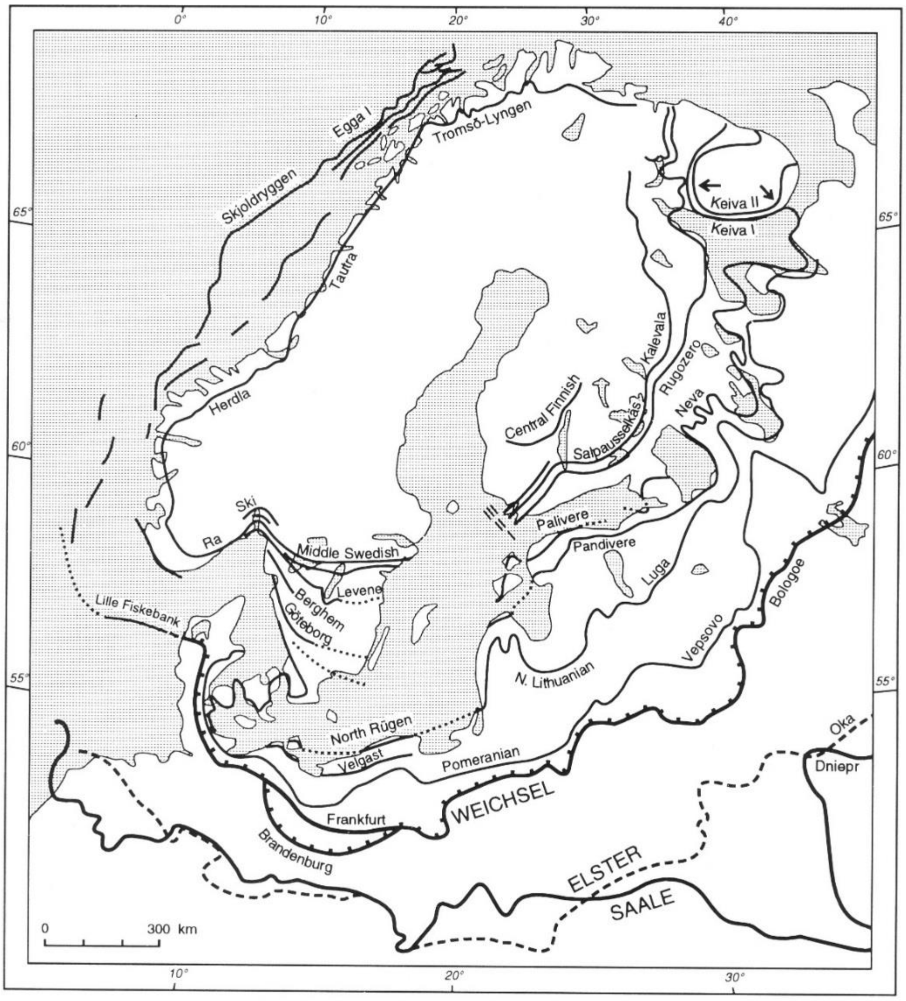


Figure 2.2. *Extent of the Elsterian, Saalian, and Weichselian glaciations and the main ice-marginal positions of the Late Weichselian and Early Holocene deglaciation. From Donner (1995).*

Figur 2.2. *Udbredelse af iskapperne under Elster-, Saale- og Weichsel-istiderne, samt de vigtigste israndspositioner i Sen Weichsel og under deglaciationen i Tidlig Holocæn. Fra Donner (1995).*

The models mentioned by van Geet et al. (2012) also showed that the next glaciation would probably be less severe than the previous Pleistocene glaciations – again a result of using high levels of industrial CO_2 values. A preliminary conclusion based on the mentioned studies is that, within the next 500,000 years, Northern Europe will most likely experience between one and four glaciations with magnitudes that, probably, will not exceed those of the Middle and Late Pleistocene glaciations.

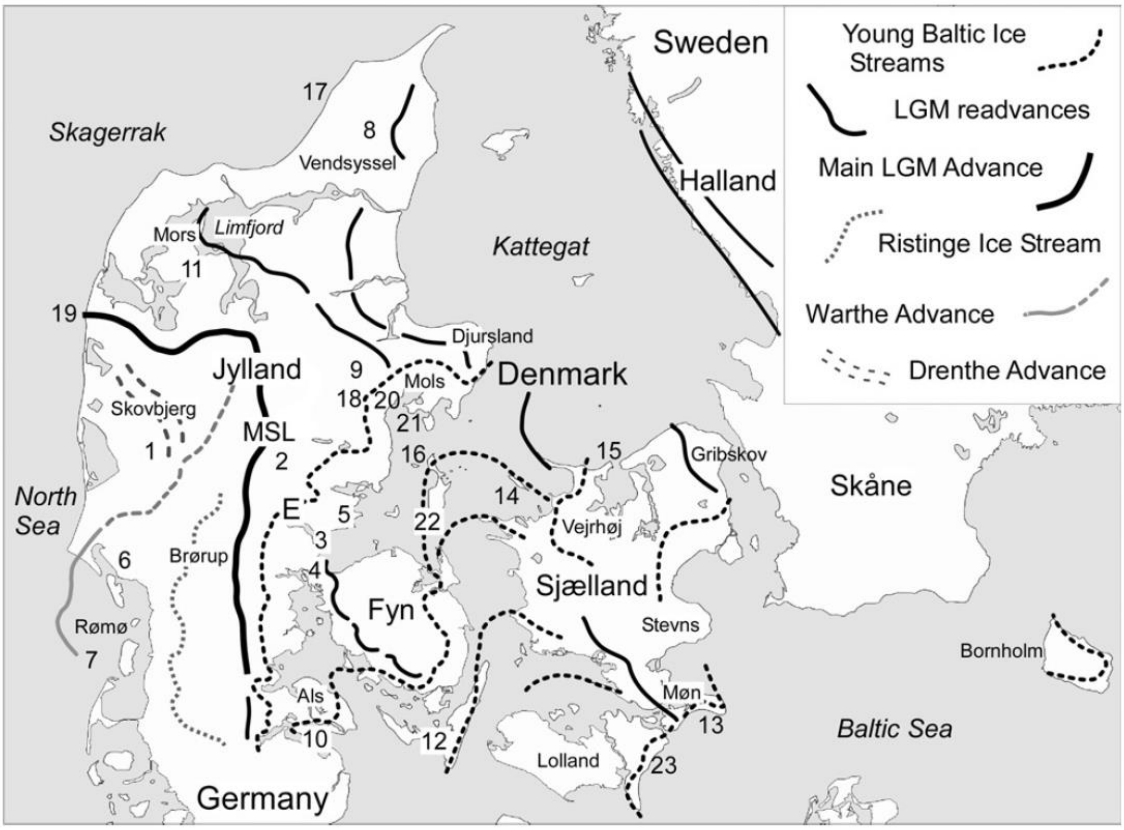


Figure 2.3. *Distribution of end moraines of Saalian (Drenthe and Warthe; MIS 6), Middle Weichselian (Ristinge ice stream) and the Late Weichselian (Main advance and Young Baltic ice streams). From Houmark-Nielsen (2011); the numbers refer to key sites mentioned in this paper.*

Figur 2.3. *Fordelingen af randmoræner fra Saale (Drenthe og Warthe; MIS 6), Mellem Weichsel (Ristinge Isstrømmen) og Sen Weichsel (Hovedfremstødet og De Ungbaltiske Isstrømme). Fra Houmark-Nielsen (2011); nummereringen på kortet refererer til beskrevne nøglelokaliteter i denne artikel.*

2.2.2 Pleistocene glaciations in Scandinavia

Sedimentary remains of Early Pleistocene glaciations from the time interval 2.6–0.78 Ma have been described in the Northern Hemisphere, but in most cases lack of dating makes interpretations problematic (Ehlers & Gibbard, 2008). In Scandinavia, sparse data even make the interpretation of many pre-MIS 6 observations and interpretations uncertain (pre-Late Saalian; see Figure 2.1) (Houmark-Nielsen, 2011). The size and extent of the older ice sheets is unknown, but, in contrast, the maximal extent of the Elsterian, Saalian and Weichselian ice sheets in Scandinavia is well-known (Figure 2.2). Although the extent of the ice sheets in Scandinavia seems to follow roughly the same form as seen on Figure 2.2, there are signs of changing centres of glaciation. The Middle Weichselian glaciation, for instance, probably had a more north-easterly dispersal centre than the Late Weichselian glaciation (Ehlers & Gibbard, 2008). In Denmark, the maximum extent of the Late Saalian and Weichselian ice sheets as also individual ice margins are known in fairly high detail (Figure 2.3).

The Late Saalian and Weichselian glaciations are the most studied glaciations in Denmark (Figure 2.3), because their sediments are accessible in coastal cliffs, gravel pits and shallow wells, and because the youngest ice advances have left their imprint on the topography in general. Therefore, the understanding of the behaviour of the Pleistocene ice sheets in Denmark mainly comes from research covering the past 150,000 years (e.g. Houmark-Nielsen et al. 2005). However, deeper and older erosional features, such as tunnel valleys with infill of, for example, Holsteinian deposits, add important information about erosion patterns during the Elsterian or even older glaciations (Jørgensen & Sandersen, 2006).

As seen on Figure 2.3, different ice advances have since the Late Saalian reached the Danish area from directions ranging from north to south-southeast. More details than shown in Figure 2.3 are available from local or regional studies. For example, shown in Figure 2.4 are details of a series of ice margins created by the receding Late Weichselian ice sheet in Vendsyssel in the northern part of Denmark.

During the Weichselian glacial maximum, ice flowed radially from the centre to the margins and into the Danish area from north and easterly directions (Figure 2.2). Later on, the ice flow was strongly controlled by the shape of the Baltic Sea depression and the Young Baltic ice streams advanced from the south and southeast (Boulton et al. 2001; Ehlers & Gibbard, 2008; Houmark-Nielsen, 2011).

Siegert et al. (2001) used a numerical ice-sheet model to reconstruct the Eurasian Ice Sheet during the full Weichselian glacial–interglacial cycle (Figure 2.5). The results showed that maximum ice thickness in the Weichselian was attained at the Last Glacial Maximum, approximately 20,000 years ago. These modelled ice thickness values showed that the ice was thickest at the Bay of Bothnia (2250-2750 m) and thinnest close to ice margins. In the Danish area, the modelling showed values ranging from 0-2500 meters. Modelling by Lambeck et al. (2006) showed that during the Late Saalian (MIS 6; 140 ka), maximum ice thicknesses exceeded 3000 meter and may have reached thicknesses between 1000 and 2000 metersin the Danish area.

During the Pleistocene glaciations, the build-up of ice masses resulted in a significant global lowering of the relative sea level of around 150 meters (e.g. Lambeck & Chappell, 2001; Waelbroeck et al. 2002). Important for the present context, a lowering of the sea level implies a lowering of the erosional base level in the same order of magnitude.

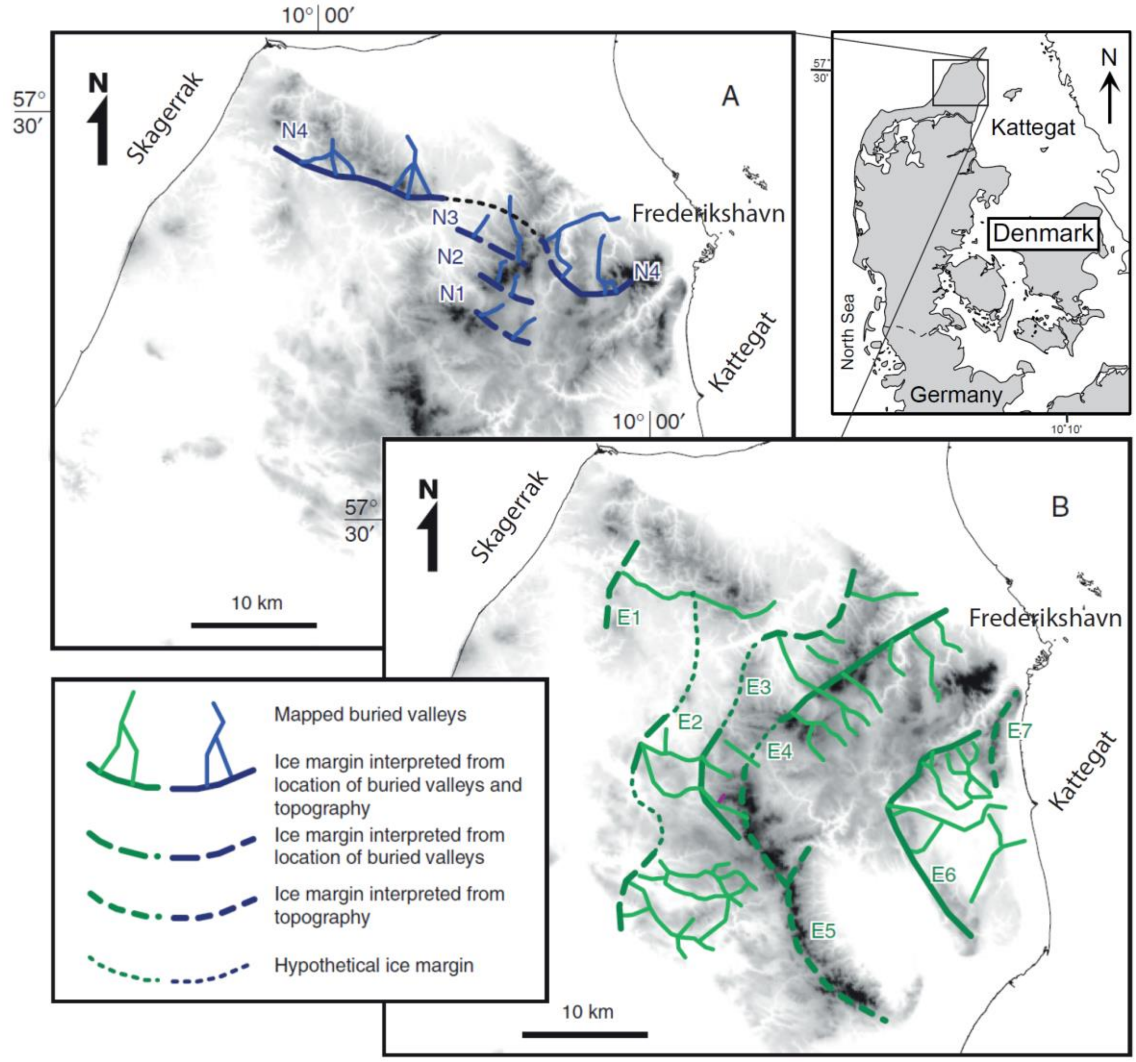


Figure 2.4. *Late Weichselian Vendsyssel: Ice-margin positions inferred from buried tunnel valleys and the topography. The two valley groups shown represent (A) buried tunnel valleys formed under ice margins at temporary standstills during the northward recession of the ice sheet ('N'-ice margins) and (B) buried tunnel valleys formed at temporary standstills during the eastward recession of the ice sheet towards the east ('E'-ice margins). The topography is shown in the background using grey scale and with dark grey colours representing the highest areas (up to 136 meters above sea level (masl.)). Modified from Sandersen et al. (2009).*

Figur 2.4. *Vendsyssel i Sen Weichsel: Israndsstillinger tolket fra kortlægning af begravede dale og fra topografien. De to dalegrupper repræsenterer (A) begravede tunneldale, som er dannet under midlertidige isrande ved den generelle tilbagetrækning mod nord ('N'-isrande), og (B) begravede tunneldale, som er dannet i forbindelse med midlertidige isrande under den generelle tilbagetrækning mod øst ('E'-isrande). Topografien er i baggrunden gengivet med en gråtoneskala, hvor den mørkeste grå farve repræsenterer de højest beliggende områder (op til 136 meter over havet (m.o.h.)). Modificeret efter Sandersen et al. (2009).*

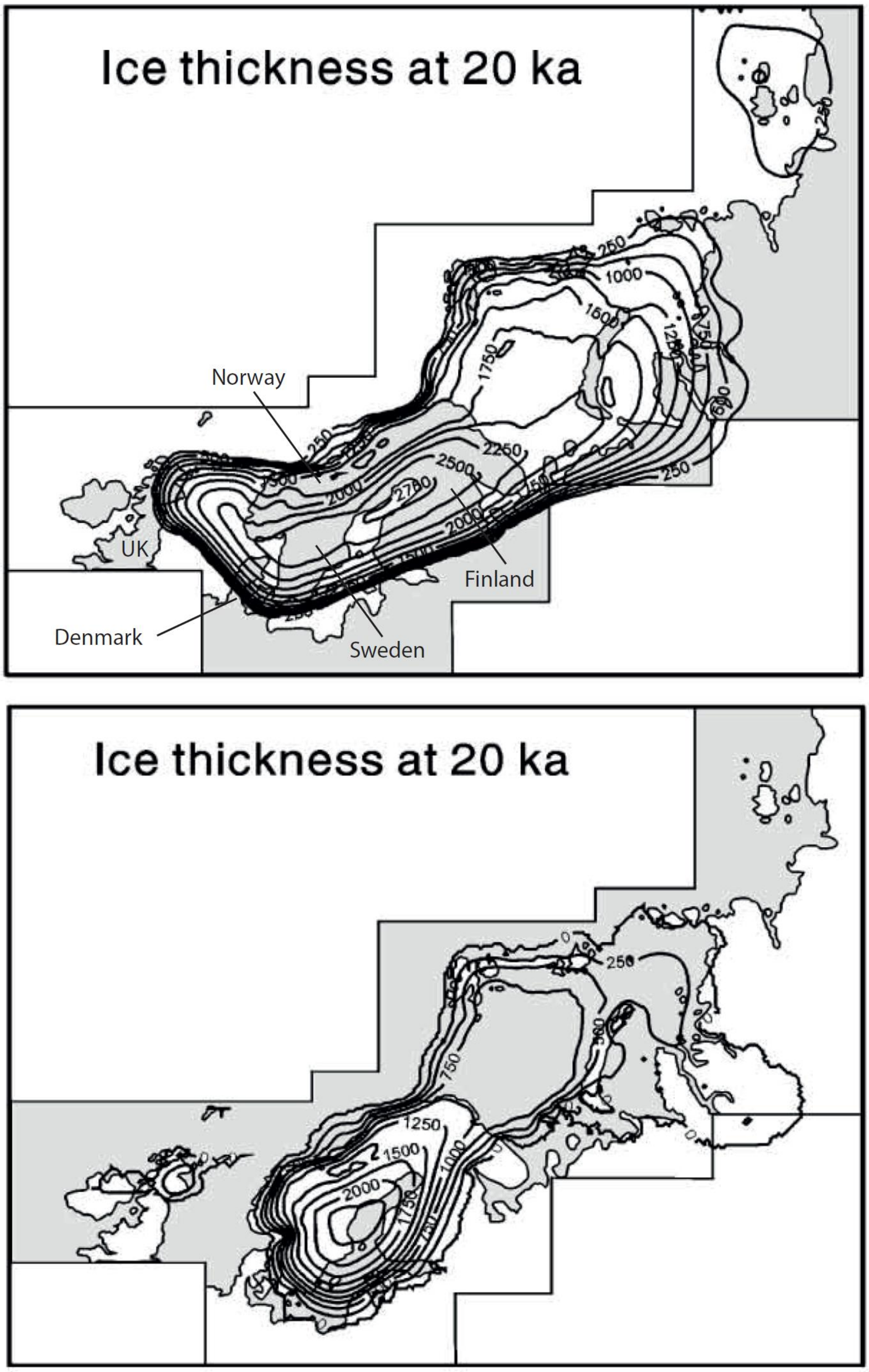


__Figure 2.5.__ Modelled ice-sheet thickness for the 'maximum' and 'minimum' c. 20,000 years ago. Upper figure shows 'maximum' values; the lower shows 'minimum' values. Contour interval: 250 meters. Modified from Siegert et al. (2001).

__Figur 2.5.__ Modelleret tykkelse af iskappen for 'maksimums-' og 'minimums-' scenarier ca. 20.000 år før nu. Den øverste figur viser 'maksimumsscenariet', mens den nederste viser 'minimumsscenariet'. Modificeret efter Siegert et al. (2001).

2.3 Physical impact on the subsurface related to glaciations

Physical impacts of ice sheets and glaciers on the terrain and the subsurface are substantial. Ice sheets are highly dynamic systems having the ability to erode and deform the layers beneath, to capture and transport material over great distances, and eventually to facilitate re-sedimentation. Glaciers are effective erosive agents either acting by direct excavation or scouring, or by the erosive forces of their meltwater. Glaciers also modify and create landforms, and they alter prevailing hydrologic systems (i.e. Benn & Evans, 2010). During the Pleistocene, repeated growth and decay of the ice sheets caused large changes in their vertical load, fluid pressures and crustal strain. Importantly, the resulting crustal deformation not only affected areas previously covered by ice sheets, but it also affected large areas outside former ice-sheet margins (Stewart et al. 2000).

The magnitude and type of erosion in glacial environments depends on the temperature and velocity of the basal ice, concentrations of debris in the ice, the ice thickness and subglacial water pressure (e.g. Benn & Evans, 2010; Fischer et al. 2015). Erosion occurs either as direct erosion where the substrate is eroded by the glacier itself, by meltwater or the two in combination. The temperature at the sole of the ice is important: compared to warm-based glaciers, erosion underneath cold-based glaciers is limited (e.g. Fischer et al. 2015; Hildes 2001). The warm glacier enables basal sliding and abrasion – a process in which subglacial meltwater plays an important role. It is beyond the scope of this chapter to give a thorough review of all facets of the impact glaciers have on the subsurface. Instead, the next sections will deal with examples of considerable physical impact - focussing on the magnitude and type of impact on the Danish subsurface.

2.3.1 Erosion during a glacial cycle

Glaciers move sediment by entrainment in the ice itself, by subglacial meltwater transport and by deforming the substrate (Iverson & Person, 2012). Meltwater and wind act as erosional agents outside the ice margin, resulting in removal of sediment in the proglacial environment (Benn & Evans, 2010). Glacial erosion beneath the ice sheets during the Pleistocene glaciations vary greatly – between 0.05 and 15 mm per year - and with total erosion during a single glacial cycle probably not exceeding a few tens of meters (Iverson & Person, 2012). Estimates of erosion rates have been made by determining volumes of sediments in adjacent basins (fjords, lakes and oceans). Two specific calculations estimated the total erosion in North America during the Quaternary (c. 2.6 million years) to 80 meters and 120 meters respectively (Bell & Laine, 1985; Hay et al., 1989). Referring to modern examples, Iverson & Person (2012) mention that higher rates of erosion can be expected in tectonically active areas, such as the Alps and the Himalayas.

In the northern part of Denmark, deep Cenozoic erosion has removed a considerable amount of sediment (Japsen & Bidstrup, 1999). The Quaternary succession rests directly upon Maastrichtian Chalk and the oldest Quaternary sediments consist of Late Saalian tills (Larsen et al. 2009). According to results from basin modelling, Japsen & Bidstrup (1999) found that, during the Quaternary, the amount of erosion in Denmark varied from 100 meters in the southwestern part to more than 200 meters in the north-north-eastern part. Probably, erosion in the north was mostly related to the Norwegian Channel Ice Stream (Sejrup et al. 2003).

Although on the high side, the erosion estimated by Japsen & Bidstrup (1999) are of the same order of magnitude as the erosion estimated by Bell & Laine (1985) and Hay et al. (1989).

The general erosion rates mentioned above will probably not remove sediments to great depths over large areas, even under several glacial cycles. However, it is important to note that the estimates do not take local erosion into account. In addition, the rate of erosion depends on whether the substrate is made of bedrock or unlithified sediment. In this light, the following two sections focus on localised erosion connected to subglacial meltwater erosion and glaciotectonic deformation, as described in published examples from Denmark.

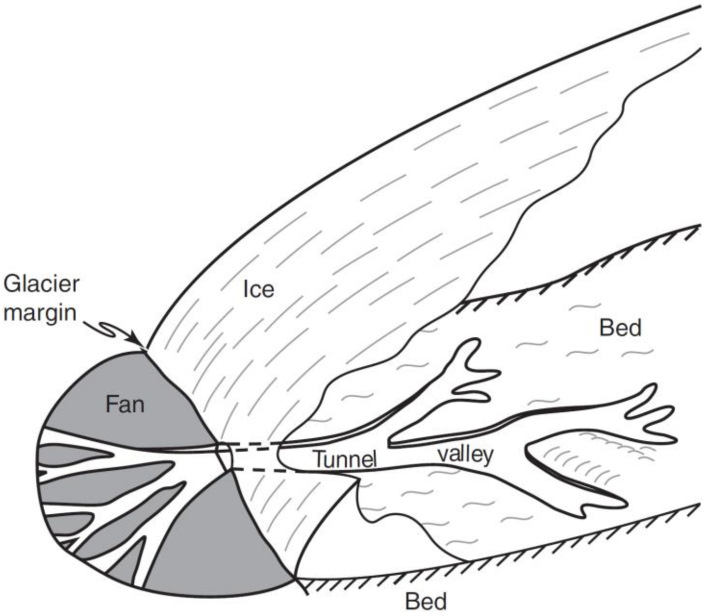


Figure 2.6. *Sketch of a tunnel valley at the ice/bed interface close to the glacier margin. From Hooke & Jennings (2006).*

Figur 2.6. *Skitse af en tunneldal ved grænsefladen mellem is og underlag tæt ved isranden. Fra Hooke & Jennings (2006).*

2.3.2 Subglacial meltwater erosion – tunnel valleys

Subglacial hydrology is an important part of the ice-sheet drainage system (Piotrowski et al. 2009). Meltwater under high pressure at the ice/bed interface has the ability to erode channels or valleys (tunnel valleys) deep into the substrata (Benn & Evans 2010); Figure 2.6. Tunnel valleys are known from the areas formerly covered by Pleistocene glaciers in the northern Hemisphere, and especially in northern Europe mapping has revealed a very high density of tunnel valleys (van der Vegt et al. 2012).

Figure 2.7. *Mapped buried valleys in Denmark shown with dark-grey polygons. The light grey colour indicates areas mapped using the Transient ElectroMagnetic method (TEM). Modified from Sandersen & Jørgensen (2017).*

Figur 2.7. *Kortlagte begravede dale i Danmark vist med mørkegrå polygoner. De lysegrå arealer viser områder, der er kortlagt med den Transient ElektroMagnetiske metode (TEM). Modificeret efter Sandersen & Jørgensen (2017).*

In Denmark in particular, more than 20 years of mapping has shown a very high number of buried valleys and with a cumulated length of 5600 km; see Figure 2.7 (Sandersen & Jørgensen 2016). With a few exceptions, all valleys are interpreted as tunnel valleys because they share the characteristics of the Late Weichselian open tunnel valleys in the Danish landscape (Jørgensen & Sandersen 2006). The tunnel valleys have been mapped using a combination of geological and geophysical data; see Figure 2.7, Figure 2.8 and Figure 2.9.

The typical width of the buried valleys is 500-1500 m, but valleys of up to 3500 meters wide have been found. The depth varies between 25 and 400 m, and, in some cases, their length exceeds 25-30 km (Sandersen & Jørgensen 2017).

The tunnel valleys have been eroded by high-pressure meltwater underneath the margin of the ice sheets; the meltwater flows in narrow channels that gradually erode the full width of the valley. The eroded valley becomes filled with ice, and when the ice retreats the valley is filled with sediments (Jørgensen & Sandersen 2006). Investigations in northern Denmark show that tunnel valleys about 1 km wide and 100-200 meters deep can be created and infilled with sediment within just a few hundred years (Sandersen et al. 2009).

Incised valleys reaching deep into the Miocene and Palaeogene successions are shown in Figure 2.8 where large impact on the subsurface architecture is obvious. The cross-section in Figure 2.9 also shows a tunnel valley incised deeply into Miocene sediments.

Although the valley depths in many cases can be difficult to interpret from available data (Sandersen & Jørgensen 2016), it is reasonable to believe that only very few valleys with depths of more than 400 meters can be found in Denmark.

The mapped buried valleys have regional differences in dominant valley orientations (Figure 2.10). Even though the valleys represent different generations separated in time, the data show geographic patterns that indicate reuse of older valley traces. If the valley infill is coarser than the surroundings and thereby have a higher hydraulic conductivity, most likely, the valley will be reused for drainage of subglacial meltwater during a subsequent ice advance (Sandersen & Jørgensen 2012). Extensive reuse of buried valleys is a very common phenomenon in Denmark as seen by, for example, occurrences of interglacial fresh or marine valley infill (Jørgensen & Sandersen 2006). Alternatively, new valleys can be eroded if clay-dominated layers beneath the ice impede subglacial drainage. The presence of permafrost may render a coarse-grained layer impermeable, and as is the case with clay-dominated substrata, it could promote high subglacial-meltwater pressures and channel incision (Sandersen & Jørgensen 2012).

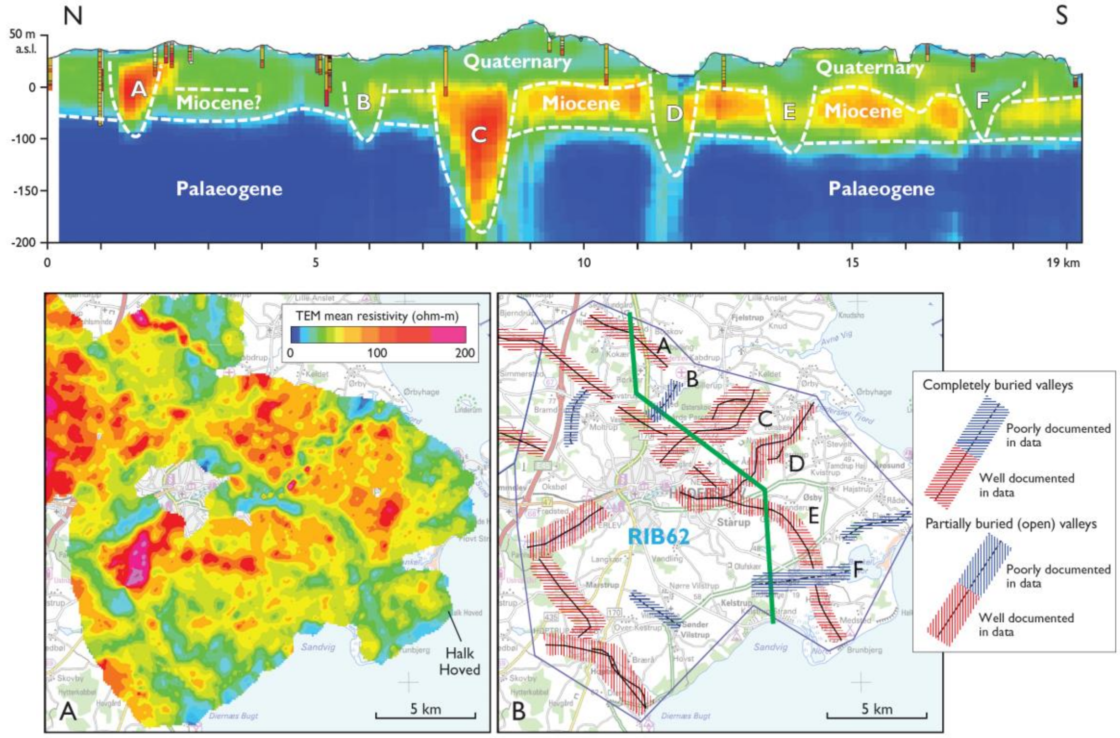


Figure 2.8. *Haderslev survey area. A: SkyTEM resistivity data (30–35 mbsl.). B: Same map window without TEM data but with interpreted buried valleys shown as hatched polygons. Green line shows location of cross-section above. Buried valleys marked A to F represent the valleys shown in the cross-section. Modified from Sandersen & Jørgensen (2017).*

Figur 2.8. *Haderslev kortlægningsområde. A: SkyTEM resistivitetsdata fra koteintervallet -30 til -35 meter. B: Samme kort uden TEM-data, men med tolkede begravede dale, der er vist som skraverede polygoner. Den grønne linje viser placeringen af profilsnittet øverst på figuren, og de begravede dale markeret A til F er også markeret på profilet. Modificeret efter Sandersen & Jørgensen (2017).*

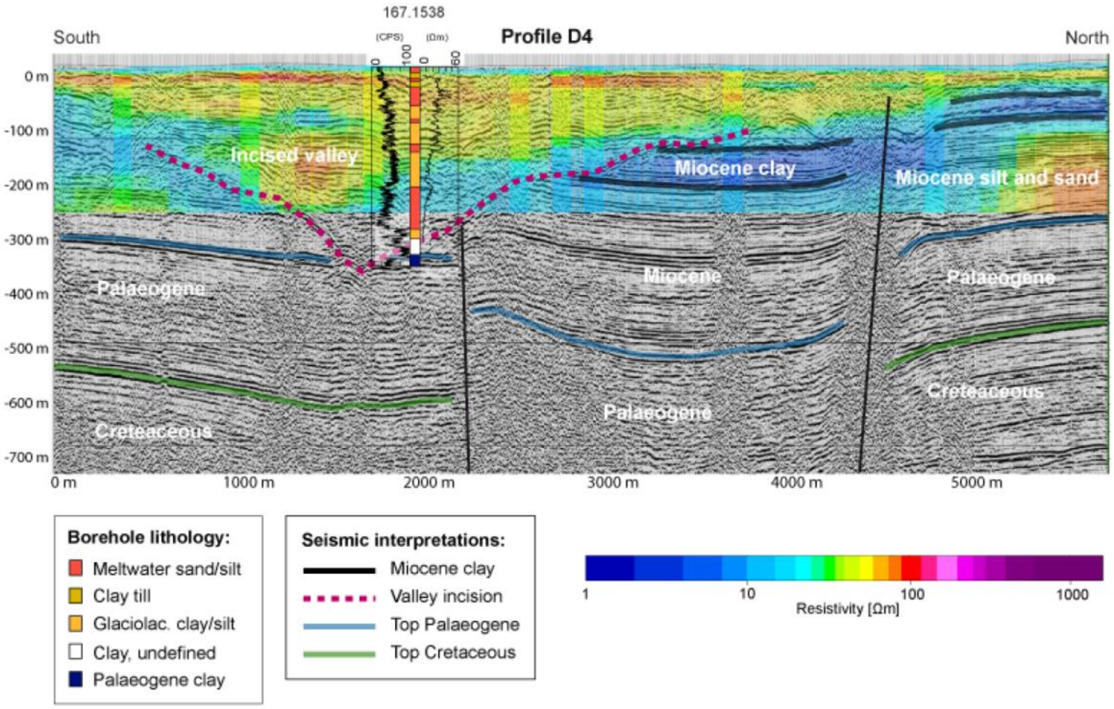


Figure 2.9. *A deep buried tunnel valley at Tønder, southwestern Denmark: The incised valley is shown on a seismic section with SkyTEM resistivity data superposed as coloured shading in the uppermost 250 meters. Modified from Jørgensen et al. (2012).*

Figur 2.9. *En dyb, begravet dal ved Tønder, Sønderjylland: Dalen er vist på en seismisk linje med SkyTEM resistivitetsdata lagt henover med transparente farver i de øverste 250 meter. Modificeret efter Jørgensen et al. (2012).*

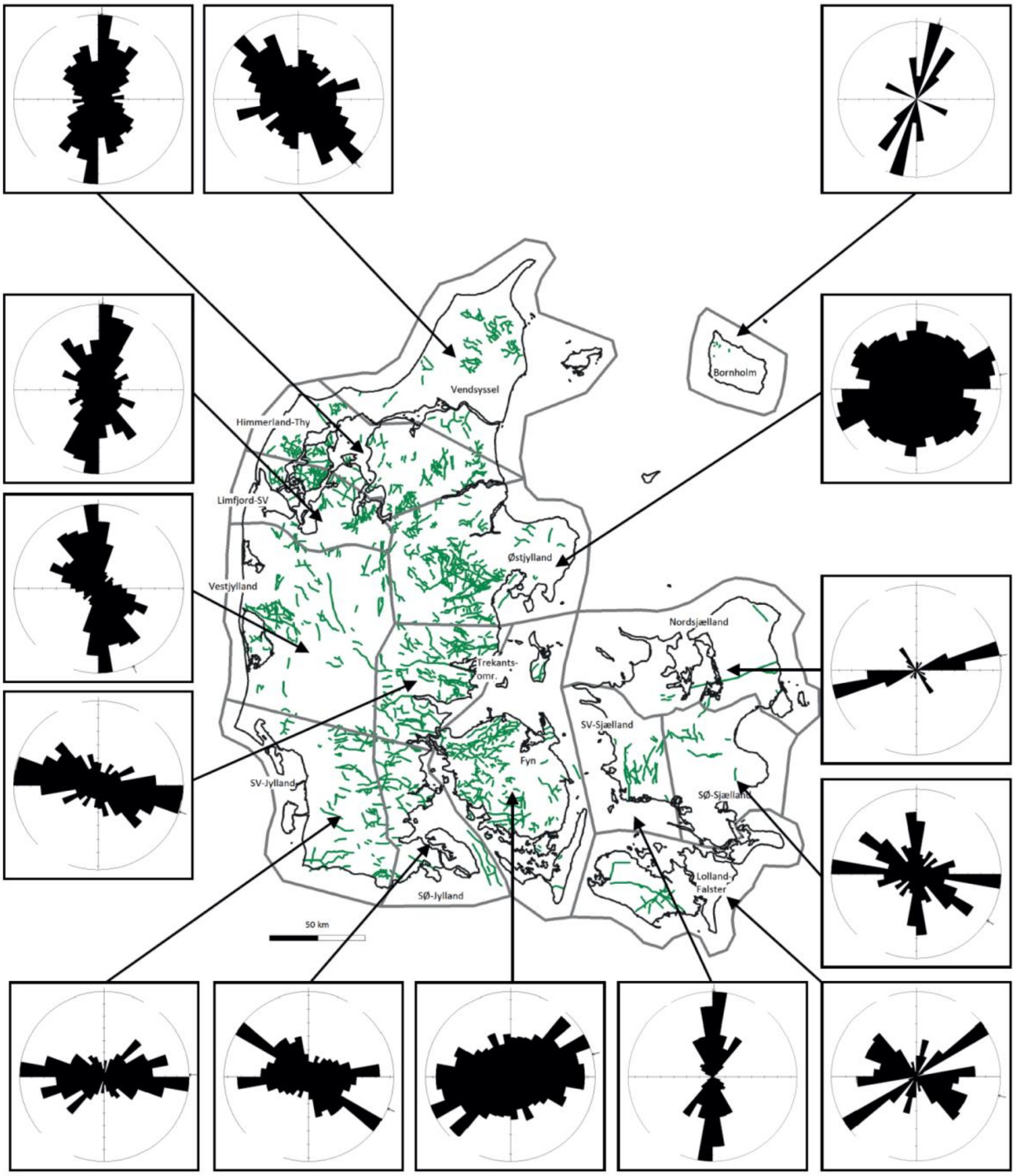


Figure 2.10. *Orientations of buried valleys in selected areas of Denmark. Rose diagrams show total length of valleys within 10-degree intervals. Modified from Sandersen & Jørgensen (2016).*

Figur 2.10. *Orienteringer af begravede dale i udvalgte områder af Danmark. Roset-diagrammer viser den totale længde af dale indenfor 10-graders intervaller. Modificeret efter Sandersen & Jørgensen (2016).*

2.3.3 Glaciotectonic deformation

Glaciotectonic deformation may take place in front of the glacier, beneath the ice margin or even under the centre of a thick ice sheet. Deformations of the subsurface can happen when the ice sheet is advancing, at its maximum, or during recessional phases (Aber & Ber 2007). Factors determining the degree of glaciotectonic deformation are mainly the weight and movement of the ice, the character of the subsurface (lithology, degree of consolidation, presence of permafrost etc.) and pore water pressures near the ice margin (e.g. Iverson & Person 2012; Aber & Ber 2007). According to Iverson & Person (2012), the deformation depth is usually in the range of a few tens of meters but, locally, it can be as deep as 300 meters.

The uppermost few hundred meters of the Danish subsurface are dominated by unconsolidated Quaternary and Tertiary sands and clays underlain by layers of limestone and chalk; compared to bedrock with a thin cover of loose sediments, this setting is generally more susceptible to glaciotectonic deformation. Glaciotectonic complexes can be observed as disturbed sedimentary sequences in outcrops and in subsurface data, and as topographic features consisting of ridges and hills. In Denmark, glaciotectonic complexes can be found both on- and offshore.

Most of the known glaciotectonic complexes in Denmark were formed during the ice advances of the Saalian and Weichselian glaciations. Glaciotectonic complexes formed during the Weichselian glaciation are found north and east of the Main Stationary Line (MSL), and Saalian glaciotectonic complexes are found south of the MSL; see Figure 2.3 (Aber and Ber 2007; Houmark-Nielsen 2011). Older glaciotectonic complexes are only known from superimposed deformations or from successions of deformed Quaternary sediments (Ehlers 1983; Pedersen & Boldreel 2016).

Glaciotectonic complexes are exposed in coastal cliffs at several locations in Denmark, but usually the basal part of the thrust-fault complexes cannot be seen in outcrops (see Figure 2.11). The glaciotectonic complexes consist of a deformed zone above the more or less horizontal basal detachment zone – the décollement surface (see Figure 2.12). The deformed zone is a complex succession of folded, faulted and thrusted sediments that thereby contain information about the deformation history and the ice sheet dynamics (Phillips et al. 2011). The thickness of glaciotectonic complexes in Denmark range from a few tens of meters to some hundreds of meters. The largest glaciotectonic complex yet mapped in Denmark is the Jammerbugt Glaciotectonic Complex which has a décollement zone more than 400 meters below sea level (Figure 2.13). The Jammerbugt Glaciotectonic Complex was formed during the Saalian glaciation and occupies an area of more than 300 km^2 offshore Jylland. The deformed sediments include the main part of the Cretaceous Chalk Group in the North Sea (Pedersen & Boldreel 2016).

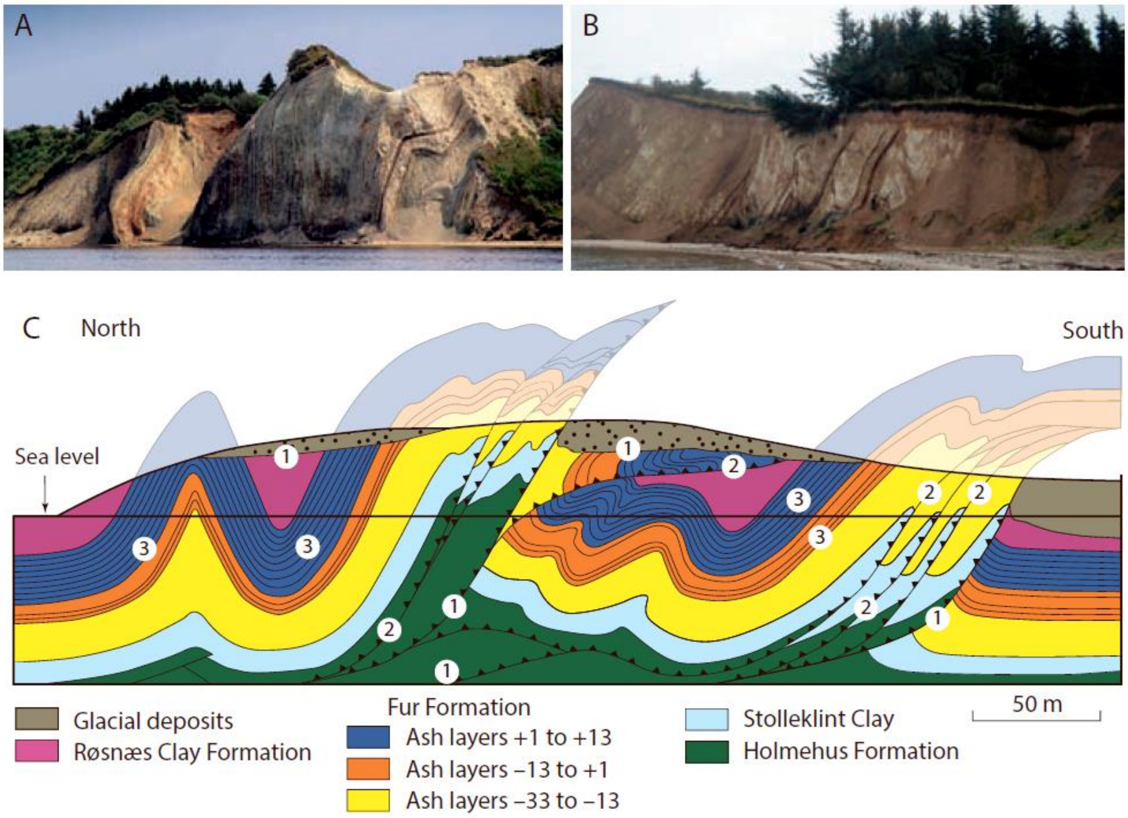


Figure 2.11. *The Fur Knudeklint Glaciotectonic Complex. The Norwegian Ice Advance in the Late Weichselian deformed the Palaeogene clay formations. A and B: Photos from the cliff section: An anticline, a syncline, steeply dipping layers and imbricate duplexes. C: Schematic section. From Pedersen & Boldreel (2015). For further explanation, see Pedersen & Boldreel (2015).*

Figur 2.11. *Fur Knudeklint glacialtektoniske kompleks. Det norske isfremstød i Sen Weichsel deformerede de palæogene formationer. A og B: Fotos fra kystklinten: En antiklinal, en synklinal, stejlt hældende lag samt imbrikerede duplekser. C: Skematisk profilsnit. Fra Pedersen & Boldreel (2015). For yderligere forklaring, se Pedersen & Boldreel (2015).*

Onshore, several examples of glaciotectonic deformations have been described. In the southern part of Denmark, a large glaciotectonic complex near Tønder have deformation depths reaching 100 to 200 meters below sea level (Figure 2.14). Further to the north, a major cupola-hill-type thrust complex generated by ice-marginal glaciotectonism has been described at Ølgod (Høyer et al. 2013). Here, the deformation reaches down at least 150 meters and palaeo-glaciological calculations suggest that the Saalian ice sheet responsible for the thrusting was thick and had a steep profile. The study also showed that the ice sheet advanced slowly, which is in contrast to the thin and highly mobile ice lobes of the Last Glaciation (Høyer et al. 2013). Pedersen & Boldreel (2015) found similarities between the Jammerbugt Glaciotectonic Complex (Figure 2.13) and the ‘classic’ Danish example of a glaciotectonically disturbed sequence at Møns Klint (Figure 2.15); these similarities concerned both the architecture and the age of the deformed sediments.

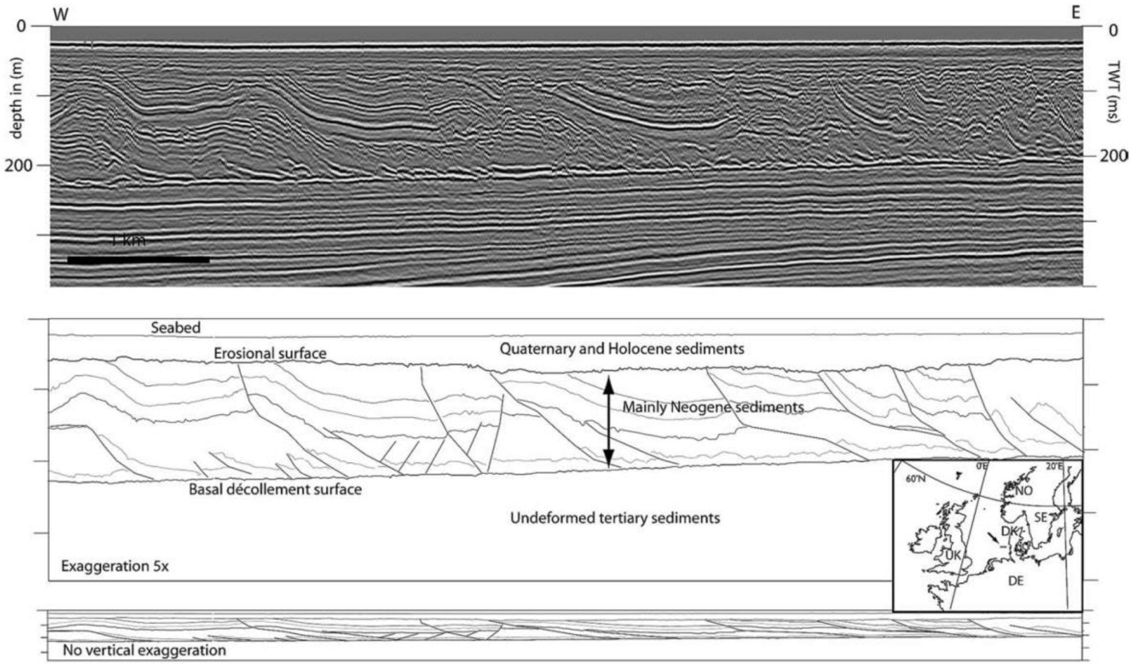


Figure 2.12. *High-resolution seismic line FL01-05 from the offshore Fanø Bugt Glaciotectonic Thrust Complex. The seismic section reveals a series of thrust sheets detaching at a weakly inclined basal décollement surface. From Andersen et al. (2005).*

Figur 2.12. *Høj-opløselig seismisk linje FL01-05 fra det glacialtektoniske kompleks i Fanø Bugt. Den seismiske profil viser en serie af overskydninger, som er afkoblet fra de underliggende aflejringer langs en svagt hældende décollement-flade. Fra Andersen et al. (2005).*

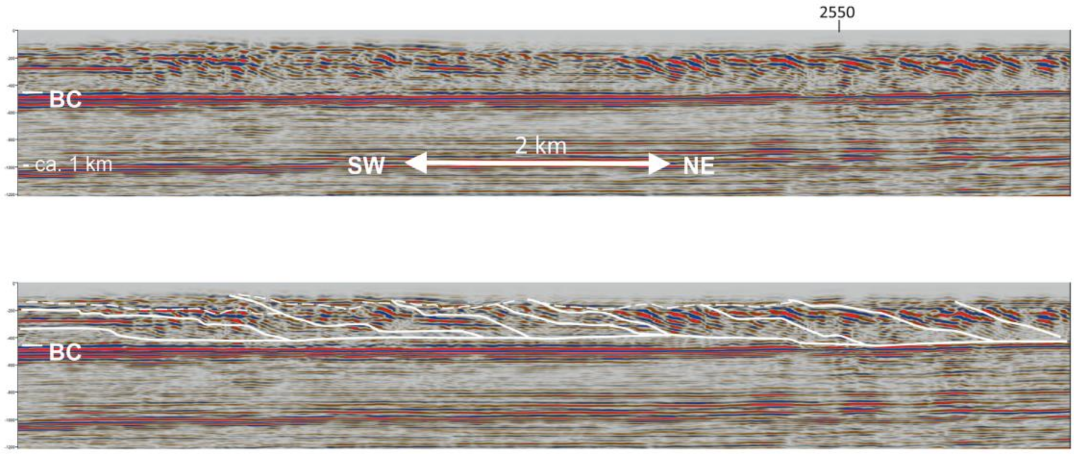


Figure 2.13. *The Jammerbugt Glaciotectonic Complex. A seismic cross-section through the central zone of the complex. White lines in the lower panel outline the thrust faults. The décollement surface drops down from just above to a level below the base of the Chalk Group (BC). From Pedersen & Boldreel (2016).*

Figur 2.13. *Det glacialtektoniske kompleks i Jammerbugten. Et seismisk profilsnit gennem kompleksets centrale zone. Hvide streger i det nederste figurpanel viser overskydningerne. Décollement-fladen dykker fra et niveau lige over til et niveau under Basis Kalkgruppen (BC). Fra Pedersen & Boldreel (2016).*

Glaciotectonic complexes consist of stacked or folded sequences of sediments, and often a hill of stacked sediments lies just down-ice from the hole that the material was removed from. A ‘hill-hole pair’ such as this represents a basic combination of an ice-scooped basin and an ice-shoved hill. For the youngest hill-hole pairs, the volume of the depression should ideally match the volume of the hill, but as depressions can be partly filled with younger sediment, it may be difficult to get a perfect fit (Aber & Ber 2007). An example of a young hill-hole pair is at Hundborg in Thy; here the ‘Hundborg Arch’ constitutes the hill consisting of ice-pushed sediment and Sjørring lake to the north constitutes the source depression for the hill; Figure 2.16 (see Aber & Ber 2007). For older hill-hole pairs, identifying the hole associated with the glaciotectonic complex can be difficult.

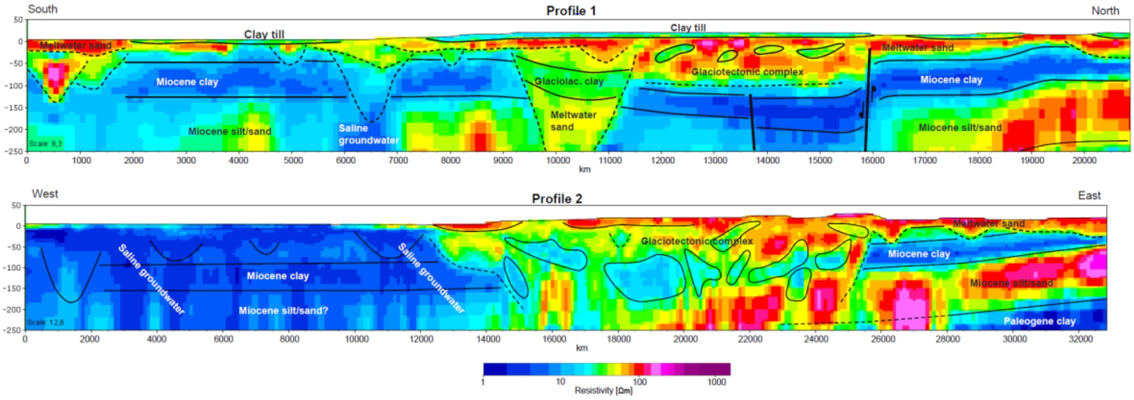


__Figure 2.14.__ Glaciotectonic complex near Tønder in south-western Denmark. The profiles represent cross sections through a SkyTEM 3D resistivity grid. Glaciotectonically deformed areas is seen in central parts of the profiles. From Jørgensen et al. (2012).

__Figur 2.14.__ Glacialtektonisk kompleks ved Tønder, Sønderjylland. Profilerne repræsenterer vertikale snit gennem et 3D SkyTEM resistivitets-grid. Glacialtektonisk deformerede områder ses i de centrale dele af profilerne. Fra Jørgensen et al. (2012).

The general intensity of glaciotectonic onshore deformation in Denmark has been analysed using borehole data showing signs of disturbed sedimentary successions (Figure 2.17; Jakobsen, 1996). Figure 2.17 shows the concentration of recorded indications of glaciotectonic deformation. Despite the rough scale used, there is generally a good agreement between observations from exposures and the terrain morphology. Accordingly, glaciotectonic sequences or complexes can be expected to be present in most parts of Denmark, but the spacing and the degree of associated deformation vary a lot.

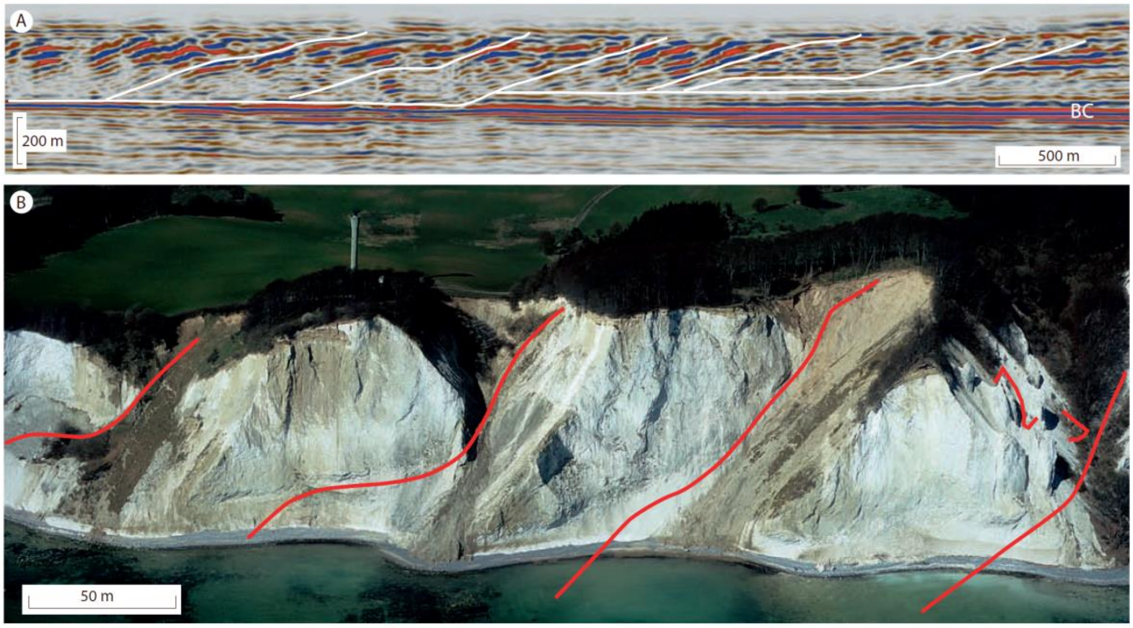


__Figure 2.15.__ A comparison of thrust-fault architecture in two glaciotectonic complexes: A: Seismic section from the Jammerbugt Glaciotectonic Complex. See also Figure 2.13. B: The Møns Klint Glaciotectonic Complex. From Pedersen & Boldreel (2015).

__Figur 2.15.__ En sammenligning af arkitekturen i overskydninger mellem to glacialtektoniske komplekser: A: En seismisk linje fra det glacialtektoniske kompleks i Jammerbugten. Se også figur 2.13. B: Det glacialtektoniske kompleks ved Møns Klint. (Pedersen & Boldreel (2015).

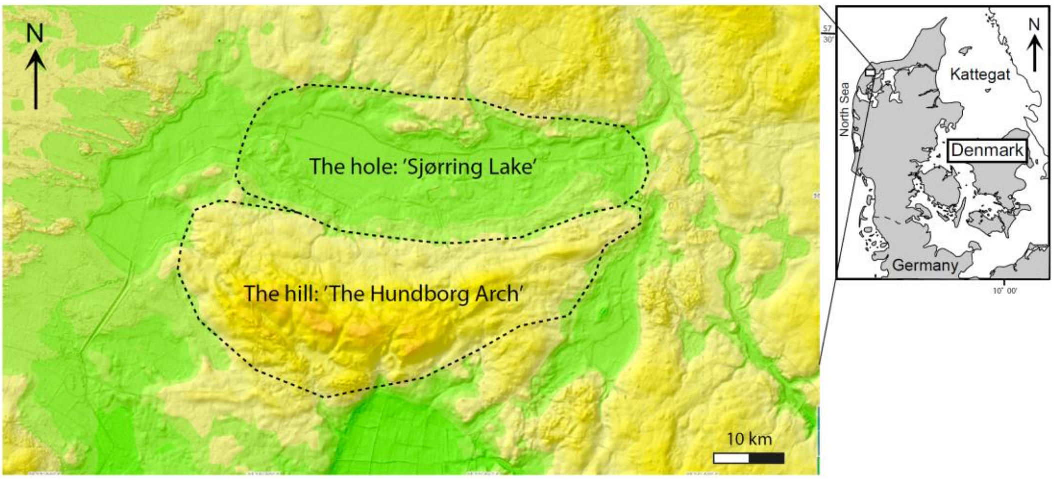


__Figure 2.16.__ A hill-hole pair: 'Hundborg Arch' and Sjørring Lake. The ice-movement direction was from north to south. The highest elevations are shown in orange (up to c. 70 meters above sea level (masl)) and the lowest in green colours (down to c. 10 masl.). Map from www.kortforsyningen.dk.

__Figur 2.16.__ Randmorænebakke og inderlavning. 'Hundborg-buen' og Sjørring Sø. Isbevægelsesretningen har været fra nord mod syd. De højest liggende dele af landskabet er vist med orange farve (ca. 70 meter over havniveau (m.o.h.) og de lavest liggende er vist med grønt (ned til ca. 10 m.o.h.). Kort fra kortforsyningen.dk.

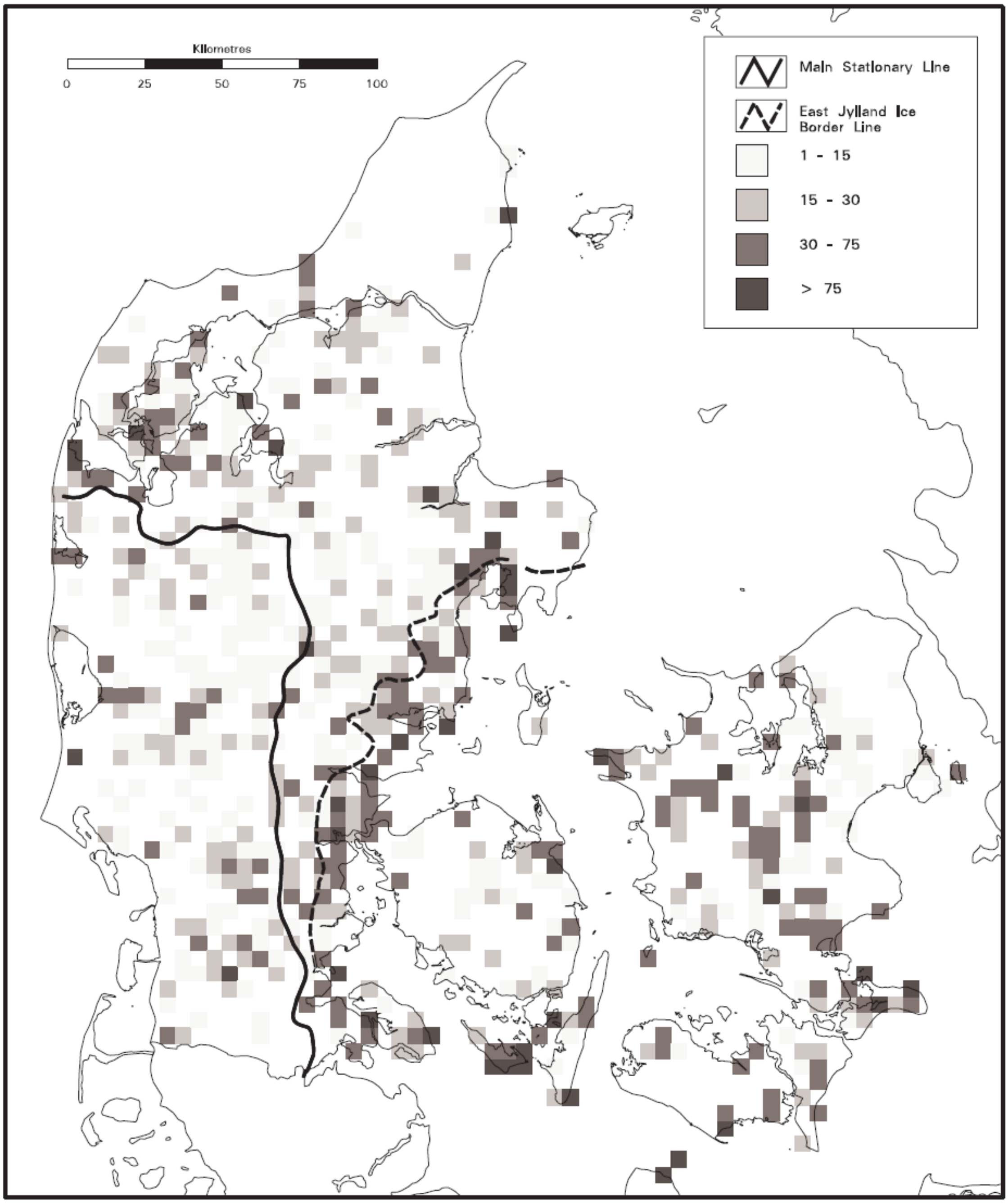


Figure 2.17. *Grid map displaying the intensity of glaciotectonic deformation recorded in wells. Each grid cell is 5x5 km. The density in each grid cell is shown as the number of wells with recorded deformation in per thousand of the total number of wells. From Jakobsen (1996).*

Figur 2.17. *Intensitet af glacialtektonisk deformation tolket ud fra boredata. Kortet viser gridceller på 5x5 km. Tætheden af observationer er angivet som antallet af boringer med beskrevne deformationer i promille af det totale antal boringer. Fra Jakobsen (1996).*

2.3.4 Impacts on groundwater during a glacial cycle

Groundwater hydrology related to the glacial environment is influenced by factors such as meltwater production, glacier thermal regimes, overburden ice pressure, bed lithology and permafrost (Ravier & Buoncristiani 2018). The impact on groundwater flow, hydraulic head, hydraulic properties of the substrata, groundwater penetration depths, and subglacial porewater pressure is large. Meltwater is produced supraglacially at the surface of the ice and subglacially at the ice/bed interface. Most of the supraglacial meltwater will find its way down into the ice and, via conduits and fractures/crevasses in the otherwise impermeable ice, continue down to the subglacial regime (Benn & Evans 2010).

The subglacial meltwater pressure is largely governed by the thickness and slope of the ice, and during glaciations the hydraulic head would attain levels many times higher than under non-glacial conditions (Ravier & Buoncristiani 2018). The pressure and distribution of meltwater at the ice/bed interface has great impact on the movement of ice sheets. Basal sliding, for instance, is not possible without water at the sole of the ice (Benn & Evans 2010), and high subglacial water pressures can facilitate both glaciotectonic deformation and subglacial erosion (see preceding sections).

The groundwater system in a glacial environment is complex and it is outside the scope of this chapter to go into detail. In relation to a geological repository, the most important factor directly related to the hydraulic conditions underneath an ice sheet is the change to the pre-glacial hydrological system and the circulation depth of the meltwater. Investigations in Europe and North America point to meltwater penetration depths of up to 1000 m during the Pleistocene glaciations (McIntosh et al. 2012). For the North German Basin, however, the maximum penetration depth was up to around 300 meters. For comparison, the results of the Greenland Analogue Project showed a penetration depth of glacial meltwater at the investigated site of at least 500 meters (Liljedahl et al. 2016). In relation to a nuclear waste repository, Ravier & Buoncristiani (2018) mention that the generally high content of dissolved oxygen in the glacial groundwater may potentially increase the solubility and mobility of radionuclides.

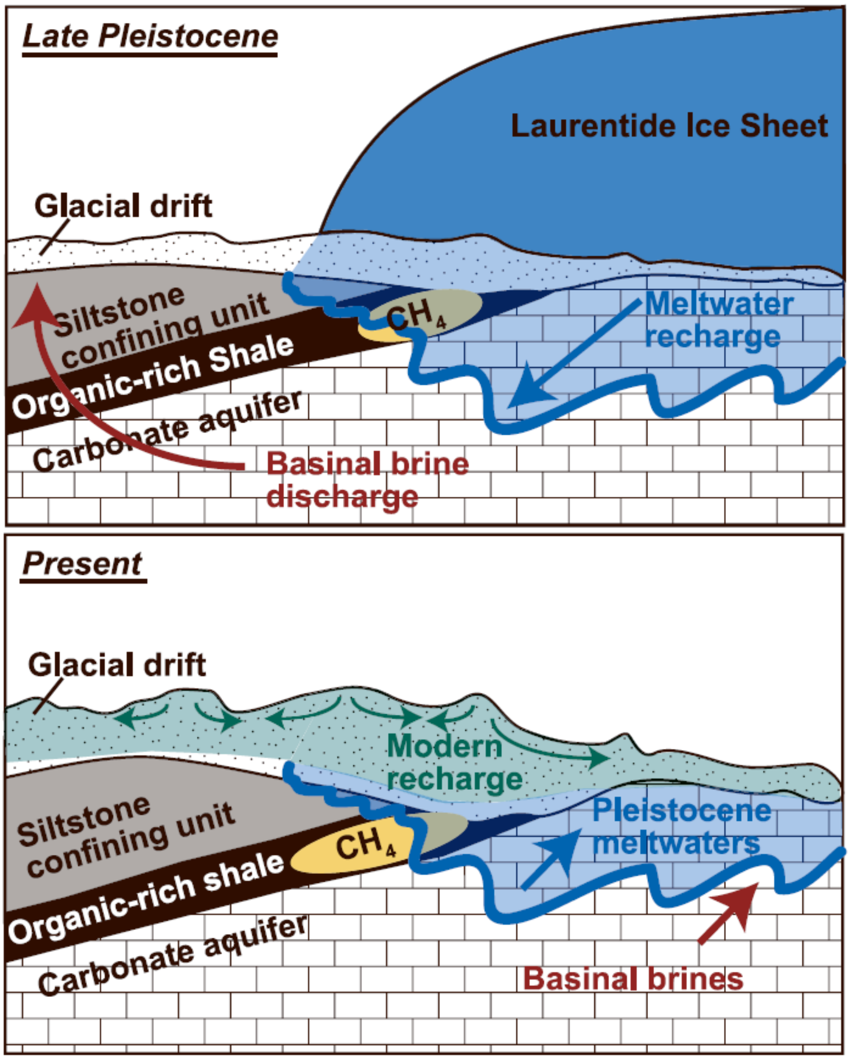


Figure 2.18. *Conceptual model of hydrology for the northern Michigan Basin, North America – comparing Late Pleistocene hydrology with the modern hydrology. During the glaciations, meltwater from the ice sheet recharged the aquifers, flushing basinal brines at depth. From McIntosh et al. (2011).*

Figur 2.18. *Konceptuel model for Sen Pleistocæn versus nutidig hydrologi for det nordlige Michigan Basin, Nordamerika. Smeltevandet fra iskappen forårsagede grundvandsdannelse til grundvandsmagasinerne under istiderne og fortrængte derved dybt saltholdigt grundvand. Fra McIntosh et al. (2011).*

Glaciation causes a shift from catchment-scale and topographically driven recharge to glacially driven recharge on a much larger scale, as illustrated in Figure 2.18 (Ravier & Buoncristiani 2018). The Laurentide Ice Sheet caused freshwater infiltration and displacement of saline fluids to great depths underneath the ice. The modern recharge would not have the ability to recharge deep aquifers the same way.

During glaciations, the infiltration rate is strongly increased; compared to present-day conditions, the infiltration rate is up to 10 times higher. However, the presence of permafrost can stop or impede groundwater recharge (Persson et al. 2012). During glaciations, permafrost can attain thicknesses of several hundred meters and cover large areas underneath the margin of the ice sheet and in front of the ice. In the Greenland Analogue Project permafrost has been found in boreholes at a depth of 350-400 meters (Liljedahl et al. 2016). Permafrost will change the recharge and discharge patterns and, thereby, influence the regional groundwater flow (Ravier & Buoncristiani 2018).

The pre-Quaternary sediments in Denmark range from predominantly Cretaceous chalk in the north and east to Miocene sand and clay in the west and southwest (Figure 2.19-A). On top of this rests a Quaternary succession dominated by sand and clay (Figure 2.19-B). These sediments will constitute the substrata when the first future ice sheet enters the Danish area.

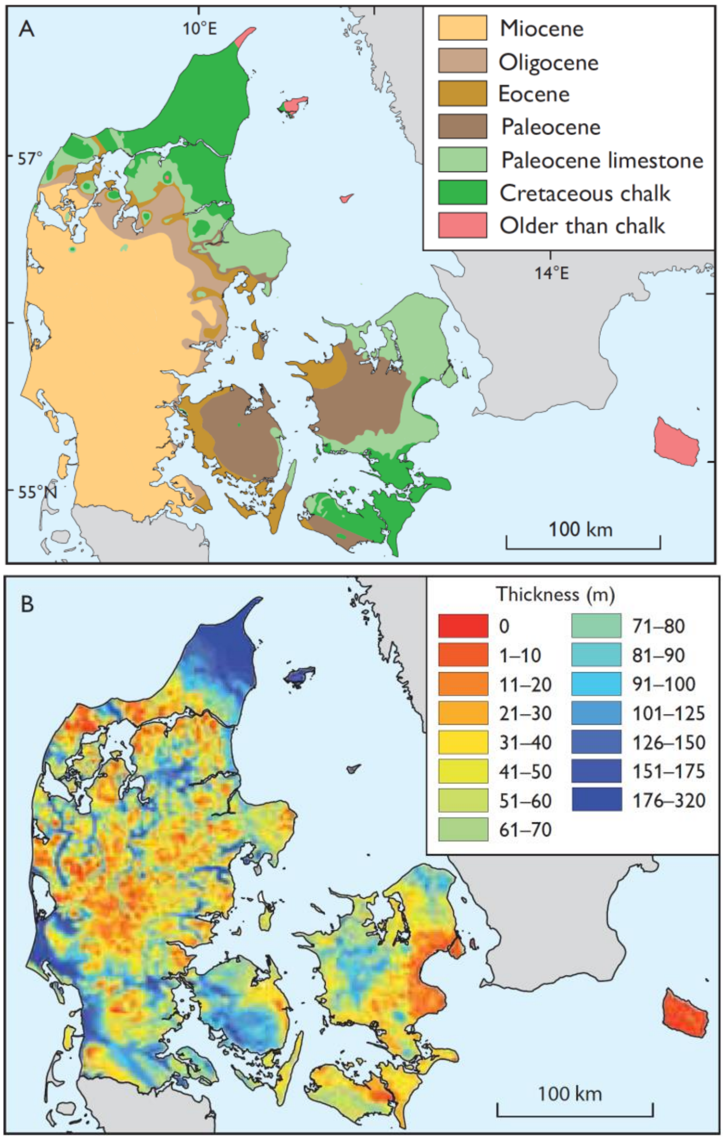


Figure 2.19. *Maps showing (A) The pre-Quaternary geology and (B) thickness of Quaternary sediments in Denmark. From Vangkilde-Pedersen et al. (2012).*

Figur 2.19. *Kort over (A) Den prækvartære geologi og (B) tykkelsen af de kvartære sedimenter i Danmark. Fra Vangkilde-Pedersen et al. (2012).*

Depending on the character and the thickness of both the pre-Quaternary sediments and the Quaternary succession (Figure 2.19-B), the possibilities of subglacial meltwater drainage to deeper levels will vary greatly. Obviously, a combination of highly permeable pre-Quaternary sediments and thin and/or permeable Quaternary sediments above will provide optimal conditions for deep recharge. Conditions for this can be found, for instance, in northern and eastern/southeastern Denmark, where chalk and limestone lie close to the terrain, and in west and southwestern Denmark where thick layers of Miocene sand are found at high elevations with limited Quaternary cover (Figure 2.19). Conversely, deep recharge is less likely to happen where the substrata are dominated by clay, for instance in the central parts of Denmark where the Palaeogene clays are thick. However, there are variations to this overall picture, mainly because of local to regional structures, such as anticlines, salt diapirs and deep Quaternary deformation and erosion.

An example from Denmark where a deep layer of Danian limestone is covered by thick Palaeogene clay and an overlying heterogeneous succession of Quaternary sand and clay is presented in Figure 2.20. A buried tunnel valley is eroded deep down into the Palaeogene clay (centre of cross-section). The generally low electrical resistivities in the limestone (blue colours) points to the occurrence of saline porewater (on the right side of the profile), but underneath the buried valley, high resistivities (red colours) show that saline porewater has been displaced by freshwater (Sandersen et al. 2015). Local occurrences of shallow salt groundwater in topographic lows point to a modern topographically driven system; however, because of the considerable depth at which displacement of saline porewater can be seen (up to 200 m), it is probable that the deep fresh water and brackish water in the limestone are remnants of Pleistocene meltwater recharge. This would be in line with what Ravier & Buoncristiani (2018) finds: that it is likely that the present-day subsurface hydrogeological conditions in former glaciated areas are not yet in equilibrium; thus, to a certain degree, these present-day conditions reflect the hydrological conditions during the latest glaciation. See also Chapter 5 in this report.

An example of a deep buried valley that has eroded through thick layers of Miocene clays, thus exposing deeper aquifers is presented in Figure 2.9.

Figure 2.21 presents an example of a rising salt structure that has created a dome of chalk and limestone and has facilitated erosion of the Palaeogene clays above (Krogsbøll et al. 2012). Throughout the Danish subsurface, salt diapirs and pillows frequently occur; consequently, locally in many areas, deep permeable layers have been lifted to levels very close to the surface.

Figure 2.14 shows a large glaciotectonic complex that has caused deformations of a large part of the Quaternary and pre-Quaternary sequences, including thick layers of marine Miocene clays and, thereby, altered the hydraulic properties of the subsurface.

The examples above show that regional as well as local structures can change the hydraulic framework of the subsurface, creating corridors for deep groundwater recharge and circulation during glaciations.

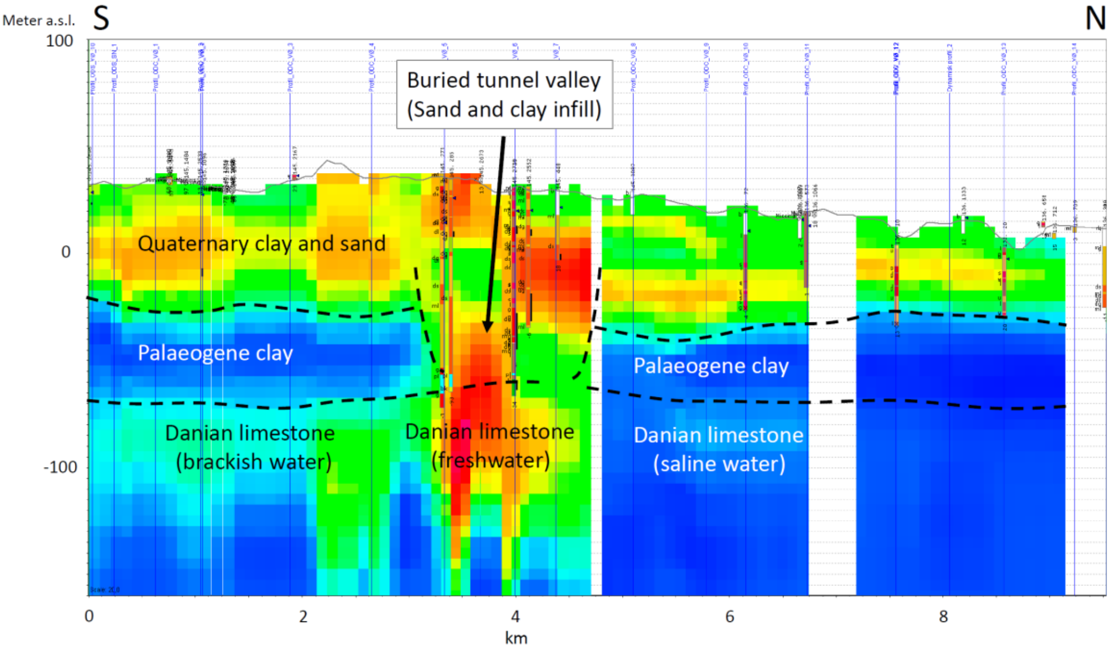


***Figure 2.20**. Deep groundwater recharge of freshwater in Odense, Denmark. A deeply incised tunnel valley facilitates deep recharge and the displacement of saline porewater. Coloured background is a 3D grid of electrical resistivities based on electromagnetic soundings (blue: low resistivity; red: high resistivity). Coloured vertical rods depict borehole data. Modified from Sandersen et al. (2015).*

***Figur 2.20.** Dyb grundvandsdannelse i Odense, Danmark. En dybt nedskåret tunneldal har åbnet for nedadrettet transport af fersk grundvand og dermed fortrængning af dybt, saltholdigt grundvand. Farverne på figuren viser et 3D-grid af elektriske modstande (blå: lav modstand; rød: høj modstand). Lodrette, farvelagte stave udgør boredata. Modificeret efter Sandersen et al. (2015).*

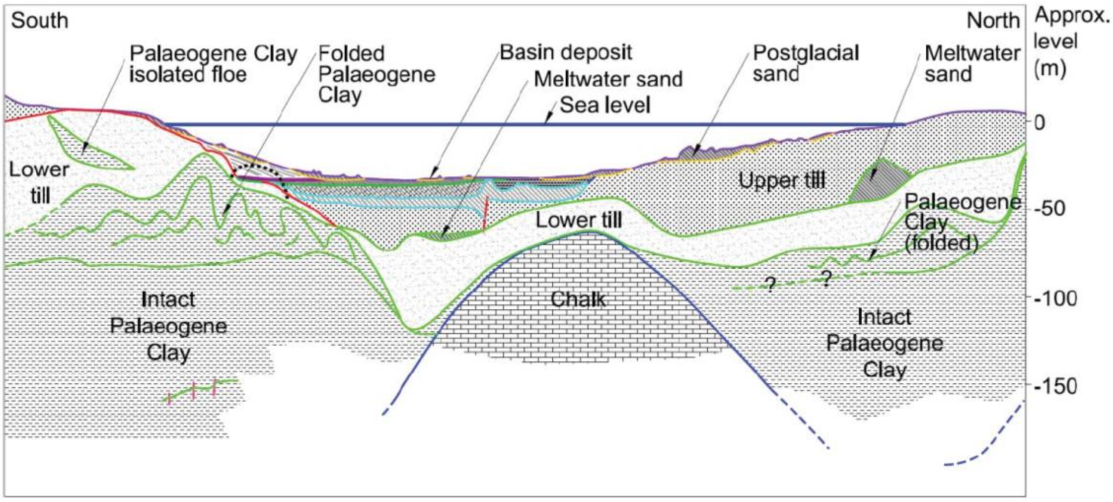


***Figure 2.21.** Geological profile across Fehmarn Belt. From Krogsbøll et al. (2012).*

***Figur 2.21.** Geologisk tværsnit af Fehmarn Bælt. Fra Krogsbøll et al. (2012).*

2.3.5 Glacially induced reactivation of faults

The weight of the ice sheets during the Pleistocene glaciations not only caused vertical depression of the subsurface, but also horizontal movement of mass in the upper mantle away from the ice-sheet centre (Stewart et al. 2000). During the deglaciation, the process reversed, resulting in rebound due to the relief from the weight of the ice.

Several spectacular faults disrupting the terrain surface have been observed in northern Scandinavia (e.g. Dehls et al. 2000; Fjeldskaar et al. 2000; Olesen et al. 2013; Ojala et al. 2019). These faults have been interpreted to be the result of reactivation of old fault zones shortly after deglaciation. Since the deglaciation, plate tectonic movements and postglacial rebound forces have dominated the stress regime in Scandinavia (e.g. Fjeldskaar et al. 2000; Gregersen & Voss 2009). However, there has been a shift from domination by glacio-isostatic forces right after the deglaciation to the present-day domination by plate-motion stress (e.g. Gregersen & Voss 2009).

Changes in near-surface stresses caused by the ice load are sketched in Figure 2.22. The amount of crustal depression related to the loading and unloading of the ice sheet is shown in Figure 2.23. Figure 2.23 illustrates the fast, vertical loading of the ice and the delayed rebound after the deglaciation. The most prominent examples of fault reactivation are seen in regions of maximum ice thickness and areas marginal to the ice sheets. The mantle response to the ice mass fluctuations caused considerable crustal deformation, even hundreds of kilometers from the former ice margins (Stewart et al. 2000). According to Neuzil (2012), the weight of the ice and the flexural bending of the lithosphere may increase fluid pressures in geological units unable to drain. A possible consequence of this is changes in the mechanical behaviour of the layers causing seismicity, faults, and fractures.

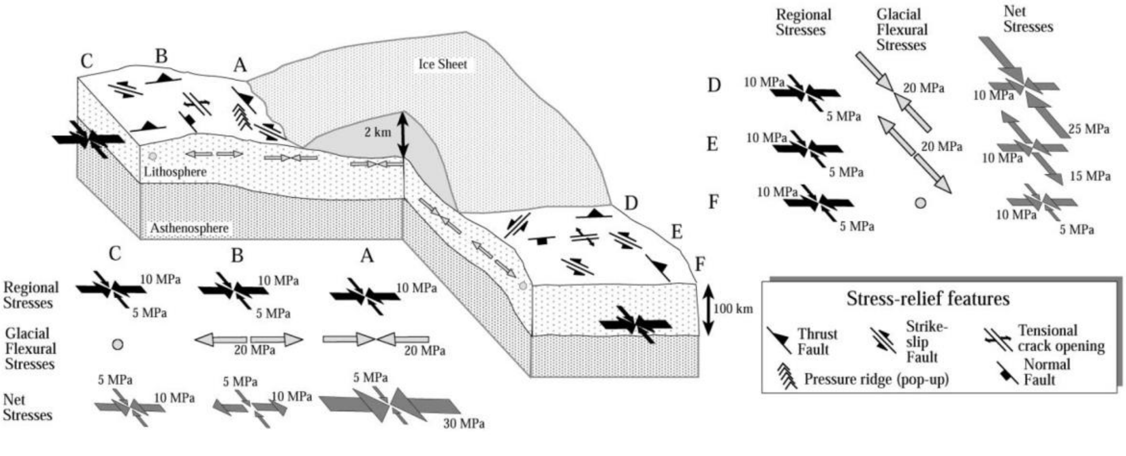


Figure 2.22. *Conceptual model for near-surface postglacial stresses during deglaciation. The exploded block model illustrates how the superimposition of changing glacial flexural stresses (light grey arrows) on a uniform regional tectonic stress field (black arrows) results in contrasting stress states (dark grey) and different styles and orientations of stress-relief phenomena at the ice margin (A and D), the forebulge (B and E) and the undeformed foreland (C and F). From Stewart et al. (2000).*

Figur 2.22. (forrige side). *Konceptuel model af overfladenær postglacial stress i forbindelse med deglaciation. Blokmodellen illustrerer, hvordan det varierende, glacialt inducerede stress (lysegrå pile) overlejrer det ensartede regionale tektoniske stress (sorte pile). Dette skaber kontrasterende stress (mørk grå) og forskellige aflastningsfænomener ved isranden (A og D), i 'for-bølgen' og i det udeformerede forland (C og F). Fra Stewart et al. (2000).*

Lithosphere models for Fennoscandia predict the onset of postglacial faulting to approximately 11-9 ka and maximum instability around 10-7 ka (Wu 1999), whereas numerical simulations and field evidence from the northern part of Denmark point towards Late Weichselian phases of tectonic activity around ~14.5 to 12 ka; Figure 2.24 (Brandes et al. 2018). Apparently, palaeoseismic events took place at different points in time, during and after deglaciation. This has recently been confirmed by investigations of postglacial faults in Finland (Ojala et al. 2019).

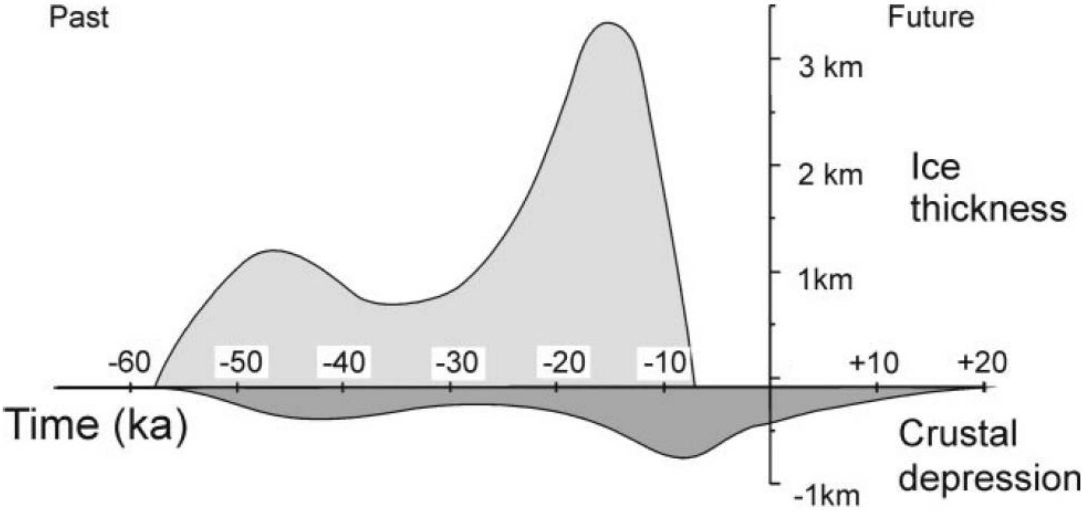


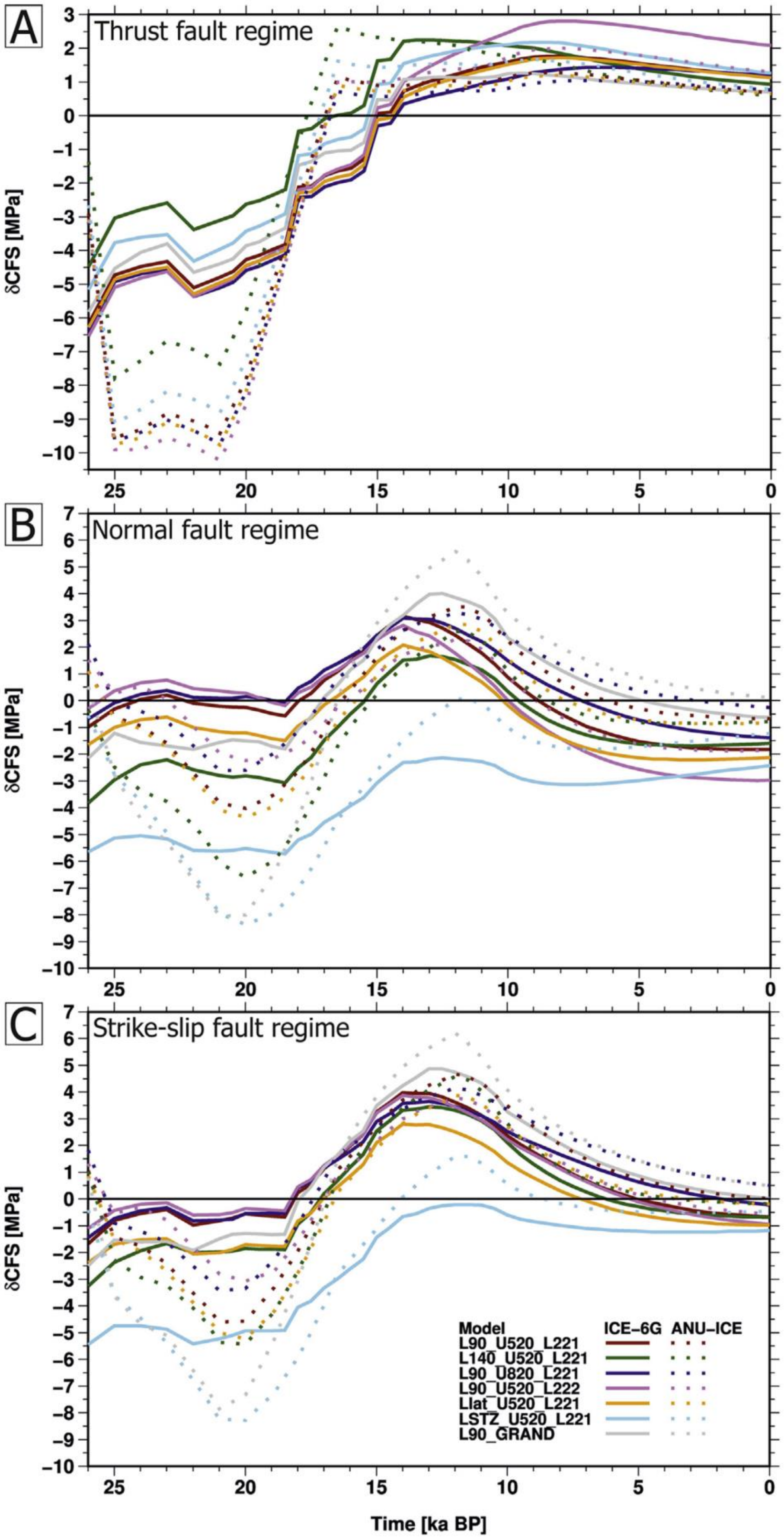
Figure 2.23. *A simplified loading history for Fennoscandia during the Weichselian glaciation. Ice thickness above the x-axis and crustal depression below. From Talbot (1999).*

Figur 2.23. *En simplificeret belastningshistorie for Fennoscandia under Weichsel Istid. Istykkelsen er vist over x-aksen og depressionen af kappen under x-aksen. Fra Talbot (1999).*

FIGURE 2.24, NEXT PAGE:

Figure 2.24. *Lithosphere modelling in northern Denmark. Development of the Coulomb failure stress over the last 26,000 years. The simulation was performed with two different ice history models. The solid lines represent the results for the North-European part of the global ice model ICE-6G_C. The second ice history model (dashed lines) is a combination of the ANU-ICE ice history models for the British Isles and Fennoscandia. From Brandes et al. (2018). See paper for detailed information.*

Figur 2.24. *Litosfæremodellering i den nordlige del af Danmark. Udviklingen af 'Coulomb failure stress' gennem de seneste 26.000 år. Simuleringen blev foretaget med to forskellige iskappe-modeller. De fuldt optrukne linjer repræsenterer resultaterne for den Nordeuropæiske del af den globale ismodel ICE-6G_C og den anden viser med stiplede linjer en kombination af ANU-ICE-modellen for de britiske øer og Fennoskandia. Fra Brandes et al. (2018).*


A
Thrust fault regime
B
Normal fault regime
C
Strike-slip fault regime
δCFS [MPa]
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
7
6
5
4
25
20
15
10
5
0
Time [ka BP]
Model
ICE−6G
ANU−ICE
L90_U520_L221
L140_U520_L221
L90_U820_L221
L90_U520_L222
Llat_U520_L221
LSTZ_U520_L221
L90_GRAND

Denmark is situated in the interior of a plate characterized by a low level of historic seismic activity (Gregersen & Voss, 2009). Large parts of Denmark are covered by thick successions of complex unconsolidated pre-Quaternary and Quaternary sediments. Because of that, glacially induced faults are generally more difficult to find in Denmark, in comparison with northern Scandinavia where the basement lies very close to the terrain. However, in the following paragraphs, two selected descriptions of Late Weichselian and postglacial tectonic events will be briefly presented.

At Nr. Lyngby in northern Denmark, Late Weichselian marine and lacustrine sediments and deformations in an exposed cliff-section have been described (e.g. Jessen and Nordmann 1915; Lykke-Andersen 1979, 1992; Fischer et al. 2013; Brandes et al. 2018). The sediments were clearly faulted and an earthquake between 12,500 and 11,800 years ago was mentioned as the possible trigger (Lykke-Andersen, 1979, 1992). Brandes et al. (2018) have added descriptions of meter-scale normal faults and soft-sediment deformation structures (SSDS) at different levels in the sedimentary sequence, and the tectonic events were placed within an interval from around 14.5 ka to 12 ka. Analyses of high-resolution LiDAR data from around Nr. Lyngby showed that the drainage network that eroded into the near-surface Late Weichselian sediments was dominated by orientations around WNW-ESE/NW-SE, comparable to the orientation of the faults of the Sorgenfrei-Tornquist Zone (STZ); Figure 2.25 (Brandes et al. 2018).

The analysis of the drainage patterns and the observations of the soft-sediment deformations were supported by numerical simulations of deglaciation-related lithospheric stress build-up (Figure 2.24). The deformations in the area were interpreted to be caused by glacially induced faulting along the Børglum Fault, a boundary fault of the STZ. According to Brandes et al. (2018), the SSDS indicated that, most likely, movements were accompanied by earthquakes with magnitudes somewhere between M 4.2 and M~7.

On the Late Weichselian Tinglev outwash plain in southern Jylland, Sandersen & Jørgensen (2015) analysed high-resolution LiDAR data from the gently westward sloping outwash plain. The outwash plain was created in front of the ice when the Late Weichselian ice sheet was residing at the Main Stationary Line 25−18 ka (Houmark-Nielsen 2007). Compared to neighbouring areas, parts of the outwash plain topography showed unexpected irregularities, such as a complicated mosaic of small areas with noticeable changes in slope magnitude and orientation (Figure 2.26). Sandersen & Jørgensen (2015) also found remarkable changes in elevation across kilometre-long lineaments and areas on the outwash plain lying lower and higher than expected.

Earlier interpretations of large depressions on the outwash plain as dead-ice landforms were refuted, because borehole samples from a lake in a 16 meters deep depression showed that sedimentation did not begin until the early Holocene, approximately 9000 years after the ice sheet had retreated (Sandersen & Jørgensen, 2015). The topographical irregularities were located above or at the flank of the deep-seated Tønder Graben structure (Figure 2.26), and the deformations of the outwash plain were interpreted as a result of strike-slip movements along the graben faults. The tectonic event was interpreted to be related to the deglaciation within a short time-interval at the beginning of the Holocene.

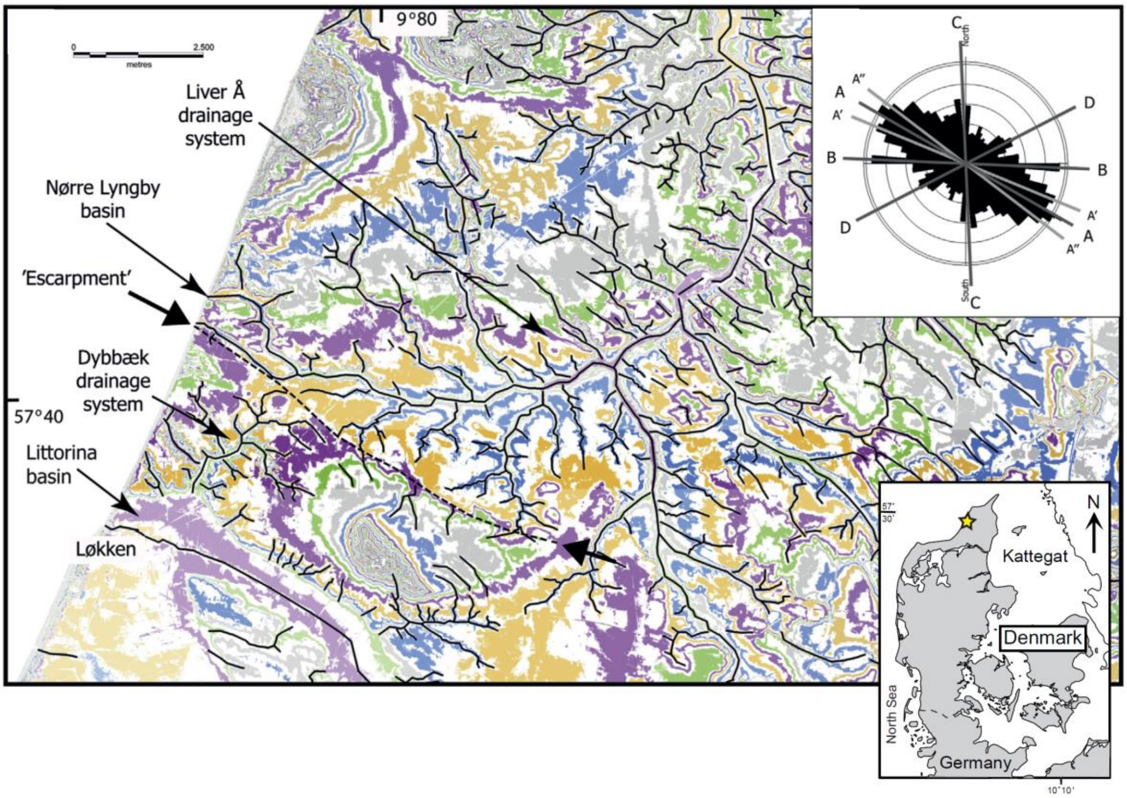


Figure 2.25. *Analysis of drainage network orientation at Nr. Lyngby. For location, see yellow star on the map in the lower right corner. Digital elevation model based on LiDAR data is seen as coloured 1-meter intervals. The terrain elevation ranges from sea level to around 80 masl. Erosional valleys in the topography are digitized as black vectors. A WNW-ESE 'escarpment' of 1-2 meters height is shown as a dotted line highlighted with thick arrows. The rose diagram shows cumulated lengths of vectors plotted as 5-degree rose petals. Highlighted orientations marked with grey lines represent inferred dominant orientations. To the north of the escarpment, the Liver Å (brook) has a drainage in a north-eastern to northern direction and to the south, the Dybbæk (brook) drains in a southwestern direction. Modified from Brandes et al. (2018). See paper for detailed information.*

Figur 2.25. *Analyse af dræneringsmønstre ved Nr. Lyngby. For lokalisering, se kort nederst til højre. Den digitale højdemodel, som er baseret på LiDAR-data, er vist med farvede 1-meter intervaller. Terrænet varierer fra havoverfladen til op omkring 80 m.o.h. Erosionsdale i topografien er digitaliseret med sorte vektorer. Rosetdiagrammet viser de kumulerede længder af vektorerne i 5-graders intervaller. Fremhævede orienteringer, som er vist med grå linjer på rosetdiagrammet, repræsenterer tolkede dominerende orienteringer. En VNV-ØSØ orienteret skrænt på 1-2 meters højde er vist med en stiplet linje og fremhævet med tykke sorte pile. Nord for skrænten drænes området af Liver Å i N-NØ-lig retning, mens Dybbækken syd for afdræner mod SV. Modificeret fra Brandes et al. (2018); se her i for yderligere information.*

In a national study of buried tunnel valleys (see Figure 2.10), Sandersen & Jørgensen (2016) found a close correlation between the orientational data of buried valleys, deep-seated faults, and erosional valleys in the present-day terrain in large parts of Denmark. In Figure 2.27, rose diagrams for these three datasets are shown for two selected regions. The two regions lie next to each other (Figure 2.10) but show very different orientation characteristics. In the Vendsyssel area, the three individual datasets show the same overall NW-SE orientation – an orientation that can also be found in the more detailed data analysis of the Nr. Lyngby sub-area (Figure 2.25). In the Himmerland-Thy area to the south all three datasets show a rather distinct N-S dominance. Thus, in each region all datasets show a similar orientation, but, when comparing the orientations of the two areas, there is a 45-degree difference.

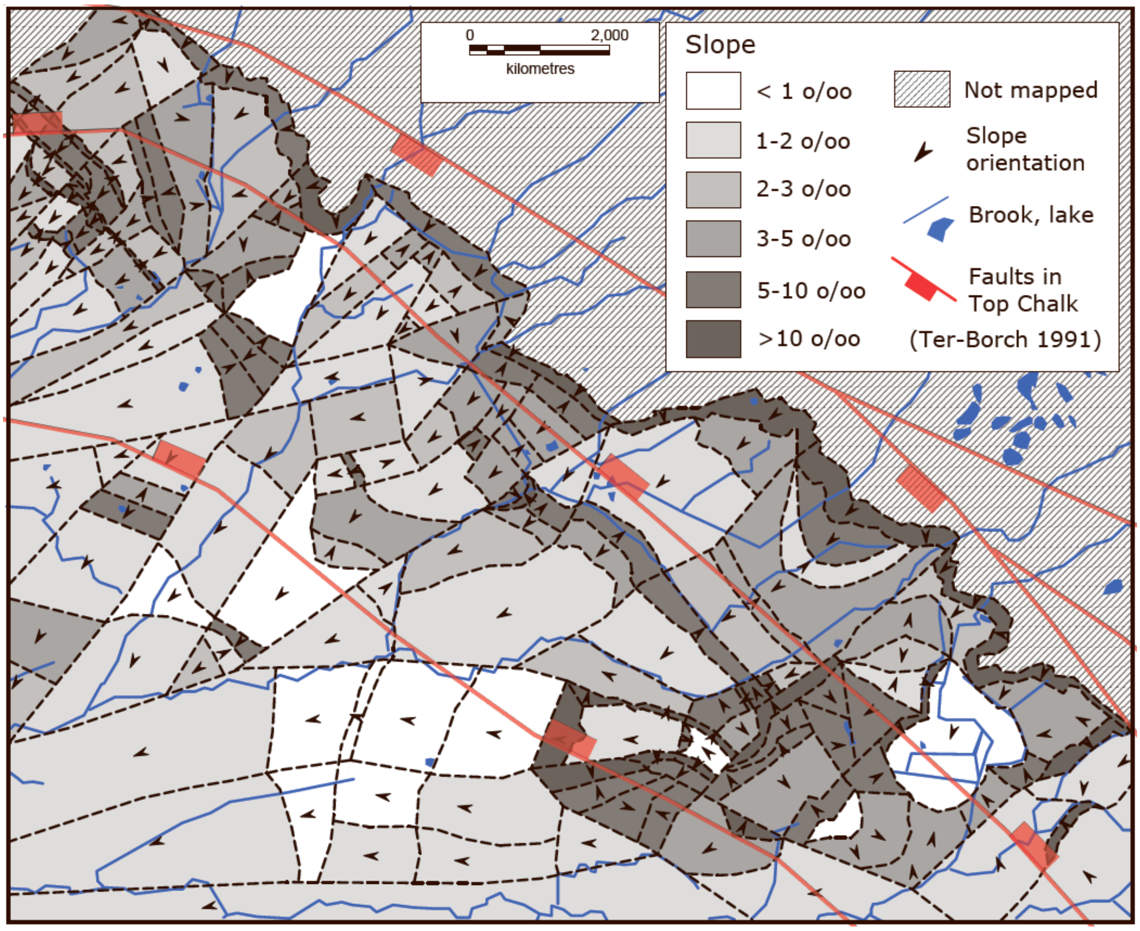


Figure 2.26. *Slope magnitude (grey shades) and slope orientation (arrows) of the Late Weichselian Tinglev outwash plain in southwestern Denmark. Streams in the area (blue) follow the mosaic pattern of the outwash plain and show signs of deflection relative to the general slope. From Sandersen & Jørgensen (2015).*

Figur 2.26. *Størrelse (grå skygge) og hældningsorientering (pile) for den senglaciale Tinglev hedeslette i Sønderjylland. Åer og bække i området (blå streger) følger terrænets mosaikmønster og viser tegn på afvigende orienteringer i forhold til den overordnede hældning af hedesletten. Fra Sandersen & Jørgensen (2015).*

According to the Sandersen & Jørgensen (2016), this pointed to a relationship between the tectonic framework and erosional patterns during the Quaternary. The dominant orientations of both buried valleys and erosional valleys in the present-day terrain matched the mapped deep faults, and the authors' conclusion was that deep tectonic movements related to the deglaciation had created deformed zones in the sediments all the way to the terrain surface.

Apparently, these deformed zones were easier to erode and, thus, they were likely to have had a pronounced impact on the drainage patterns in Late Weichselian and postglacial times.

Denmark is usually considered tectonically stable, but the examples above – together with a number of other examples not mentioned here – show that the stress changes induced by the weight-relief from the Pleistocene ice sheets appear to have created episodes of short-lived tectonic instability. The findings in the examples above point to reactivations of major fault-zones in the area of Denmark; therefore, it is likely that other fault zones would be equally susceptible to reactivation, and that such events should be expected to be recurrent during glaciation-deglaciation cycles (Sandersen & Jørgensen 2015).

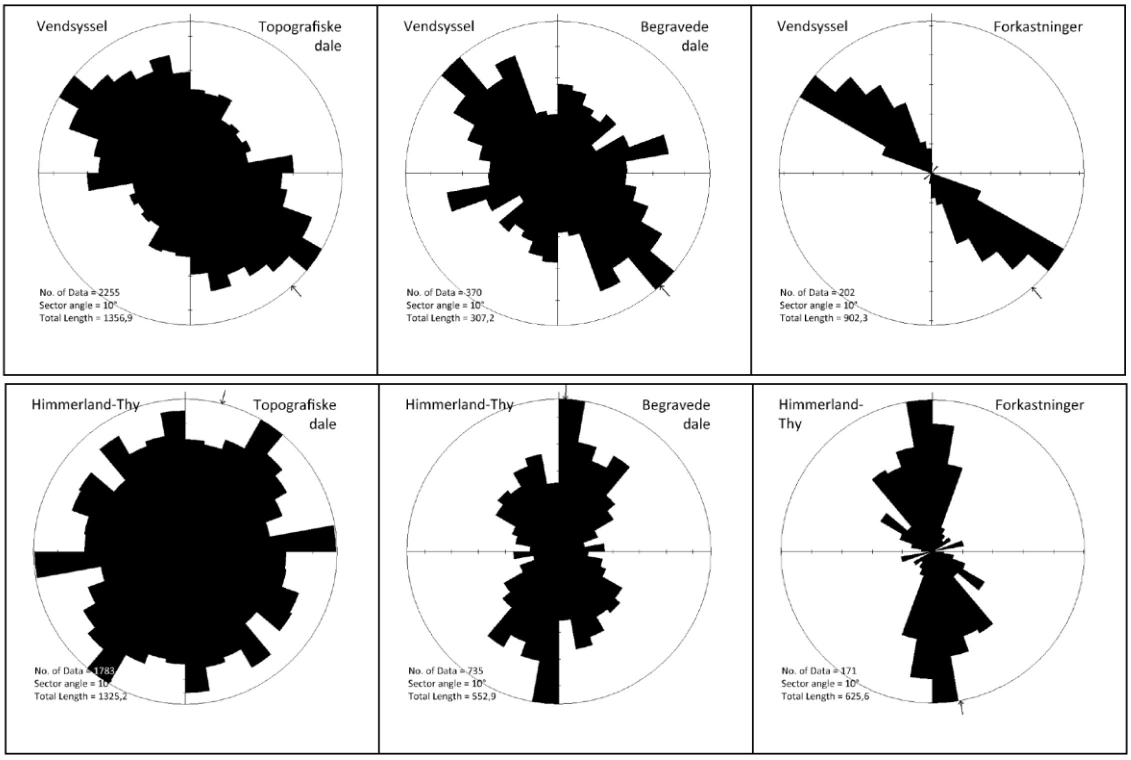


Figure 2.27. *Rose diagrams for the regions Vendsyssel and Himmerland-Thy. The rose diagrams show orientations of topographic valleys (left), buried valleys (middle) and deep-seated faults (right). See Figure 2.10 for location. From Sandersen & Jørgensen (2016).*

Figur 2.27. *Roset-diagrammer for regionerne Vendsyssel og Himmerland-Thy. Roset-diagrammerne viser orienteringer af topografiske dale (venstre), begravede dale (midten) og dybe forkastninger (højre). Se Figur 2.10 for lokalisering. Fra Sandersen & Jørgensen (2016).*

2.3.6 Impact on salt structures

Generally, how salt structures respond to ice-sheet loading and unloading is poorly understood (Lang et al. 2014). The loading and unloading of ice sheets during the Quaternary can potentially have had an impact on the large number of Danish salt structures much the same way as described and modelled for German salt structures (Al Hseinat & Hübscher 2014, Lang et al. 2014; Sirocko et al. 2008).

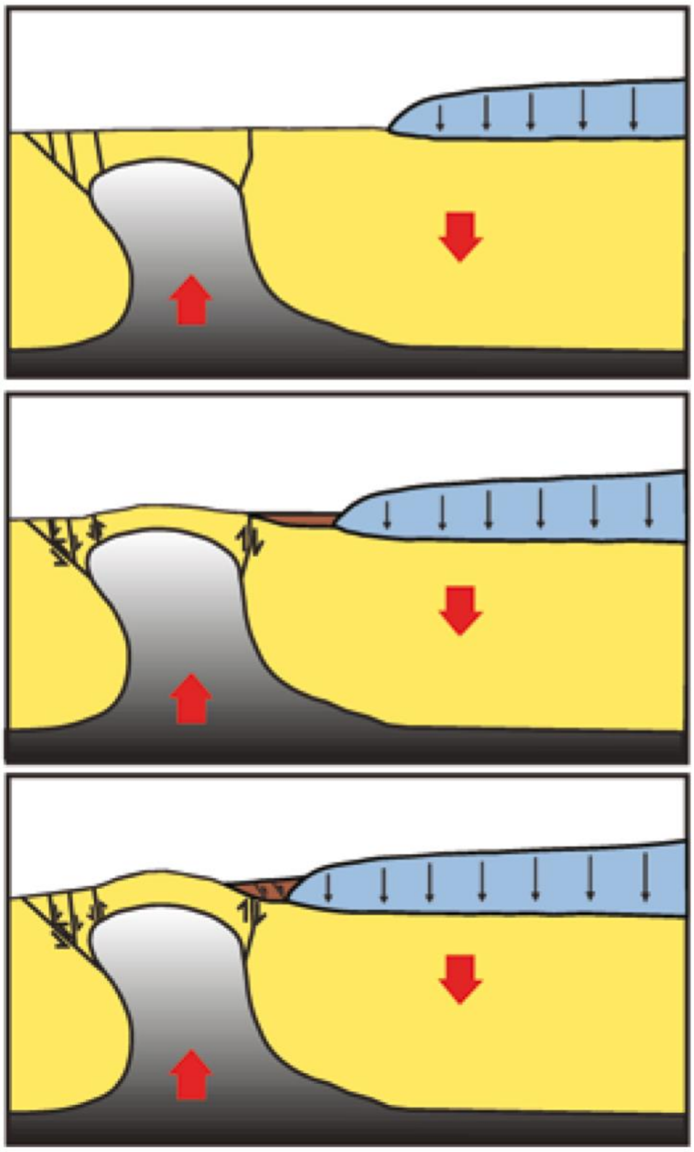


Figure 2.28. Sketch of a forward moving glacier (blue) with a salt diapir (grey/black) at the subsurface. The glacier advances towards a salt structure (top sketch). An additional load on the subsurface is created, facilitating local accommodation space for meltwater deposits (brown) between the ice and the rising salt diapir (middle sketch). The meltwater deposits subsequently became compressed, leading to the formation of a push moraine (bottom sketch). Modified from Sirocko et al. (2008); the example is from Rederstall, Schleswig Holstein, Northern Germany.

Figur 2.28. Skitse af en gletsjer (blå), der rykker frem mod en saltstruktur (grå/sort). Gletsjeren rykker frem mod saltstrukturen (øverst). Isens vægt skaber lokale indsynkninger, hvor der mellem isen og saltstrukturen aflejres smeltevandssedimenter (brunt; mellemste skitse). Smeltevandsaflejringerne blev efterfølgende deformeret af den fremrykkende is (nederst). Modificeret efter Sirocko et al. (2008); Eksemplet er fra Rederstall, Schleswig Holstein, Nordtyskland.

A few descriptions of deformations of Quaternary sediments above salt diapirs in the Norwegian-Danish Basin have pointed to a combination of halokinetics, fault-reactivation and dissolution of the salt (e.g. Madirazza, 1966, 1980; Madirazza & Jacobsen, 1998), but newer and more detailed investigations of sediments and topography above salt diapirs have not been carried out.

Based on the results of numerical modelling in Germany, Lang et al. (2014) concludes that:

- Salt structures respond to surface loading applied by a 300-1000 meters thick ice sheet
- If an ice sheet overrides a diapir, the load applied to the top of the diapir forces it to move downwards, resulting in a slight broadening of the upper parts of the diapir; this downward displacement is compensated by a reversal of the salt flow
- After the retreat of the ice, the salt flow returns to an upward movement
- If the diapir remains outside the ice margin, the ice load makes salt flow from the source layer and into the diapir causing it to rise (see illustration in Figure 2.28).

2.4 Conceptual model for future Scandinavian glaciations

Based on the results from the climate models (see Chapter 2.1), we can expect that within the next 500,000 years, glaciations will re-occur in Scandinavia and consequently affect Denmark. As mentioned in the preceding text, future glaciations will probably not exceed the magnitude of the Pleistocene glaciations, and because of the high industrial levels of CO_2, the onset of the next glaciation will probably be significantly postponed. However, within the mentioned time-interval, between one and four glaciations are likely to take place. Because the glaciations are not expected to be more severe than any of the Pleistocene glaciations, a rough conceptual model for future glaciations can be sketched, based on observations and interpretations of the impact from former ice sheets in Northern Europe.

The glaciations that affected Scandinavia during the Pleistocene were different in terms of physical extent, duration, and degree of severity. However, at a rough scale some overall characteristics can be listed:

- **Area of impact:** Ice sheets overrode Denmark several times and the record of former ice margins is extensive. Denmark also experienced large time intervals with periglacial and interglacial conditions.
- **Directions of ice transport:** The ice movement directions in the Danish area varied, but generally, ice advances from between north and south-southeast were the most frequent.
- **Glaciotectonics:** Large glaciotectonic complexes and smaller glaciotectonically disturbed successions have been recorded throughout Denmark. Glaciotectonic deformation have been assigned to different glaciations and different ice advances. The maximum depth of deformation recorded in Denmark is around 300 meters and the size of the affected areas can be up to some hundred square kilometers.
- **Erosion and erosional patterns:** Based on modelling, the amount of distributed glacial erosion during one glacial cycle did probably not exceed a few tens of meters. This amount does not account for more focused local erosion such as subglacial tunnel-valley erosion, which has been recorded at depths of up to around 400 meters.

Some degree of linking across glaciations and interglaciations seems possible, because sediments deposited during former glacial cycles act as substrate for subsequent glaciers.

- **Impact on the hydrological cycle**: Probably the most important factor directly related to the hydraulic conditions underneath an ice sheet is the character of change to the pre-glacial hydrologic system and the circulation depth of the meltwater. The infiltration rate under a glaciation is strongly increased. Regional as well as local geologic structures can change the hydraulic framework of the subsurface, creating corridors for deep groundwater recharge and circulation during glaciations. The deep circulation of groundwater will cause oxygen to be transported to levels deeper than before the glaciation.
- **Impact on the lithospheric stress-patterns:** The loading and unloading of ice sheets have affected the lithospheric stress patterns during each of the glacial cycles throughout the Pleistocene. Reactivation of existing fault zones appears to have been a common phenomenon, not only within the areas formerly covered by the ice sheets, but also in large areas outside the ice margin. For the Danish area, it is likely that late- and postglacial reactivation of faults have had an impact on the erosion patterns throughout the Pleistocene.
- **Impact on salt structures:** Salt structures will respond to surface loading applied by ice sheets; however, investigations on load-induced salt movements in Denmark are scarce.
- **Recurrence:** From the geological record in Denmark, it appears that mechanisms and processes act in much the same way during glacial cycles. Recurrence is therefore a key word when trying to forecast future events. Some events, such as valley erosion and reactivation of faults, seem to have a tendency to happen repeatedly in the same places.

Based on the observations and interpretations of the impact of the Pleistocene ice sheets on the Danish subsurface described in the preceding sections, the bullet points above can be used as a preliminary conceptual model for future glaciations.

It seems unlikely that a future glaciation, or a series of glaciations, will be able to erode and remove sediment to great depth over very large areas. Instead, it is likely that subglacial meltwater erosion and deformation by glaciotectonic events locally can disturb the sedimentary succession to depths of 300-400 m. The subglacial erosion of tunnel valleys seems to follow certain patterns and thereby opens up the possibility of predicting the likelihood of existing valleys being re-used. However, concerning future glaciotectonic deformations, it appears that the question is not if a given area in Denmark would experience glaciotectonic deformation or not; rather, the question is how pervasive and down to which depth those glaciotectonic deformations will be at.

Because of the repeated loading and unloading of the ice sheets, existing fault zones in Denmark appear to be susceptible to reactivation, mainly around the time of deglaciation. Therefore, having thorough knowledge of the location of faults and their activation history is important, both at a regional and at a local scale. The same applies for load-induced movement of salt structures.

2.5 Using the conceptual model for future glaciations on selected sites

In relation to a deep geological waste repository at a specific location, focus should therefore be on assessing the maximal future impact from the following factors:

- Glaciotectonic deformation
- Erosion by subglacial meltwater
- Impact on the hydrological cycle
- Glacio-seismotectonics (the study of the relations between glaciotectonic, earthquakes and known faults inside an area)
- Load-induced salt tectonics
- A combination of the above

As the last bullet point above suggests, the factors can act in combination and thereby potentially create a higher total impact on the subsurface than if the factors act individually. For instance, reactivated faults can facilitate local subglacial erosion, which in turn might penetrate originally separated aquifers, thereby enabling deep groundwater recharge and circulation. Detailed mapping and subsequent geological and hydrological modelling in selected areas will be able to address scenarios such as this.

2.6 Summary of future glaciations in Denmark

The geological successions of the subsurface and the morphological features of the terrain show that several glaciations have affected Denmark within the last 2.6 Ma. Based on results from climate models, it can be expected that within the next 500,000 years, glaciations will re-occur one to four times in Scandinavia and, consequently, affect Denmark. However, due to the currently increasing amount of greenhouse gases in the atmosphere, climate models foresee a postponement of the onset of the next glaciation. Also, according to climate models, future glaciations will most likely not exceed the magnitude of recorded past glaciations; therefore, in order to predict possible effects of future glaciations in Denmark, it is relevant to look to the effects of past glaciations.

During the Pleistocene, ice sheets have overridden Denmark several times – the effects of this being deep deformation and erosion by the forces of meltwater and glacier ice, and significant alterations of the hydrological cycle underneath and in front of the glaciers. It is likely that subglacial meltwater erosion and deformation by glaciotectonic events will be able to disturb the sedimentary successions to depths of some hundreds of meters. Added to this is also the impact on the subsurface stress fields going down as deep as to include the upper mantle, caused by the loading and unloading of the ice sheets. During times of deglaciation, these stress changes can make existing fault zones in Denmark susceptible to reactivation, thus affecting the succession from the surface and down to depths of several kilometers.

3. Earthquakes in Denmark

Tine B. Larsen

This investigation evaluates the earthquake hazard in Denmark and is based on known earthquake activity, past and present. The data material includes instrumentally recorded earthquakes as well as historical and modern accounts of shaking.

The available data are fundamentally different from before and after 1930. The first Danish seismograph came into service in 1927, recording the first Danish earthquake in 1930; this marked a new epoch in Danish seismology (Lehmann, 1945). Instrumentally recorded data contains information on the precise arrival times of earthquake phases, in addition to wave period and amplitude; these parameters are necessary for calculating an earthquake's epicentre and its magnitude on the Richter scale. Older earthquakes can only be evaluated macroseismically – based on written accounts of shaking without support from instrumentally recorded data.

Information on older earthquakes is typically limited to descriptions of the region in which the earthquake was felt, how it was felt, the date, and, in most cases, the time of day. Based on how an earthquake was felt, it is possible to assign an intensity value on the Mercalli Scale (e.g., Grünthal, 1998). The Mercalli Scale consists of 12 levels describing the effects the earthquake has had on people, nature and structures. It is important to emphasize that no intensity value on the Mercalli scale corresponds to a magnitude value on the Richter scale; the two measures are independent and not comparable.

It is, however, in some cases possible to estimate an approximate magnitude on the Richter scale for historical earthquakes, despite the lack of direct measurements. This is achievable when at least one later earthquake has been felt in the same area and has been recorded instrumentally. Careful comparison of the felt reports can delineate how the affected area for the earthquakes overlap and to what extent the intensities match. Based on this analysis it is possible to assign the historical earthquake an approximate epicentre and magnitude.

Many earthquakes shake Denmark every year. However, Denmark is located far away from the nearest plate boundaries in the North Atlantic and in the Mediterranean; as a result, the earthquakes are in general small to moderate. Every few years one of the earthquakes is strong enough to be felt by people and not just registered by the network of seismographs. The primary cause of earthquakes in Denmark is the stress that builds up from the Mid-Atlantic Ridge pushing the Eurasian Plate (Gregersen, 1992). Also, it is possible that post-glacial rebound still plays a role, but the findings are inconclusive.

Most Danish earthquakes, as also the largest ones, occur below Kattegat, Skagerrak, and in the northern part of the Nordsøen (Figure 3.1). On land, the central part of Sjælland and northwestern part of Jylland are the seismically most active regions in Denmark. In the rest of the country, earthquakes are rare.

Earthquakes recorded between 1960-2013

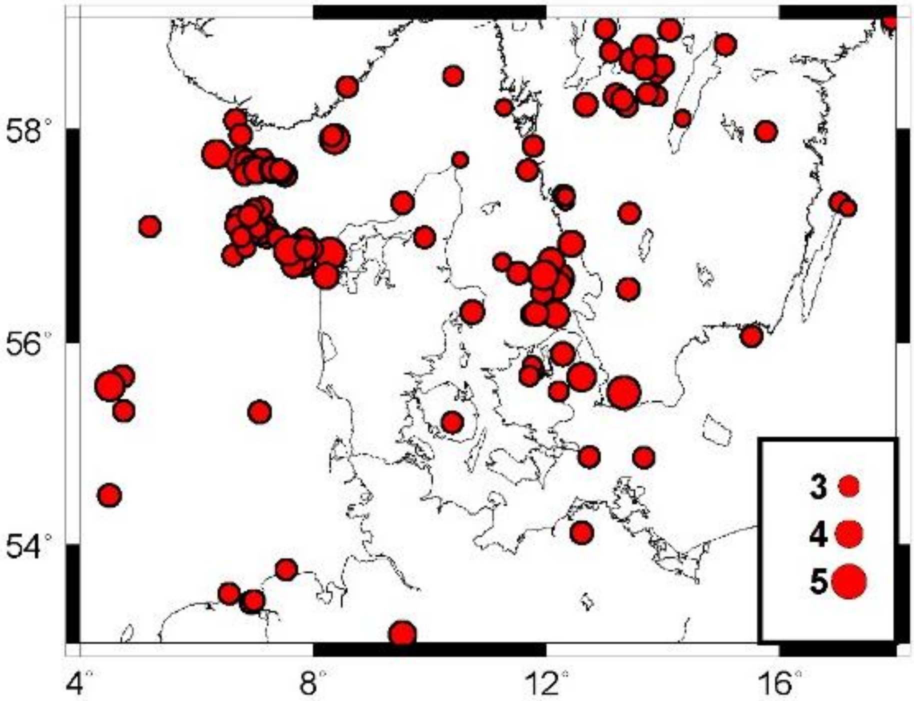


Figure 3.1. *Earthquakes recorded between 1960-2013 with a magnitude of at least 3 on the Richter scale. From Voss et al. (2015).*

Figur 3.1. *Jordskælv i perioden 1960-2013, som er mindst 3 på Richterskalaen. Fra Voss et al. (2015).*

3.1 Earthquake epicentre, magnitude and intensity

The earthquake epicentre is defined as the point on the surface found by projecting the earthquake’s origin (at depth) perpendicular to the surface. This point is represented by a dot on a map. For smaller earthquakes, this is a sensible graphical representation, as the lateral extent of the displacements at depths is smaller than the uncertainty on the epicentre; however, for large earthquakes where displacements can be tens or even hundreds of kilometers, showing the earthquake epicentre as a dot can be misleading. The earthquakes discussed in this report are sufficiently small to have a dot represent each of them without further explanation.

For a comparison of different earthquakes and their effects, it is necessary to have standardized measures to describe the shaking. There are two fundamentally different ways to characterize the size of an earthquake: the earthquake magnitude on the Richter scale (in short: magnitude) and the earthquake intensity on the Mercalli scale; magnitude is based exclusively on instrumental recordings, and intensity is based entirely on human observations. The magnitude on the Richter scale pertains to the epicentre, whereas the intensities have a larger lateral extent. In many cases, Danish earthquakes occur offshore, but the shaking is felt on land; thus, both magnitude and intensities are relevant for understanding the possible implications of the earthquake. The scales are described in more detail below.

3.1.1 Richter magnitude

The Richter scale is based on the measured amplitude of ground motion and the corresponding wave period at a distance of 100 kilometers from the epicentre. As the seismograph in the real world can be located at any distance from the epicentre and the wave propagation depends on subsurface conditions between seismograph and epicentre, it is necessary to apply corrections in order to obtain consistent values for comparable earthquakes across the world. This is done by adopting a local magnitude scale to fit the relevant conditions. The Danish magnitude scale is defined as (e.g. Geodætisk Institut, 1983):

$ML = \log(a) + \log(V(T)) + 1.61 \log(\Delta) - 2.76$

The parameters are:
ML: magnitude
a: vertical ground motion in µm based on maximum observed amplitude
V(T): magnification of Wood-Anderson seismograph
Δ: epicentral distance in kilometer

The magnitude is not directly linked to physical quantities in the subsurface. It is, however, a reproduceable value based on measurements, giving consistent values across seismograph networks and boundaries. This is achieved by applying local corrections based on statistical studies of large earthquake populations. The Richter magnitude is related to the energy radiated by the earthquake at the origin.

Due to local noise conditions and the current seismograph network in Denmark, earthquakes with an approximate magnitude smaller than 0.5 are difficult to locate reliably. Earthquakes with a magnitude smaller than 2.5 are in general not felt by people in Denmark.

3.1.2 Mercalli intensity

The Mercalli scale, in Europe known as the European Macroseismic Scale 1998 (EMS98) (Grünthal, 1998), is based on human observations. The scale is used to describe how an earthquake affects a given locality. Observations are collected and categorized by asking people who felt a given earthquake to fill out a questionnaire with standardized questions. Each questionnaire is assigned coordinates (based on the respondent’s address) and a Mercalli level. When an earthquake causes destruction, the damage is inspected by a seismologist before a Mercalli level is assigned.

The EMS98 has 12 levels:

I. Not felt: Not felt, even under the most favourable circumstances.

II. Scarcely felt: Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.

III. Weak: The vibration is weak and is felt indoors by a few people. People at rest feel a swaying or light trembling.

IV. Largely observed: The earthquake is felt indoors by many people, outdoors by very few. A few people are awakened. The level of vibration is not frightening. Windows, doors and dishes rattle. Hanging objects swing.

V. Strong: The earthquake is felt indoors by most, outdoors by few. Many sleeping people awake. A few runs outdoors. Buildings tremble throughout. Hanging objects swing considerably. China and glasses clatter together. The vibration is strong. Top-heavy objects topple over. Doors and windows swing open or shut.

VI. Slightly damaging: Felt by most indoors and by many outdoors. Many people in buildings are frightened and run outdoors. Small objects fall. Slight damage to many ordinary buildings; for example, fine cracks in plaster and small pieces of plaster fall.

VII. Damaging: Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many ordinary buildings suffer moderate damage: small cracks in walls; partial collapse of chimneys.

VIII. Heavily damaging: Furniture may be overturned. Many ordinary buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse.

IX. Destructive: Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapses completely.

X. Very destructive: Many ordinary buildings collapse.

XI. Devastating: Most ordinary buildings collapse.

XII. Completely devastating: Practically all structures above and below ground are heavily damaged or destroyed.

In Denmark, most observations range from level III to V, but historically a maximum intensity level of VII has been observed twice as described below.

3.2 Felt earthquakes in Denmark

Some of the Danish earthquakes generate shaking powerful enough to be felt by people (Figure 3.2). For those earthquakes, felt reports are collected and intensity maps produced (e.g., Voss et al., 2017). Intensity maps are useful for assessing local site effects, such as amplification or damping. The intensity of shaking depends on a wide range of factors such as earthquake magnitude, source directivity, hypocenter depth, distance to the earthquake as well as subsurface geology and soil conditions. The general noise level, building design and the respondent’s location within a building also contribute to how the shaking is perceived. Observations from higher than second floor are not used as tall buildings amplify shaking, thus giving an exaggerated picture of the shaking.

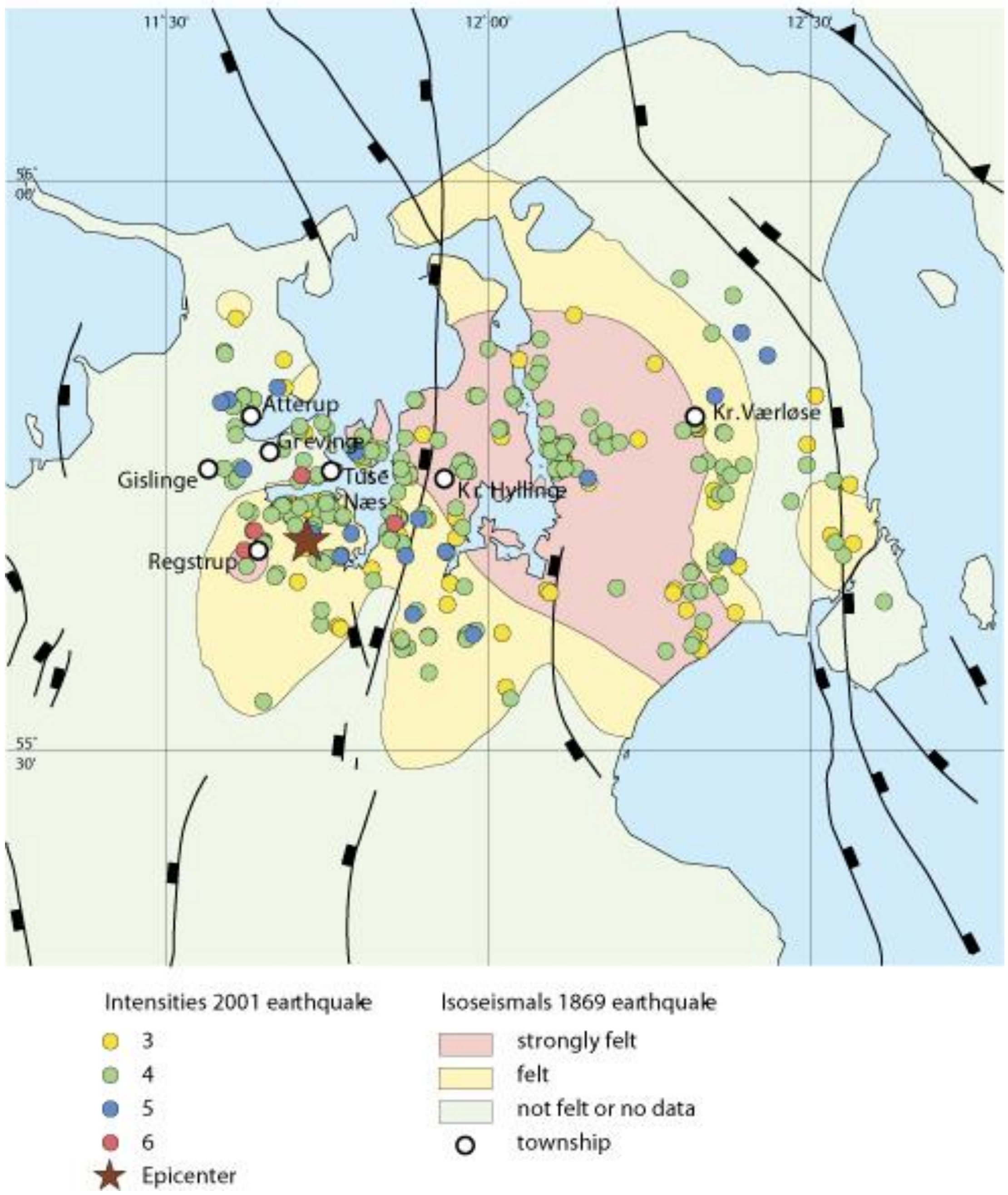


Figure 3.2. *Comparison of felt reports from earthquakes near Holbæk in 1869 and 2001, from Larsen et al. (2008). The shaking felt in 1869 is marked by coloured areas, whereas felt reports from 2001 are marked by dots with colours indicating the intensity. Faults are at the Top Pre-Zechstein level, redrawn from Vejbæk & Britze (1994).*

Figur 3.2. *Sammenligning af rystelser følt i forbindelse med jordskælv nær Holbæk i hhv. 1869 og 2001, fra Larsen et al. (2008). Rapporter om rystelserne i 1869 er markeret med farvede flader, rapporter fra jordskælvet i 2001 er markeret med prikker, hvor farven angiver, hvor kraftigt rystelsen blev oplevet. Forkastningerne er på Top Pre-Zechstein fladen, gentegnet fra Vejbæk & Britze (1994).*

Credible reports of earthquake shaking date back to 1629 (e.g., Lehmann, 1956). Prior to the installation of seismographs in Denmark, these written reports constitute the only data available. After the installation of seismographs, felt reports provide a valuable data link between historical earthquakes and instrumentally recorded, modern earthquakes.

The highest earthquake intensities reported in Denmark date back to the pre-instrumental period. Two earthquakes caused damage up to intensity level VII. On 22nd December 1759, the oldest known intensity level-VII earthquake occurred, causing strong shaking in all of Denmark and southern Sweden (Wood, 1988). Based on the felt reports it is assumed that the epicentre was in northern Kattegat. The most extensive damage was in the form of cracked walls and knocked down chimneys as reported along the Swedish west coast, but also Aalborg experienced cracked walls and considerable damage to a church (Trap, 1961).

The other known intensity VII earthquake in Denmark occurred on 3rd April 1841. This earthquake was also felt in southern Norway. Damage was reported from Thisted to Vestervig to Mors (Lehmann, 1956). Besides damage to buildings, wave motion was observed on the ground floor of a house, and a 13 meters long surface crack in the ground with a vertical displacement of 2.5-7.5 cm was observed (Forchhammer, 1869).

Between 1759 and 2012, 10 earthquakes with intensity level V-VII have been felt in Denmark (Voss, et al., 2015). Many more earthquakes with intensity levels ranging from III-IV have been reported.

Written reports on pre-instrumental earthquakes need careful evaluation: the reports contain valuable and unique information; however, it is necessary to read them critically. Typically, the reports are written by priests who would retell the incident as experienced by the congregation; information may be tainted by non-scientific interpretations, and earthquake observations are in some cases mixed up with observations of thunder or storm. It can be difficult to discern from the written reports if a smaller earthquake felt in northern Jylland had its epicentre in Denmark, Norway or Nordsøen. Some earthquake observations relate to earthquakes outside Denmark. The most spectacular example is the Lisbon 1755 earthquake, which was felt in large parts of Europe, including Denmark.

3.3 Instrumentally recorded earthquakes in Denmark

It is GEUS' assessment that all earthquakes in Denmark with a magnitude of at least 3.0 on the Richter scale have been recorded since 1960 (magnitude of completion). During the latest 15 years, the instrumentation in and around Denmark has improved to a degree where all earthquakes of at least 2.5 on the Richter scale have been recorded. This is primarily a result of the vast expansion of the seismograph network in Sweden and, to a lesser extent, in Norway. Earthquakes significantly smaller than 2.5 on the Richter scale are also recorded, but GEUS cannot guarantee that the catalogue is complete, meaning, smaller earthquakes (smaller than 2.5) might go undetected. Earthquakes as small as 2.7 have generated shaking strong enough to be felt by people in the epicentral area in Denmark (Voss et al., 2017).

The uncertainty on a calculated epicentre depends on the number of seismographs having recorded a signal, in addition to the geographical distribution of seismographs relative to the epicentre (Figure 3.3). The more seismographs and the better azimuthal coverage, the smaller the uncertainty becomes. Larger earthquakes are typically recorded by more seismographs than smaller earthquakes, resulting in a smaller uncertainty. Due to better and more abundant instrumentation today, the epicentres of older earthquakes are typically more uncertain than epicentres of more recent earthquakes. A conservative estimate of the uncertainty on Danish earthquakes today is 20 kilometers in all directions, and up to 50 kilometers for earthquakes from before year 2000. These uncertainties are too large to enable us to pinpoint individual earthquakes to known faults. A denser network of seismograph stations in an area of particular interest could alleviate this challenge.

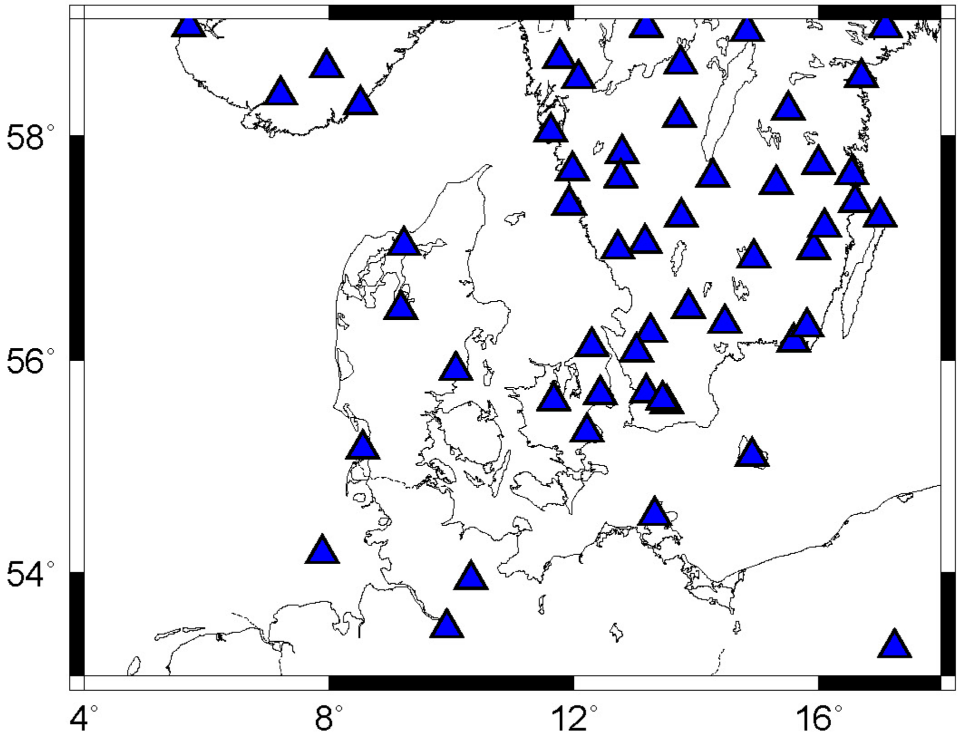


Figure 3.3. *Seismograph stations in and around Denmark used for locating Danish earthquakes. From Voss et al. (2015).*

Figur 3.3. *Placeringen af seismografer i og omkring Danmark der anvendes til at lokalisere de danske jordskælv. Fra Voss et al. (2015).*

The majority of Danish epicentres are located offshore. The most active zones are in Kattegat, Skagerrak and Nordsøen (Figure 3.1). Earthquakes occur in nearly all parts of Denmark, particularly in northern Jylland and on Sjælland in the København/Nordsjælland/Isefjord region. Sometimes earthquakes occur in unexpected places, such as the 16th September 2018 Holstebro earthquake with a calculated magnitude of 3.5. This earthquake was located in an area where earthquakes had not previously been recorded or reported, and it resulted in almost 1000 felt reports to GEUS from people who felt the earthquake. The surprise caused by earthquakes, like the one near Holstebro, is due to the discrepancy in the length of timescale between earthquake observations (hundreds of years) and the forces causing the earthquakes (10.000 years for postglacial rebound, millions of years for tectonic forces). The time span in which observations have been made is very short compared to the time span over which the driving forces are operating.

The Danish earthquakes are recorded by the Danish seismograph network operated by GEUS, supplemented by data from national networks in our neighbouring countries. The Danish network currently consists of seven seismograph stations. The seismographs transmit continuous waveform data to GEUS in real time. Data are quality controlled and processed manually; earthquake phases are identified, and epicentres and magnitudes are calculated. Due to the relatively large spacing between stations and the high noise level, automatic data processing is not possible. Prior to the transition to an entirely pure digital operation of the seismograph stations around year 2000, the stations were equipped with analogue instruments recording the signals on paper drums. The digital data provide better opportunities for identification of weak signals from small earthquakes, thus resulting in an increase in numbers of recorded earthquakes since 2000.

See Voss et al. (2015, Table 3) for a list of instrumentally recorded, felt earthquakes and Figure 3.4 for the location of epicentres in Denmark during the period 1930-2018.

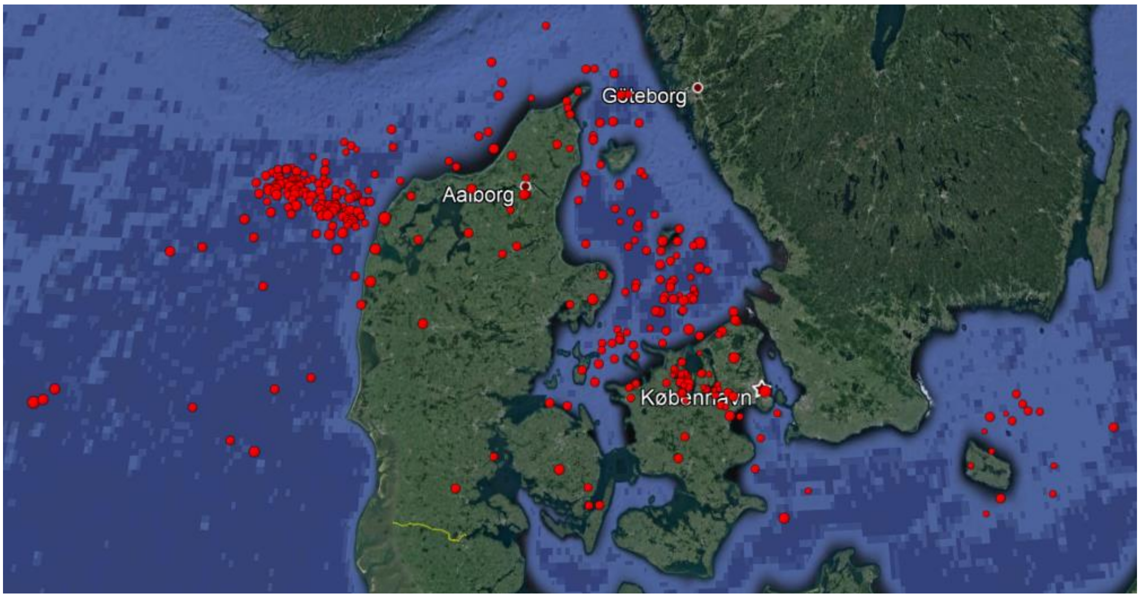


Figure 3.4. *Instrumentally recorded seismicity in Denmark during the period 1930-2018. Epicenters (red dots) are from the GEUS earthquake database, and all epicentres are determined using data from a minimum of three stations. In addition to earthquakes, the map may contain data based on explosions that have not yet been screened out.*

Figur 3.4. *Instrumentelt registreret seismicitet i Danmark i perioden 1930-2018. Epicentrene (røde prikker) er fra GEUS´ jordskælvsdatabase. Ved alle epicentre er der brugt mindst tre stationer til lokaliseringen. Kortet kan indeholde punkter, der er registreret i relation til eksplosioner, som endnu ikke er fjernet fra databasen.*

3.4 Earthquake hazard in Denmark

Probabilistic seismic hazard analysis (PSHA) based on methodology by Cornell (1968) is commonly used in seismic hazard studies around the world. The basic idea is to quantify the ground shaking from earthquakes that may be expected in the future, using all available earthquake data from the region concerned. Statistically, low intensity shaking occurs more often than high intensity shaking. Combining statistical earthquake data with mathematical models of ground motion and earthquake location models can produce predictions of potential, future shaking. The resulting models are the best extrapolations we can make, but it is important to bear in mind that these are built on several assumptions. The more earthquakes available for the analysis, the more solid are the results. This can be a challenge for low-seismicity regions like Denmark. Another challenge is to estimate the maximum magnitude for a future earthquake. Given the short observational timeline of a few hundred years of historical sources (e.g. Lehmann, 1956), the much longer timescale for the controlling forces of 10,000 years for postglacial rebound and millions of years for tectonic forces, it is relevant to look at similar geological settings elsewhere for insight into possible long-term stability.

The earthquake hazard for Denmark is calculated using both historical and instrumentally recorded earthquakes (Voss et al., 2015; see Figure 3.5). To estimate the maximum magnitude an earthquake in Denmark could produce we include data on earthquakes from Skåne (2008), Kaliningrad (2004), Kattegat (1985, 1759), North Sea (1931), and Oslo Fjord (1904). The calculations are only valid for onshore areas and potential future glaciations, and resulting postglacial rebound is not considered.

The resulting hazard map depends on the return period for the earthquakes being considered. A return period for earthquakes of 475 years corresponds to a 90 % non-exceedance probability in 50 years. This means that if the largest expected earthquake in an area generating a certain peak ground acceleration occurs every 475 years, the probability that this acceleration will not be exceeded during a 50-year period is 90 %.

The calculated hazard reflects the known seismicity with the highest peak ground acceleration expected in north-western Jylland and in northern and central Sjælland. The highest values of 90 % non-exceedance of peak ground acceleration in 50 years is around 0.25 m/s^2 (Voss et al., 2015, Wahlström and Grünthal, 2001) and the lowest values are 0.06-0.08 m/s^2 (Figure 3.6). For comparison, the values for Forsmark, Sweden, are approximately 0.1 m/s^2 (Wahlström and Grünthal, 2001).

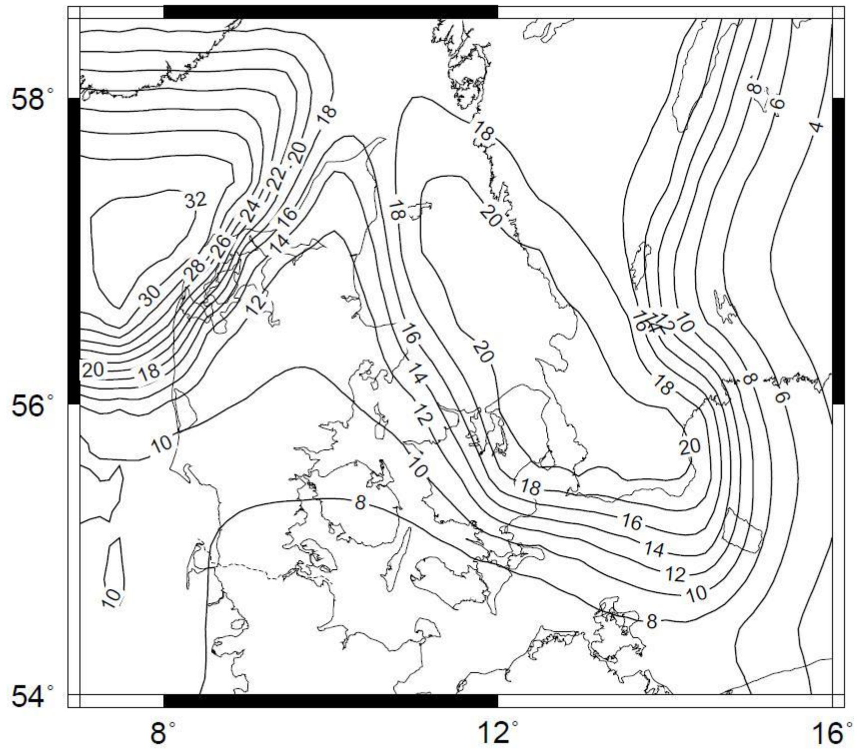


Figure 3.5. *Estimated hazard for a return period of 475 years, corresponding to a 90 % non-exceedance probability in 50 years. Unit is peak ground acceleration cm/s^2. From Voss et al. (2015).*

Figur 3.5. *Kortet viser niveauet for horisontale accelerationer (cm/s^2) forårsaget af jordskælv, som med 90 % sandsynlighed ikke vil blive overskredet over en periode på 50 år. Beregningen er baseret på jordskælvene der er vist i Figur 3.1. Fra Voss et al. (2015).*

The input parameters for the hazard calculation are built on many assumptions, as the earthquake time series for Denmark is short and sparsely populated. The knowledge of Danish earthquakes dates back only a few hundred years, whereas the forces driving the earthquakes operate on geological time scales of millions of years. The time series contains only ten earthquakes of at least level 4 on the Richter scale. As the amount of available earthquake data grows every year, it is relevant to recalculate the earthquake hazard at least every 10 years.

Compared to other regions of the earth, the seismicity in Denmark is low; however, it is not negligible. Occasionally, a strong earthquake will hit unexpectedly somewhere on the earth, and with the surprising element coming from the difference between the short historical time series and the significantly longer geological time scales on which the driving forces operate. The strongest of the most surprisingly large earthquakes close to Denmark in modern times are the two Kaliningrad events in 2004 of magnitude 5.2 and 5.0, respectively. The largest of the Kaliningrad events was felt in Denmark (Gregersen et al., 2007).

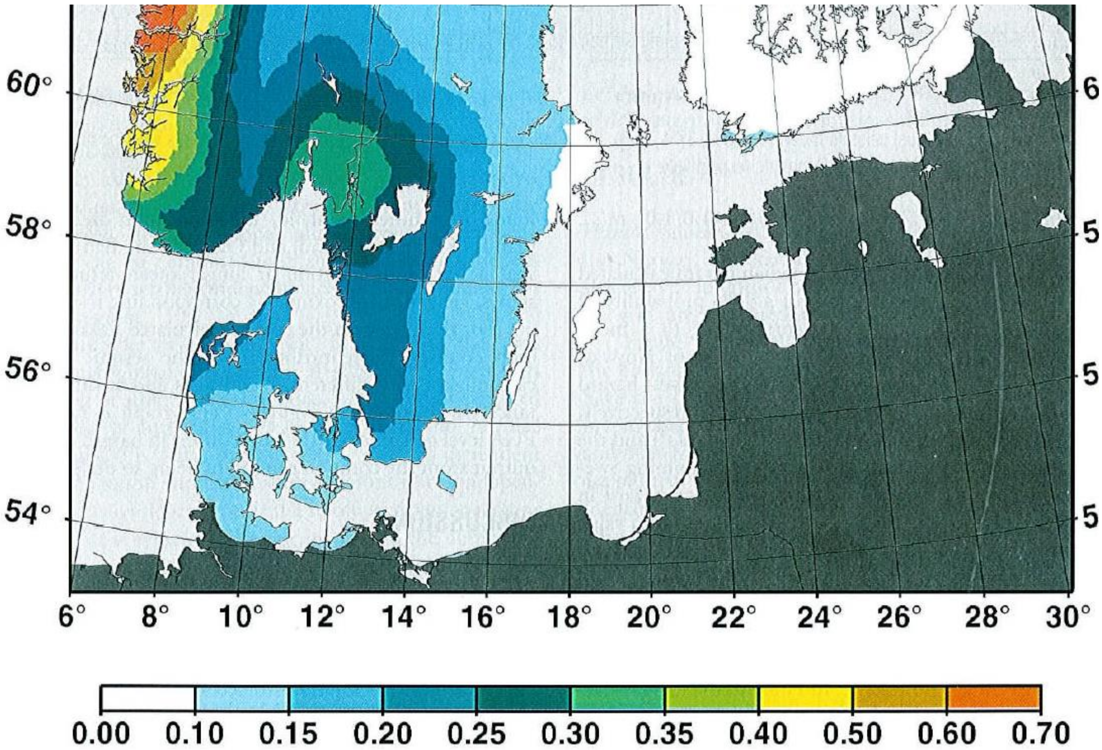


Figure 3.6. *Map of 90% probability of non-exceedance of horizontal PGA (m/s^2) in 50 years. From Wahlström and Grünthal (2001).*

Figur 3.6. *Kortet viser niveauet for horisontale accelerationer (m/s^2) forårsaget af jordskælv, som med 90 % sandsynlighed ikke vil blive overskredet over en periode på 50 år. Fra Wahlström og Grünthal (2001).*

3.4.1 Postglacial events

For assessing seismic hazard over long-time periods, it is relevant to consider the effects of future glaciations and deglaciations. Northern Scandinavia has several large fault scarps that hosted major earthquakes following the last deglaciation. The earthquakes were most likely caused by reactivation of existing faults due to the changed stress conditions (e.g. Munier and Fenton, 2004). The largest scarp on the Pärvie Fault is equivalent to a magnitude 8 earthquake (e.g., Arvidsson, 1996).

Modelling earthquakes at end-glacial stress conditions at the Forsmark site in Sweden shows that a magnitude 5.6 earthquake generating a 14 km^2 rupture area can cause secondary shear displacements of tens of mm in the vicinity of the fault. The secondary displacements peak around 200 meters from the fault (Fälth et al., 2016). Modelling fault behaviour under different stress regimes requires knowledge of the fault geometry as well as the local geological conditions.

3.5 Summary of seismic activity

The seismicity in Denmark is low to moderate. The seismicity is known from both instrumental recordings and historical sources. Instrumental data have been recorded since 1930, whereas historical accounts date back several hundred years. The ability to record small earthquakes has gradually improved due to developments in instrumentation. The magnitude of completion, i.e. the Richter magnitude above which we register all earthquakes, was 3.0 between 1960 and 2000 and is currently 2.5.

The intensity of shaking generated by earthquakes is as important as the Richter magnitude; where the magnitude relates to the displacements along faults at the earthquake origin, the intensity is a measure of the shaking felt at the surface. Geological conditions can dampen or amplify the local ground motion. Earthquakes as small as 2.7 on the Richter scale have generated shaking strong enough to be felt by people locally in Denmark.

The earthquake hazard calculated for Denmark is low and comparable to the earthquake hazard for southern Sweden. Earthquakes occur most frequently in northern Sjælland and northern Jylland, in Kattegat-Skaggerak and the North Sea offshore Jylland. The largest hazard is found in northwestern Jylland and in the Northern part of Sjælland. The calculation is based on all available data, instrumental recordings as well as historical accounts. The calculation does not take into account potential future glaciations and the resulting postglacial rebound, which is known to generate large earthquakes in, for example, Sweden.

4 Climate change and sea level development

Merete Binderup

This chapter focuses on the Danish conditions concerning climate and sea-level development. To illustrate the variations in 'newer' times, the section starts with a resumé of the development of the climate and the sea level throughout the Holocene. This is followed by a short discussion of which future climate and sea level parameters that are important to focus on for the identification of a site suitable for deep geological disposal and with regards to long term stability in the subsurface.

4.1 Holocene climate change and sea-level development

The text in Chapter 4.1 is primarily based on Binderup et al. (2017).

Our current warm period, which is probably also an interglacial period, began with the Holocene that began with a temperature rise 11,700 years ago.

Ice cores drilled from Greenland's Inland Ice show signs of a marked increase in the temperature of the deposited snow. A rapid increase in temperatures during the first few years was followed by a short shift back to the cold ice-age temperatures; however, hereafter, in only 50 years approximately, the mean temperature rose 12-15º C. Studies of pollen show a similar abrupt change in vegetation in Denmark.

This significant increase of temperature caused the Scandinavian Ice Sheet to melt rapidly. Huge amounts of meltwater flowed into the sea, causing the sea level to rise and the sea to transgress low-lying earlier dry land areas. Amongst other things, this can be determined by observing a decrease in the amount of dust content in the ice cores, as there was a reduction of areas of exposed, dry sediments.

During the Holocene, the position of the Danish coastline has continuously been shifting – not only according to the development of the eustatic sea level but also influenced by the isostatic movements. During the Weichsel glaciation, the border zone of the Scandinavian Ice sheet transgressed a major part of Denmark from the northeast. The load of the ice pushed the land down. Later, when the ice melted away, the land was relieved from the load of the ice and began to rise. This 'isostatic rebound' was greatest in the north-eastern part of Denmark, where the ice loading had been largest; see Figure 4.4.

Overall, the climate became warmer in the Preboreal time (11,700-10,300 years ago). At first, it was appreciably warmer, but this short warm period was followed by 100-150 cooler years (the Preboreal Oscillation). Denmark was connected to southern England and Sweden. In Danish, the time is called 'Fastlandstiden' (Continental time), because the land was isostatically raising when the weight from the ice masses disappeared, and the elevation was faster than the sea level rise; see Figure 4.1. Some 10,300 years ago, the water level of the Baltic Ice Lake dropped 25 meters catastrophically fast when the lake was drained through the central part of Sweden.

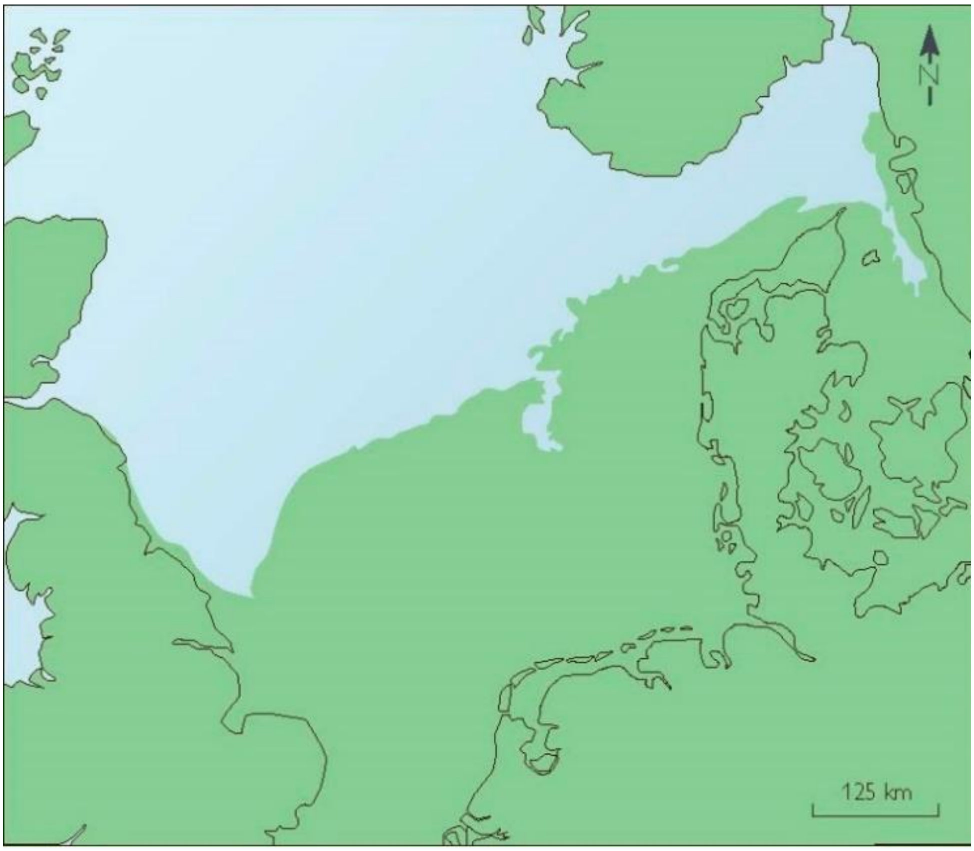
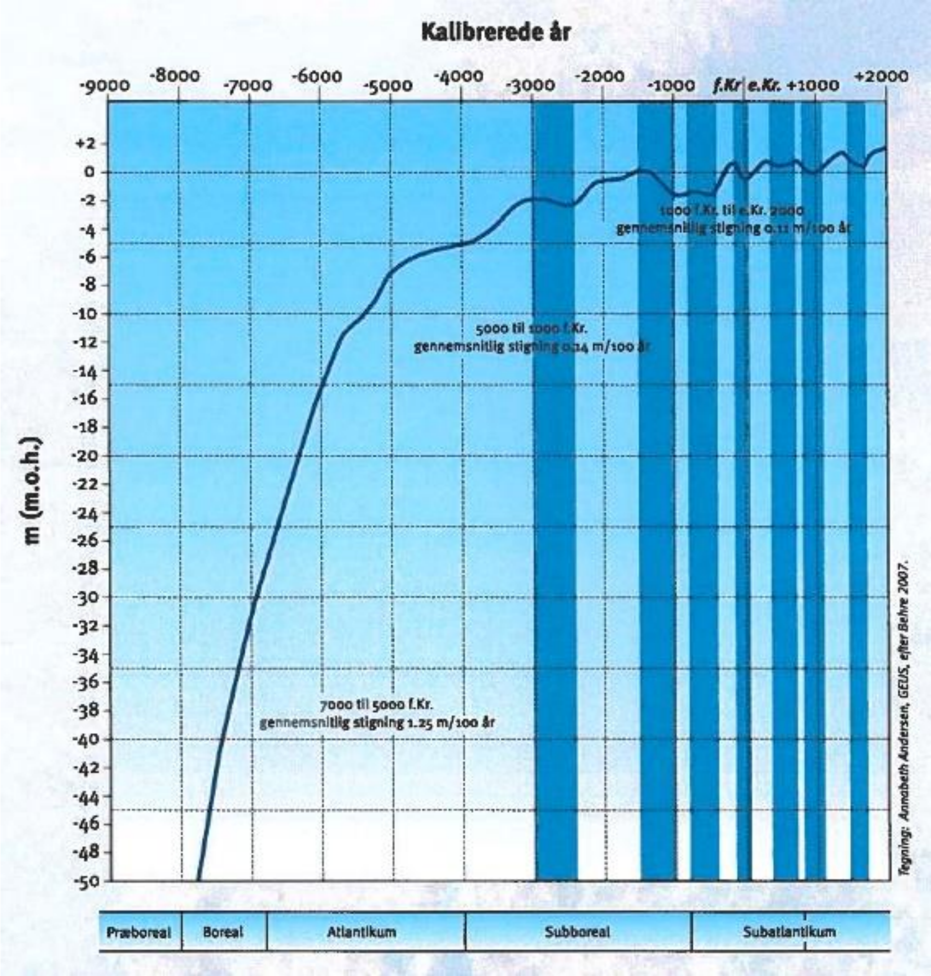


Figure 4.1. *Paleogeographic map of Denmark and Noth Sea areas in Preboreal and Boreal time. Land areas are green, the sea is blue. From Mathiassen (1997).*

Figur 4.1. *Palæogeografisk kort af Danmark og Nordsøområdet i Præboreal og Boreal tid. Land er markeret med grøn farve, hav med blå. Fra Mathiassen (1997).*

During Boreal time (10,300-9,000 BP), the climate became drier. The mean summer temperature was above 16^{o} C and the winters were not 'too cold' (the mistletoe was able to grow in Denmark) – the winter temperature for the coldest month (January) was not much below -1^{o} C.

Atlantic is the name of the period 9,000-6,000 years BP. During this period, the remaining part of the large ice sheets of Scandinavia and North America melted away and caused the sea level to rise rapidly; see Figure 4.2. In Denmark, this transgression is called the 'Littorina Sea'.



Tegning: Annabeth Andersen, GEUS, efter Behre 2007.

Figure 4.2. *The sea-level development in the southern North Sea during the last 10,000 years. The curve shows the level of the high-water stand – thus, it ends in +2 meters. The blue bars mark periods of falling sea level. The youngest of these was contemporaneous with the Little Ice age. From Behre (2007).*

Figur 4.2. *Havspejlsudviklingen i den sydlige Nordsø gennem de sidste 10.000 år. Kurven viser niveauet af højvandstanden – derfor ender den i +2 meter. De blå søjler angiver perioder med faldende havspejl. Den yngste af disse er samtidig med Den lille Istid. Efter Behre (2007).*

About 8,900 years BP, the global sea level had raised to such a level that the English Channel came into existence, and Denmark was separated from England. However, the South Danish archipelago and the Wadden Sea were still part of a continuous land mass.

The sea-level rise was faster than the isostatic rebound and caused a transgression in parts of Denmark; see Figure 4.3. The melting of the ice sheets was due to the fact that the temperature during the Holocene reached its maximum in the Atlantic Time. The climate of Denmark became warm and humid like the present-day climate of Middle Europe.

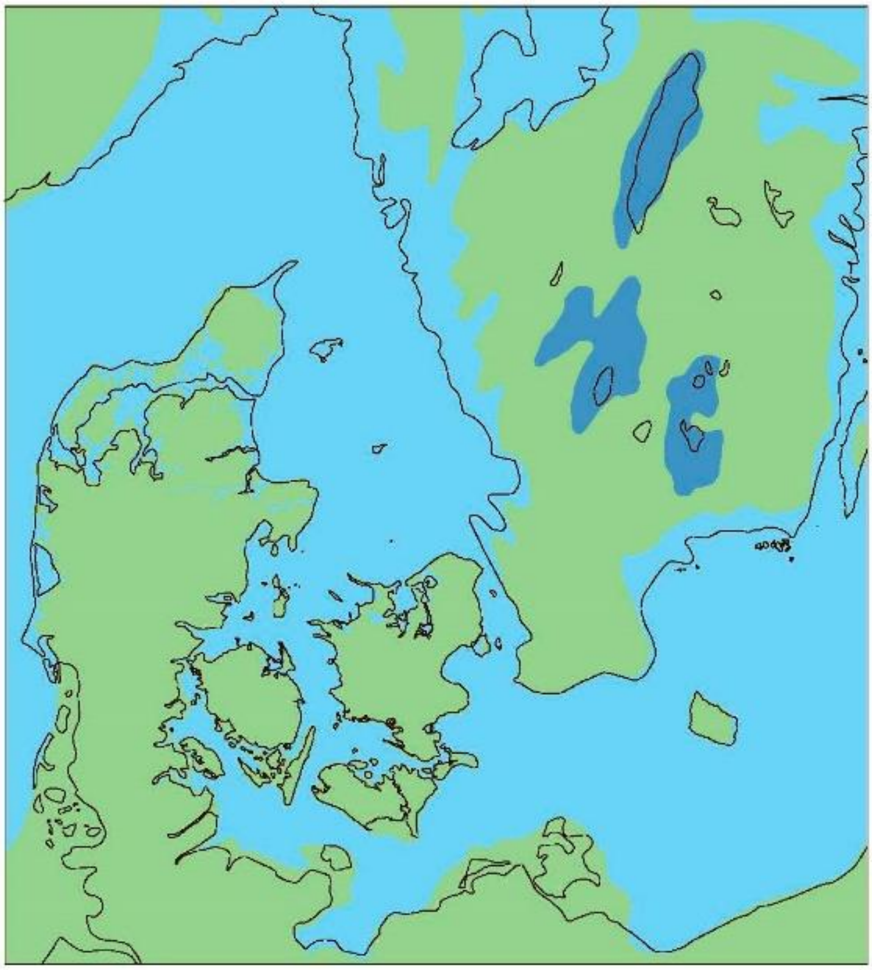


Figure 4.3. *Paleogeographic map. The Atlantic time with the Littorina Sea transgression. Land areas are green, the sea is blue. From Mathiassen (1997).*

Figur 4.3. *Palæogeografisk kort. Atlantisk tid med Littorina-transgressionen. Landarealer er vist med grøn farve, hav med blå. Efter Mathiassen (1997).*

The transgression was not a single event – at least four transgressions (called the Littorina transgressions) have been documented in Denmark: An early Atlantic, a high Atlantic, the sub-Atlantic and the Subboreal phase.

The period from 6,000 to 3,500 years BP is called Subboreal. The temperature,as reconstructed from drillings into the Greenland's Inland Ice, saw a drop of approximately 2^{o} C during the last 6,000 years, primarily from 5,000 to 3,000 years BP. About 2,800-2,600 years ago, the climate changed to a more humid climate; possibly, a simultaneous change took place toward more storminess and higher wind speeds causing sand drift.

The last 2,000 years have been particularly marked by a warm period which peaked about the year 900, and by the Little Ice Age between 1,300 and 1,750 AD.

After the sea level reached its maximum some 2,000 years ago, the isostatic rebound continued – and it is still going on; although, compared to the situation right after the ice melted away, the rate is much smaller now (see below).

As seen in Figure 4.4, the isostatic rebound continuously happening since the Atlantic time has resulted in a distribution of the ‘highest marine level’ (also called the Littorina coastline). Farthest north-east where the ice load was largest, the coastline is situated at the highest level. Towards southwest the level decreases. South of the line from the southern part of Nissum Fjord in the west to the northern part of Falster in the east (the 0-meter isobath in Figure 4.4), the sea level rise has exceeded the isostatic rebound, and the coastline from the Littorina Sea is located on the sea bottom under several meters of water.

Figure 4.4. *Isobaths of the relative land uplift since the maximum of the Littorina Sea in Denmark – presented in meters. From Mertz (1924).*

Figur 4.4. *Isobaser for den relative landhævning siden Littorinatidens maksimum i Danmark, angivet i meter. Efter Mertz (1924).*

4.2 Climate change and sea level development until 2073

This chapter is partly based on reports from the Intergovernmental Panel on Climate Change (IPCC). The chapter focuses on the topics that may have an impact on the Danish land area, including the coastal zone, in the future.

The ongoing climate change will affect many climate parameters (and parameters connected with these) such as temperature, precipitation, cloudiness, the sea level, wind conditions etc. However, the deposit is planned to be a deep geological repository safely located 500 meters below terrain for 500,000 years; from this point of view and added that the deposit has to be able to, for example, withstand one or more ice ages and interglacial periods with deep erosion, large isostatic movements and eustatic fluctuations, floods and so on (see Chapter 2), most of the above parameters are not critical.

When the repository is operating in 2073, what *is* relevant to deal with is the risk of having the entrance to the subsurface facilities flooded.

Flooding can be caused in two ways: either from a net sea level rise or from individual sea floodings caused by wind and the tide; therefore, sea-level rise and changing wind patterns are necessary to be reckoned with. Because Denmark is located between the North Sea and the Baltic Sea (see Figure 4.6), and because changing wind conditions (strength, duration, direction and frequency of storms) can make the flood/wind setup larger and more frequent, this can affect the entrance to the shaft/repository. At the stage where the repository is under construction and until it is finally sealed, it is important that it is not flooded.

4.2.1 Sea-level development until 2073

IPCC published its First Assessment Report in 1990. Since then, several reports have followed. As new knowledge and data have been included to refine the models in each of these, the forecast for the sea-level development in this century has changed slightly from report to report.

In the fifth and latest Assessment Report published in 2014 (IPCC, 2014), IPCC writes:

‘There has been significant improvement in understanding and projection of sea level change since the AR4. Global mean sea level rise will continue during the 21st century, very likely at a faster rate than observed from 1971 to 2010. For the period 2081–2100 relative to 1986–2005, the rise will likely be in the ranges of 0.26 to 0.55 meters for RCP2.6, and of 0.45 to 0.82 meters for RCP8.5 (medium confidence) (Figure 4.5b). Sea level rise will not be uniform across regions. By the end of the 21st century, it is very likely that sea level will rise in more than about 95 % of the ocean area. About 70 % of the coastlines worldwide are projected to experience a sea level change within ±20 % of the global mean, see [Figure 4.5].’

In 2073, the global mean sea level is predicted to be some 0.23-0.57 meter higher relative to 1986-2005 (see Figure 4.5b) or approximately 15 to 49 cm above the present (2019).

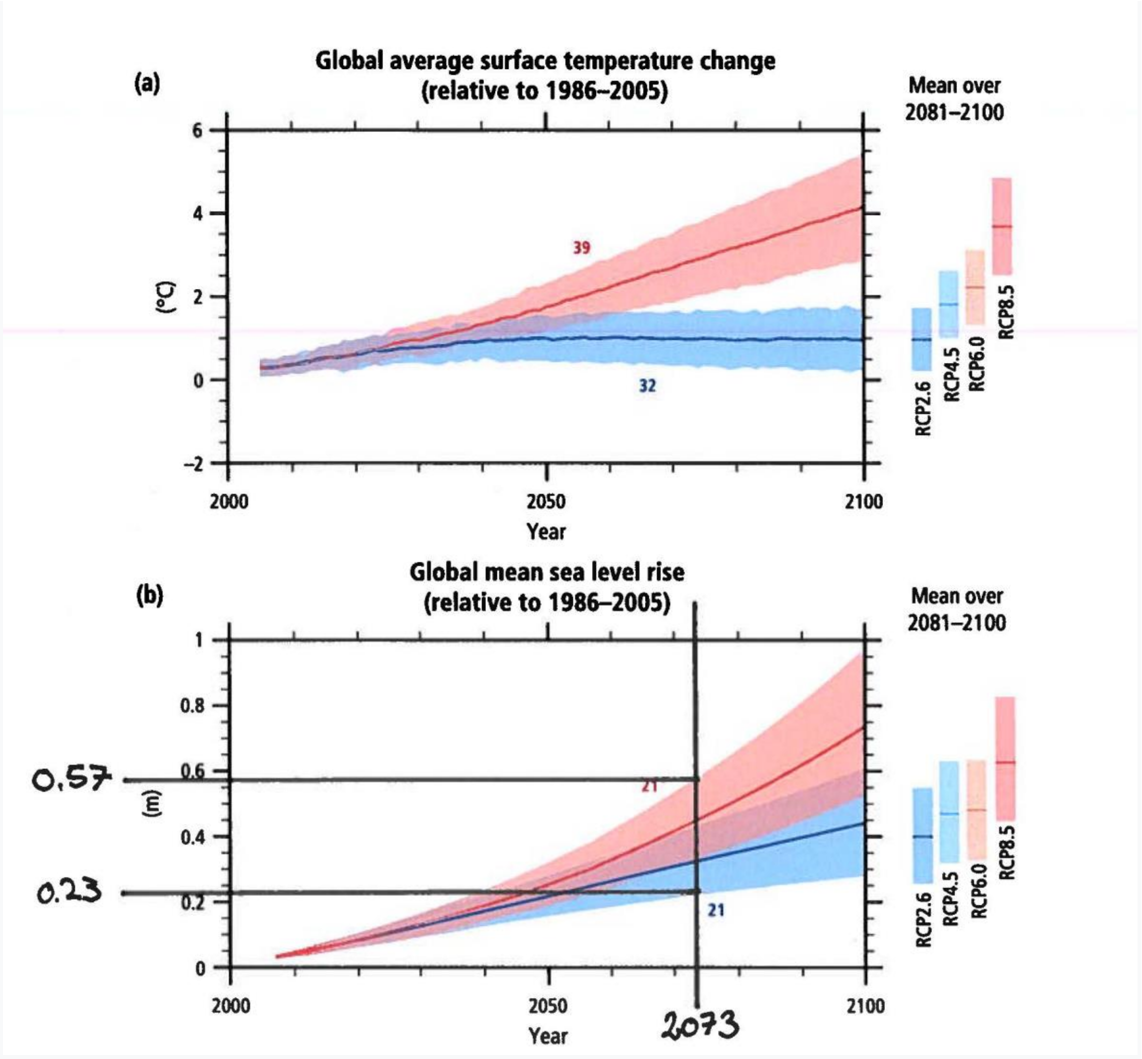


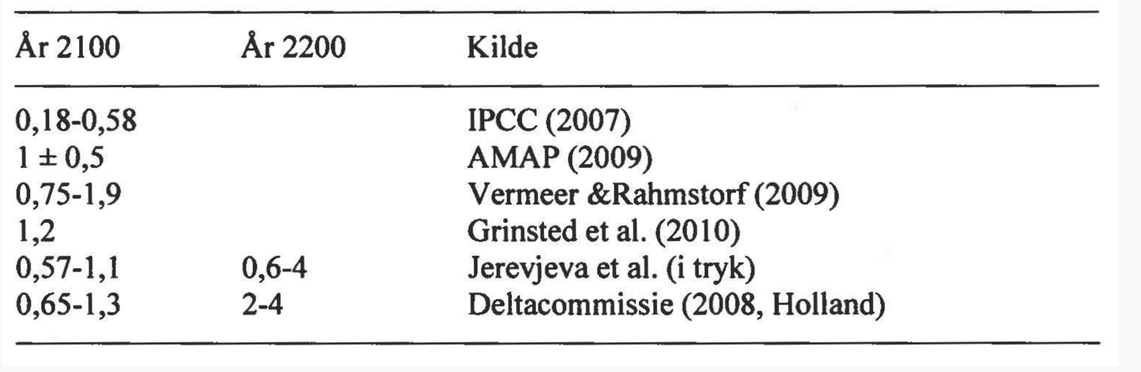
Figure 4.5. *Global average surface temperature change (a) and global mean sea level rise (b) from 2006 to 2100 as determined by multi-model simulations. All changes are relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as colored vertical bars at the right-hand side of each panel. The number of 'models' used to calculate the multi-model mean is indicated with numbers inside the diagram. From IPCC (2014).*

Figur 4.5. *Den globale gennemsnitlige overflade-temperaturændring (a) og den globale havspejlsstigning (b) fra 2006 til 2100 bestemt ved multi-model-simuleringer. Alle ændringer er i forhold til perioden 1986–2005. Tidsserier af fremskrivninger og et mål for usikkerheden er vist med "skraveringer" for scenarie RCP2.6 (blå) og RCP8.5 (rød). Middelværdier og tilknyttede usikkerheder midlet over perioden 2081–2100 er angivet for alle RCP-scenarier som farvede vertikale barrer i højre side af figurerne. Antallet af 'modeller' anvendt til at beregne middel-multi-modellen er vist med tal inde i diagrammerne. Fra IPCC (2014).*

As well as the estimations by IPCC changes from report to report, different papers present different estimations of the future sea-level rise. In 2012, scientists from GEUS and DMI prepared a memo (GEUS & DMI, 2012) on changes of the sea level in Denmark during the next 100-200 years. Table 4.1 is from this memo.

Table 4.1. *Different estimates of future global sea level changes (meters). From GEUS & DMI (2012).*

Tabel 4.1. *Forskellige estimater af fremtidige globale havspejlsændringer (meter). Fra GEUS & DMI (2012).*



År 2100	År 2200	Kilde
0,18-0,58		IPCC (2007)
1 ± 0,5		AMAP (2009)
0,75-1,9		Vermeer &Rahmstorf (2009)
1,2		Grinsted et al. (2010)
0,57-1,1	0,6-4	Jerevjeva et al. (i tryk)
0,65-1,3	2-4	Deltacommissie (2008, Holland)

4.2.2 Isostatic rebound

No matter the exact magnitude of the future global sea-level rise, Danish coasts will not be affected equally hard.

The process of isostatic rebound is still active, see for example Figure 4.6. In the northernmost part of Denmark, the present isostatic uplift is approximately 1.5 mm/yr (i.e. Frederikshavn). This region will not be hit by the ongoing sea-level rise as early as the southern part of Denmark, where the land is subsiding (e.g., -0.25 mm/yr in the southern part of Fyn).

FIGURE 4.6, NEXT PAGE:

Figure 4.6. *Present time isostatic uplift rates (mm/yr) in Denmark and parts of its surrounding countries. The dotted line shows the boundary between two areas with different patterns of movement. This results in two 0-lines (Nissum Fjord-Nyborg-Præstø and Fanø-Sønderborg-Gedser), where the crust does not rise nor fall. From GEUS & DMI (2012) and Hansen et.al (2012).*

Figur 4.6. *Nutidige isostatiske hævningsrater (mm/år) for Danmark og omegn. Den grå, stiplede linje angiver grænsen mellem to regioner med forskellige bevægelsesmønstre. Dette resulterer i to 0-linjer (Nissum Fjord-Nyborg-Præstø og Fanø-Sønderborg-Gedser), hvor skorpen hverken synker eller hæver sig. Fra GEUS & DMI (2012) og Hansen et.al (2012).*

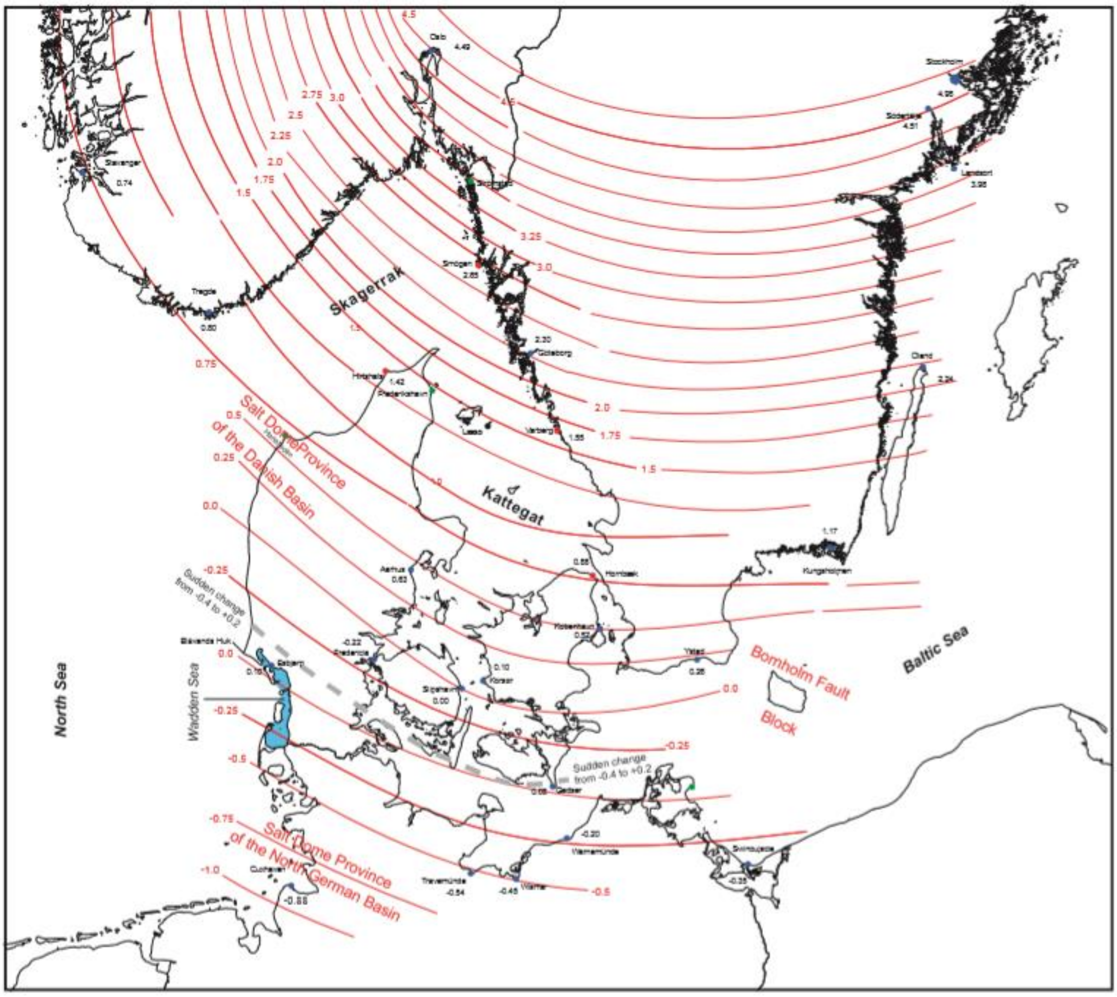


Figure 4.6. See previous page for figure text.

Figur 4.6. *Se figurtekst på forrige side.*

4.2.3 Wind forecast and flooding situations

The reasons for flooding situations along the Danish coasts differ from region to region. Below is a review of three major regions especially exposed to flooding: the Danish North Sea coast (the Wadden Sea and the Limfjord), the southern part of Kattegat and the region south of the belts.

4.2.3.1 The Danish North Sea coast

The Danish North Sea coast is exposed towards west – the direction where most of the storms come from. Especially the southwestern part of this region – the Wadden Sea coast – is exposed to flooding owing to the strength and frequency of the storms from westerly directions, the long fetch (big waves can move huge amounts of water towards the coast) and the shallow coast. On top of the wind induced water setup, the contribution from the astronomically induced tide must be added. The tidal range is largest closest to the German border (approximately 2 meters) and diminishes towards north (to about 1 m) at Blåvandshuk (primarily from DMI (2018)).

The Wadden Sea coast – examples of flooding in historical time:

1362 (January): 'The (first) Great man drowning'. The water level is uncertain, but some 10,000 people drowned, and the area was abandoned for many years.

1634 (October): 'The Second Man Drowning'. The water level reached 6.3 meters (19 feet) above normal, and the water stood high above the floor of Ribe Cathedral.

1981 (November 24th): an extremely powerful storm over the North Sea caused the water level in Esbjerg to reach 4.3 meters above normal, the highest level of water that DMI has ever measured in the port – that is, for more than 120 years.

1999 (December 3rd): Hurricane. The flood occurred due to a small, very intense low pressure that quickly moved across Denmark from west to east. In Esbjerg, the water level reached just below 4 m; see Figure 4.7. In Ribe, the water stood 5.1 meters above normal when the tidal gauge collapsed. By a fortunate coincidence, the water level peaked at low tide. If the storm had culminated either at the high water 6 hours earlier or at high water 6 hours later, the water level had been 1-1.5 meters higher and the highest registration in Ribe for 500 years – enough to flood the Ribe dike. At its peak, the water level stood only 30 cm below the top of the dike.

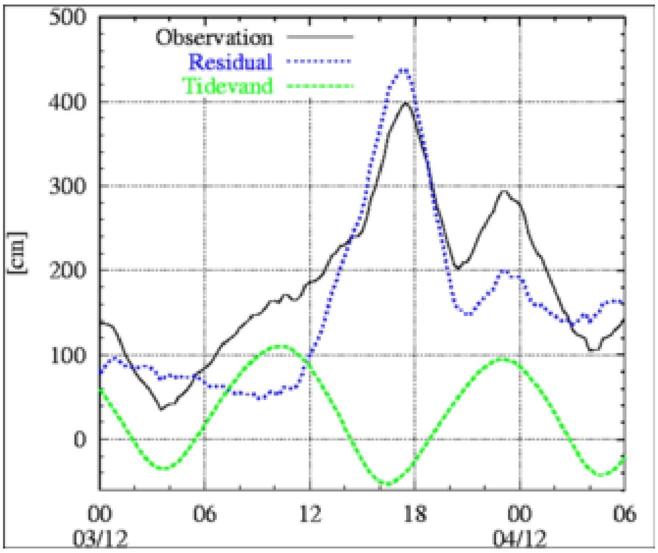


Figure 4.7. *The water level in Esbjerg during the hurricane 3rd December 1999 reached 4 meters above daily waters. The storm itself increased the water level by barely 4.4 m, but fortunately it reached its maximum at low tide. If the storm had peaked at high tide, the water level in Esbjerg would probably have reached 5.4-5.5 meters – an unprecedented level. From: DMI (2018).*

Figur 4.7 (forrige side). *Havspejlet i Esbjerg under orkanen 3. dec. 1999 nåede 4 meters over daglig vande. Selve stormen hævede havspejlet med knap 4,4 meter, men til alt held indtraf den maksimale vandstand mens der var astronomisk lavvande. Hvis stormen havde* *kulmineret ved højvande, ville havniveauet i Esbjerg sandsynligvis have nået 5,4-5,5 meter over daglig vande – et niveau uden fortilfælde. Fra: DMI (2018).*

The Limfjord coast – example of flooding in historical time:

Limfjorden, especially the western part of the fjord with the broads, is also exposed to floods during storms from westerly directions. From the North Sea, the water is forced through the Thyborøn Canal, and because of the narrow straits at Aggersund and Aalborg, the water piles up in the broads, where low-lying areas (and cities like Løgstør and Lemvig) are flooded; see example:

2005 (January): A westerly wind reached hurricane strength over Skagerrak and along large parts of the west coast of Jylland. In Hanstholm, the middle wind reached 35 meters per second (m/s). The storm gave rise to elevated water levels along the entire Jylland west coast. The Limfjord was most severely hit. Here, even before the storm, the water level was very high, due to a long period of wind from the west in the days before the storm. Parts of Løgstør and Skive had to be evacuated when the water level exceeded all previous records, and several residential areas were flooded. In Løgstør, before the tide gauge was damaged, the water level reached 2.26 meters above normal. Most likely, the maximum level reached somewhat higher.

4.2.3.2 The southern part of Kattegat

Compared to storms from westerly directions, storms from northerly directions are less frequent; however, when they hit Denmark (in average once a year), the southern part of Kattegat is exposed to floods.

Low-lying areas along Randers Fjord are especially subjected to floods from the southern part of Kattegat. In the fjord, flooding situations will be worsened by coinciding with heavy rainfall, high groundwater levels and/or melting snow covers.

Likewise, low-lying areas are threatened along Odense Fjord, Isefjord, Roskilde Fjord and Øresund as far south as København.

In the southern part of Kattegat, the astronomical tide is modest: the tidal range in Randers Fjord and Odense Fjord is less than 50 cm; in Holbæk it is less than 30 cm, København less than 20 cm and in Roskilde less than 10 cm.

In recent years, the southern part of Kattegat has been hit by several storms (e.g. Urd and Allan) and floods, but not as severely hit as by Bodil, the worst example of a flood for this region in newer time:

2013 (December): The hurricane-like storm called Bodil came from west at first and then turned to north-west – a perfect situation for forcing huge amounts of water from Skagerrak to Kattegat. Owing to bottleneck problems in the sounds, the water piled up in the southern part of Kattegat, flooded low-lying areas and caused serious coastal erosion. In the southern part of Roskilde Fjord, the water level reached 2.06 meters above normal; 1.96 meters in

Hornbæk and 1.65 meters in Nordhavn, which was 13 cm more than the old record from 1921 in København.

4.2.3.3 The region south of the belts

The southern part of Denmark is exposed to floods when storms come from an easterly direction. Once again, owing to bottleneck problems in the sounds, the water piles up in the southwestern part of the Baltic Sea and low-lying areas become flooded. In this part of Denmark, the tidal range is less than 15 cm. In 2017 (January) the southern part of Denmark was hit by a severe flood. The water level reached 1.70 meters above normal in Aabenraa; 1.65 meters in Sønderborg and 1.61 meters in Rødbyhavn and Gedser. The flood was the worst since 1913 (December), where the water level reached 1.91 meters in Gedser, the only place in southern Denmark where a tide gauge has been present since the late nineteenth century (Kystdirektoratet 2018). However, these two flood situations never came close to the catastrophic flooding of the region in 1872.

In 1872 (November) the worst storm surge known in the Baltic hit the southern part of Denmark. A very seldom weather situation led to a flooding of one third of Lolland (and many other low-lying areas) when the water level reached 3.5 meters above normal. During several days, a severe westerly wind had forced huge amounts of water into the inner Danish waters, and – likewise – the water in the Baltic was forced into the Finnish Gulf and the Gulf of Bothnia. After a few windless days and as the water was running back, a hurricane-like storm from north-east accelerated the ‘backrush’ of the waters, causing the catastrophic flooding (Klerk 2015).

4.3 Summary of climate change and sea level development

The ongoing climate change will affect many climate parameters such as temperature, precipitation, cloudiness, sea level change and wind conditions. But from the point of view that the repository will be located 500 meters below terrain most of the above parameters are not that critical. Until the repository is permanently closed, what is most relevant to deal with is the risk of it being flooded during the construction and operation phase.

The flooding risk is dependent on the altitude above sea level of the geographic location, and the regions general risk of flooding. As the sea level rises, the magnitude and frequency of flooding increase in areas of low altitude – especially in the southern parts of Denmark where the isostatic rebound is negative. Moreover, climate change will most likely cause changes in wind patterns, including wind direction, strength and frequency of storms; all of which will enhance the risk of flooding.

As part of the decision on the location of the deep geological repository the flooding risk should be addressed based on most recent flood models from The Danish Coastal Authority and The Danish Meteorological Institute. If the preferred area is in a geographic area with risk of flooding the eventual need for engineered mitigations should be identified.

5. Groundwater conditions in Denmark

Bertel Nilsson

5.1 Introduction

Subsurface water has been given different names depending on which academic discipline you are coming from. The petroleum and geothermal production industry often use the term *formation water*. Most geoscientists and engineers working within the groundwater sector usually use the term *groundwater* reserved for subsurface water that occurs beneath the water table in soils and geological formations that are fully saturated. However, geochemists sometimes use the term *formation water or porewater* for the water standing in the small pores in low permeable soils. In this chapter, the term groundwater is used as a generic term independently of what depth the water occurs in, the hydrological cycle, if the water is extracted for water supply from high permeable horizons or sampled for interdisciplinary scientific purposes in low permeable horizons.

In Denmark, groundwater supply almost all water (99.4 %) for drinking water purposes, food and industrial production. The net precipitation varies across Denmark, with more than 500 mm/year in western Jylland to about 200 mm/year at Sjælland. The recharge of the regional and deep aquifers in western Jylland is around 300 mm/year, and in most of Sjælland around 100 mm/year.

The groundwater aquifers at Jylland, Fyn and Sjælland consist of three different geological materials: chalk/limestone, sand/gravel and fractured bedrock. Figures 5.1-5.3 show three cross-sections: (a) Southwest – Northeast trending profile 1 of northern Jylland, showing regional and deep Maastrichian chalk aquifers covered by 50-100 meters thick glacial deposits, including regional and shallow glacial sand and gravel aquifers (Figure 5.1). The Quaternary deposits – and to a lesser extent, the chalk deposits – are used for water supply in northern Jylland. (b) West-Eeast trending profile 2 in southern Jylland where regional to deep Miocene sand aquifers of Odderup, Bastrup and Billund Formations with low permeable interbedding layers of Miocene clay and silt deposits (Arnum and Klinting Formations) are covered by shallow glacial sand and gravel aquifers (Figure 5.2). Quaternary and Miocene sands in southern Jylland are all used for water supply. (c) Southwest-Northeast oriented profile 3 of northern Sjælland consists mainly of a regional Danian limestone aquifer covered by glacial deposits, shallow glacial sand, and gravel aquifers (Figure 5.3). In northern Sjælland groundwater is abstracted for water supply from both the Quaternary and chalk aquifers.

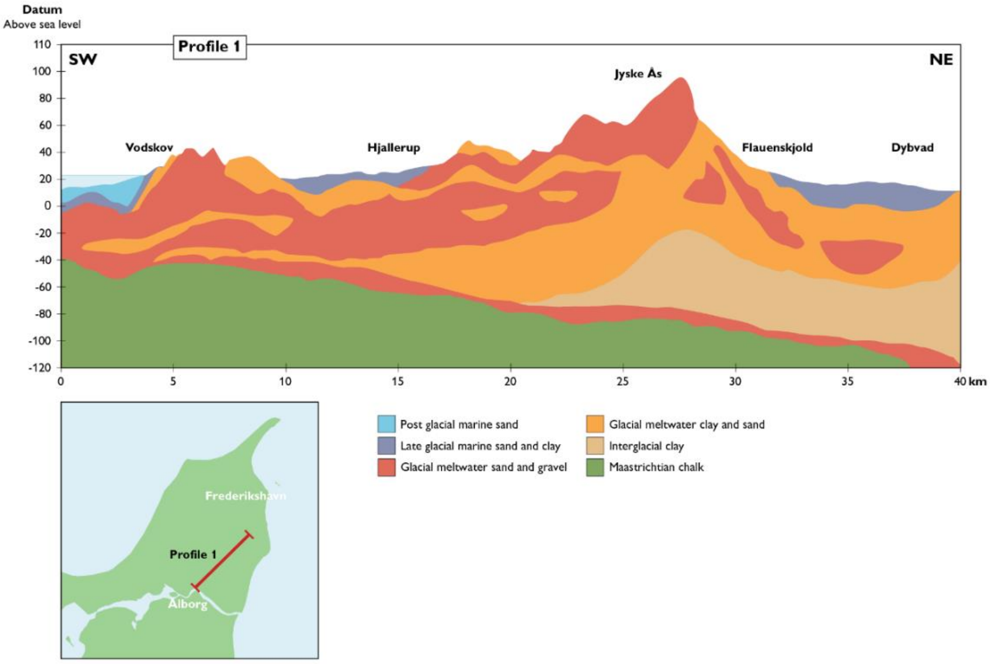


__Figure 5.1.__ A SW-NE cross-section through the upper 150-200 meters of Quaternary and Cretaceous sediments in northern Jylland (DTU et al., 2016).

__Figur 5.1.__ Et SV-NØ-tværsnit af de øverste 150-200 meter sedimenter af Kvartær og Kridt alder i nordlige Jylland (DTU et al., 2016).

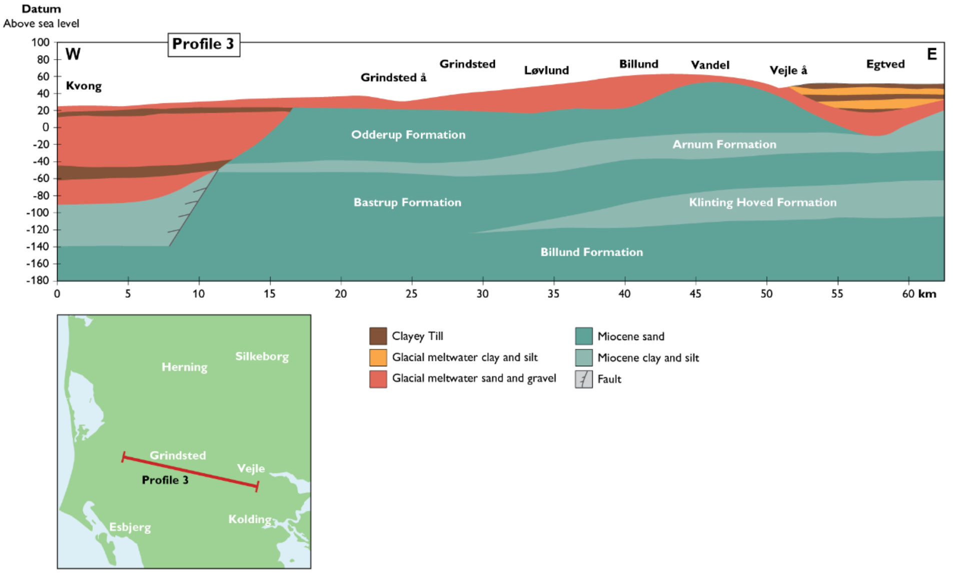


__Figure 5.2.__ A W-E cross-section through 200-250 meters Quaternary and Miocene sediments in southern Jylland (DTU et al., 2016).

__Figur 5.2.__ En V-Ø-tværprofil af 200-250 meter kvartære og miocæne sedimenter i det sydlige Jylland (DTU et al., 2016).

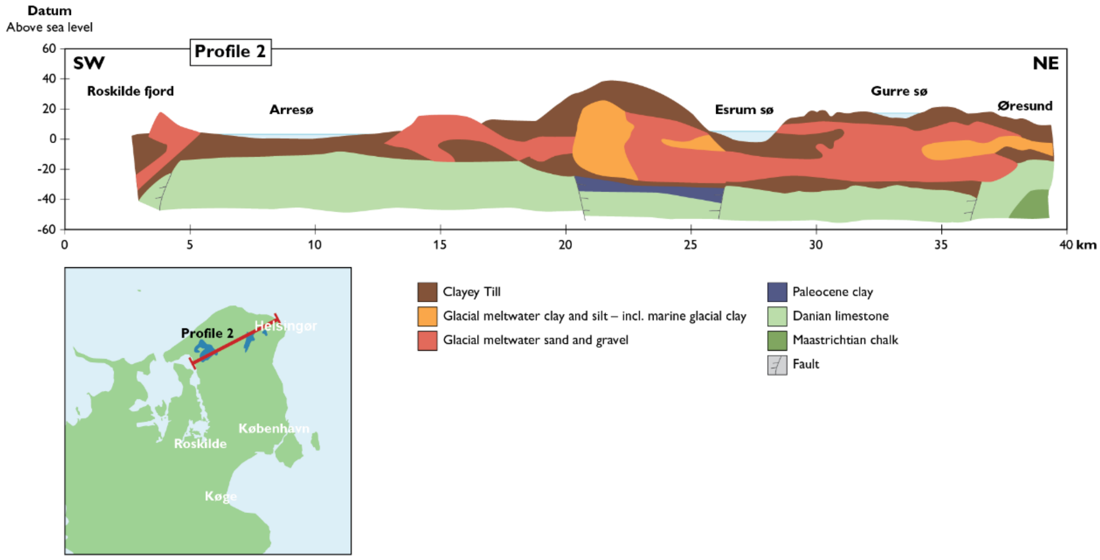


Figure 5.3. *A SW–NE cross-section through 80-100 m Quaternary, Tertiary and Cretaceous sediments in northern Sjælland (DTU et al., 2016).*

Figur 5.3. *Et SV–NØ tværprofil af 80-100 meter kvartære, tertiære og kretassiske sedimenter i Nordsjælland (DTU et al., 2016).*

5.1.1 National well database (Jupiter)

Jupiter is GEUS' nationwide database for groundwater, drinking water, raw materials, environmental and geotechnical data (https://eng.geus.dk/products-services-facilities/data-and-maps/national-well-database-jupiter/). The database is the common public database within the field and is part of Denmark's Environment Portal. The database is open to the public. The database contains information about more than 280,000 wells. Additionally, the database contains information about more than 35,000 water abstraction plants (e.g. waterworks and irrigation systems). This database is the major source of information used to evaluate the quantitative and chemical state of the Danish groundwater resources.

5.1.2 Groundwater bodies in Denmark

Prior to the third basis analysis of the EU Water Framework Directive, a new delineation of the groundwater bodies in Denmark had been made by Troldborg (2020). The term *groundwater body* is defined as an EU administrative unit of the groundwater resource that covers one or several hydraulic connected aquifers into one groundwater body. The groundwater bodies are divided into shallow, regional and deep groundwater bodies. *A shallow groundwater* body is defined as one or several hydraulic connected aquifers to a depth of less than 25 meters and a horizontal extensional area of less than 250 km^2. *A regional groundwater body* is placed deeper than 25 meters below surface and has a horizontal areal extension of more than 250 km^2. Shallow and regional groundwater bodies share the characteristic of being in potential hydraulic contact with surface water bodies (e.g. rivers, lakes or coastal waters). *Deep groundwater bodies* are characterized by laying deeper than 25 meters below surface and having no hydraulic contact to the surface water bodies on land. Location of the shallow, regional and deep groundwater bodies are shown in Figures 5.4-5.6. The geology of the groundwater bodies is divided into Quaternary sand, pre-Quaternary sand, chalk and limestone and bedrock. In each of the groundwater bodies (shallow, regional and deep) is a mixture of groundwater bodies with different geology.

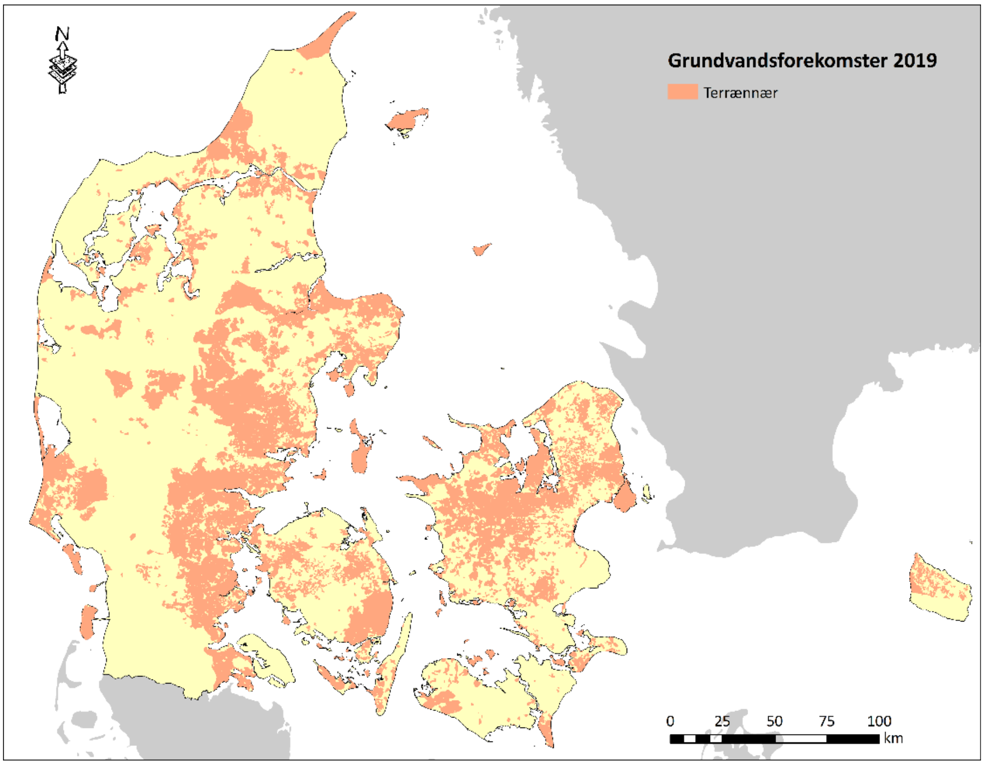


Figure 5.4. *Distribution of shallow groundwater bodies. From Troldborg (2020).*

Figur 5.4. *Udbredelse af terrænnære grundvandsforekomster. Fra Troldborg (2020).*

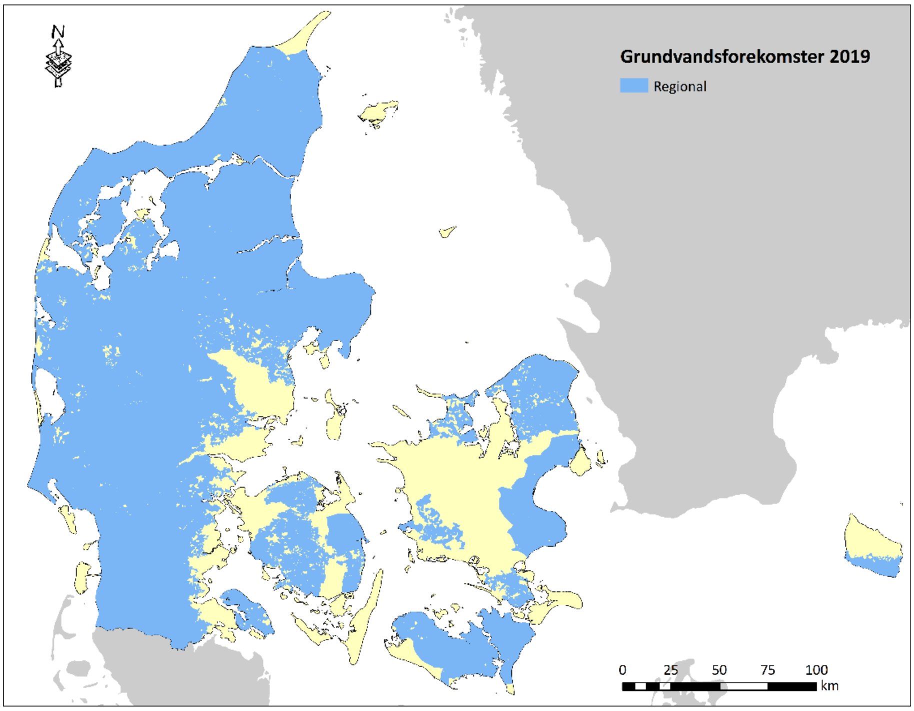


Figure 5.5. *Distribution of regional groundwater bodies. From Troldborg (2020).*

Figur 5.5. *Udbredelse af regionale grundvandsforekomster. Fra Troldborg (2020).*

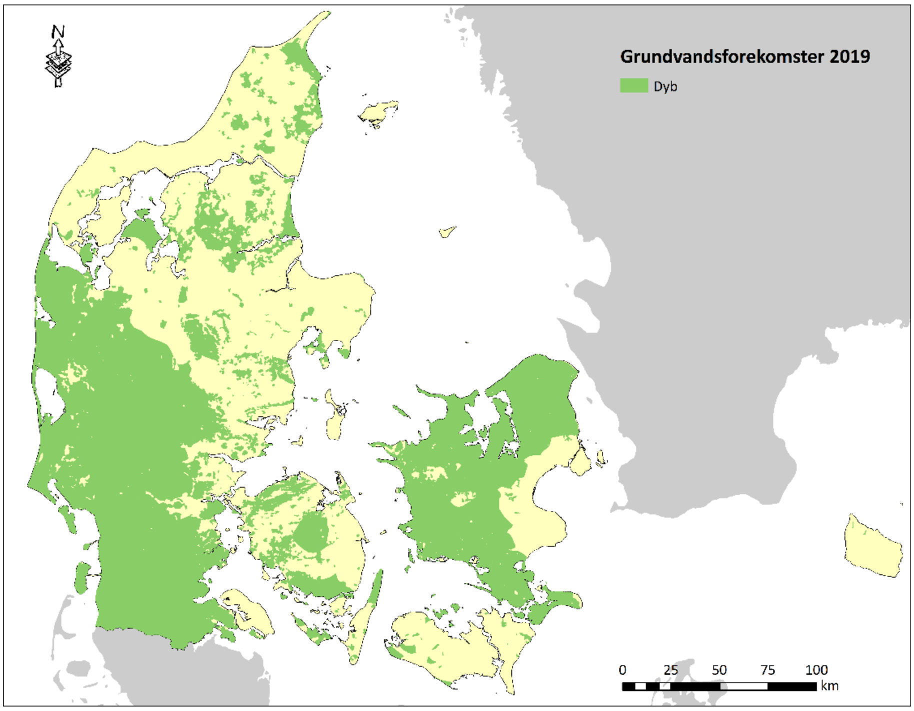


Figure 5.6. *Distribution of deep groundwater bodies. 'Deep' designates maximum depth of 200-250 meters. From Troldborg (2020).*

Figur 5.6. *Udbredelse af dybe grundvandsforekomster. I denne betydning betyder 'dybe grundvandsforekomster' til maksimale dybder på 200-250 meter. Fra Troldborg (2020).*

5.2 The hydrological cycle and saltwater/freshwater interface

In coastal areas, freshwater aquifers are in direct contact with the ocean. The dense saltwater typically circulates inland, creating a saline zone or “wedge” below the less dense overlying freshwater aquifer (Bear, 1999). The contact between the freshwater and saltwater is referred to as the freshwater/saltwater interface. This interface may be sharp and characterized by an abrupt transition from freshwater to saltwater. But more commonly, it is transitional due to mixing and diffusion processes. Under natural conditions, fresh groundwater flows towards the ocean; flow of freshwater is predominantly driven by topography but is also influenced by the aquifer’s hydraulic conductivity. The position of the freshwater/saltwater interface depends on the magnitude of freshwater discharge, which responds to climatic variation by moving seaward if the hydraulic gradient increases, or by moving landward if the hydraulic gradient decreases (Lyles, 2000). Changes in the hydraulic gradient – e.g. due to groundwater abstraction from coastal aquifers and canal drainage of low-lying areas as seen at Lolland-Falster (Rasmussen et al., 2013) – will impact the natural balance between the freshwater and saltwater.

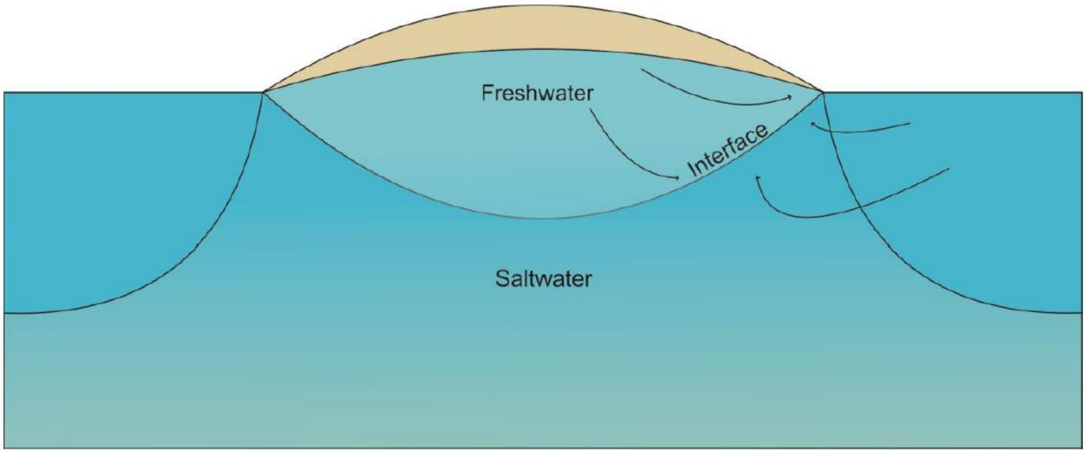


Figure 5.7. *Conceptual model of the freshwater/saltwater interface. Underneath islands, the freshwater lens is surrounded by saltwater.*

Figur 5.7. *Konceptuel model for saltvands-ferskvandsgrænsen. Under en ø er ferskvandslinsen omgivet af saltvand.*

Figure 5.8 illustrates a conceptual understanding of groundwater flow paths under an island, using Sjælland as example; it includes recharging precipitation into the soil and groundwater flow from the groundwater table along flow lines with different penetration depths to finally discharge as surface water in rivers, lakes or coastal waters. Most likely, saltwater from the coastal areas (Øresund and Storebælt) penetrates the seabed like precipitation do on land; therefore, there is a transition zone below Sjælland, beneath which, all the groundwater is salty. This can only occur because new freshwater is constantly generated from above, and, as the freshwater pushes the saltwater downwards and towards the coast, the upper layers are fresh. The endless circulation of water between ocean, atmosphere and land is called the hydrological cycle.

5.2.1 Groundwater age dating

The groundwater ages indicated in Figure 5.8 represent the expected minimum time for a water particle to follow a flow path from recharge of net precipitation, into the groundwater zone, and finally discharge of groundwater into a surface water body.

Calculated groundwater flow patterns and residence times can be verified by groundwater dating. There is a range of dating methods available based on radioactive decay (Cook and Herczeg, 2000). These comprises tritium (^{3}H), tritium/helium ($^{3}H/^{3}He$) and krypton (^{85}Kr) for young groundwaters of up to 50 years, radiocarbon (^{14}C) for older groundwaters up to 30,000 years, and finally isotopes like cosmogenic krypton (^{81}Kr) and chloride (^{36}Cl) for even older groundwaters. Using the latter method, groundwater has been dated to an age of 400,000 years (Collon et al, 2000). Groundwater dating has been most successful used in porous media as sand and gravel aquifers. More uncertain groundwater ages arise in dual porosity media like fractured chalk/limestone, due to mixing of groundwater ages in fracture/matrix domains when sampling for ground age isotopes.

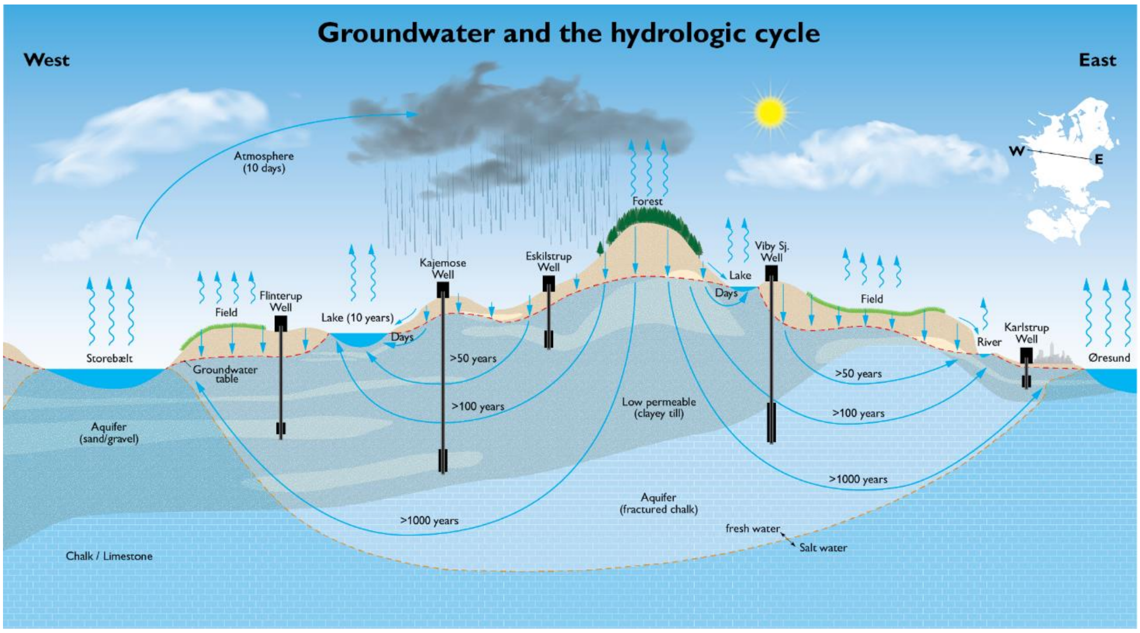


Figure 5.8. *Illustration of the hydrological cycle of an island. This island could represent the cycle for the islands Sjælland, Lolland or Falster. Hypothetic groundwater age distribution in the freshwater lens along groundwater flow paths are included; also, potential deep wells for age dating are indicated (black vertical lines). Modified from Geoviden (2019).*

Figur 5.8. *Illustration af vandets kredsløb på en ø. Øen kunne repræsentere kredsløbet på Sjælland, Lolland eller Falster. Der er vist hypotetiske grundvandsaldersfordelinger langs forskellige strømningsveje i ferskvandslinsen under øen. Mulige dybe boringer til en fremtidig aldersdatering er vist på figuren (sorte vertikale linjer). Modificeret fra Geoviden (2019).*

Bomb tritium was first measured in Danish groundwater in the mid-1960s in the Karup river catchment – during an investigation of wells with the purpose to verify the residence time of young groundwater, later presented in a simple groundwater flow model by Andersen and Sevel (1974). More recent dating of older groundwater has been carried out in screened wells from 20 to 400 meters depth in Jylland. The deep well in Tinglev reaches older groundwater from the Weichsel glaciation with an age of up to 15,000 years in a sand-filled, buried valley in Jylland (Meyer et al., 2018). In the bottom of that buried valley with chloride concentrations as high as 3100 mg/l. In addition, the National Groundwater Monitoring Program (GRUMO) groundwater dating has been done to divide groundwater into younger and older groundwater and to relate the groundwater dating with findings of agrochemicals (nutrients and pesticides) in monitoring wells to, finally, evaluate the effects of national action plans on the aquatic environment (Hansen et al., 2010).

5.2.2 Transport mechanisms below the saltwater/freshwater interface

Frykman et al. (2020) have evaluated the transport mechanisms of chemical constituents in down to 500 meters depth (the approximate depth of a future repository). Based on data on porosity and permeability compiled from different Danish chalk locations down to depths of 550 meters, it is concluded that due to very low permeabilities measured in the 300-550 meters depth range, most likely, diffusion processes control the migration of chemical constituents. These findings are in good agreement with Bonnesen et al. (2009) who investigated deep saltwater in chalk down to 450 meters depth in the Stevns Klint area. Measured vertical hydraulic heads in open boreholes suggest that vertical advective groundwater flow is restricted to the upper fractured parts of the chalk formation in this area, and that, at Stevns Klint, diffusive transport is the predominant transport mechanism at the repository depth of 500 meters.

5.2.3 Timescales of change in groundwater systems

Safety assessments for geological disposal of intermediate and high-level radioactive waste in the other countries in Scandinavia have generated a strong demand for investigation, characterization and modeling of deep-lying groundwater systems. Understanding of hydrological changes during the last 100,000 years is an essential basis for the prediction of the potential impact of past, current and future climatic and environmental changes in groundwater resources. Table 5.1 presents long-time scales for which radiological safety is to be demonstrated as also an assessment of the hydrogeological performance of the geosphere system during periglacial and glacial climate conditions. The modern groundwater system (less than 200 years) represents a period in Denmark with anthropogenic impact on the groundwater system (industrial age), in terms of groundwater abstraction and industrial pollution of the groundwater. The pre-industrial groundwater system from about 7,000 BP up to the present day represents a hydrological cycle without any anthropogenic impact. Throughout the entire pre-industrial period, the same sea level occurs, and the coastline is the same as the present-day coastline around Denmark. This has resulted in a nearly steady state condition in the groundwater system over the last 7,000 years. Before this, the related effects of the Weichsel glaciation and of the approximate 120 meters sea-level rise from roughly 18,000-7,000 years BP would have led to significant changes in the hydrodynamics. This resulted in longer flow paths towards the lower sea levels, lowering of water levels inland, and an increase in the thickness of the unsaturated zone. Much likely, the sea-level rise caused the saltwater/freshwater-interface position to alter, going from a deep to a shallower positioned saltwater/freshwater interface (Edmunds, 2001).

The use of groundwater dating isotopes is a powerful tool to understand the groundwater movements in the groundwater system during past to current climatic conditions. In addition, this knowledge can support evaluations of future climatic conditions, with focus on potential changes in deep circulation of groundwater (as thoroughly discussed in Chapter 5.1). A thorough description of how various time scales and climate conditions are related to typical European groundwater systems has been given by Edmunds (2001).

Table 5.1. *Time scales of confined groundwater systems in European coastal aquifers. Modified from Edmunds (2001).*

Tabel 5.1. *Grundvandets aldre i europæiske kystnære grundvandsmagasiner under periglaciale og glaciale perioder. Modificeret fra Edmunds (2001).*

Groundwater system	Age BP	Climate conditions
Modern groundwater	Less than 200 years	Periglacial
Pre-industrial groundwater	Holocene Age (200-c.10.000 years)	Periglacial
Palaeowater	Late Pleistocene Age (10.000-20.000 years)	Glacial
Older (saline?) formation water	20-100.000 years	Glacial

5.3 Historic trends and monitoring of hydrologic cycle during the last 150-175 years

5.3.1 Historical trends in precipitation and stream discharge since 1870

A time series starting in 1870 in the Skjern river catchment has been analyzed with respect to groundwater recharge, precipitation, temperature, evaporation, and river discharge. Results of the study indicates that since 1870, western Denmark saw a significant increase in precipitation of 26 % and a temperature change of 1.4 ˚C, leading to major increases in groundwater recharge of 86 % and to river discharge of 52 % (Karlsson et al., 2014). The increase in river discharge appears unevenly distributed across Denmark, with the largest increase occurring in the western and southwestern parts of the country (Kronvang et al., 2006).

5.3.2 Groundwater levels monitored since 1860

Measurements of groundwater levels in abstraction and monitoring wells in the upper 250-300 meters started at the same time as the water supply changed from surface water supply to groundwater supply. In 1857, the water extraction company in København started collecting more systematic water level data from the wells (Colding, 1872). In addition, the counties had local monitoring networks of water level measurements, but a national monitoring program was not started until 1989. Since then, the quantitative state of the groundwater has been reported in an annual report by GEUS (Thorling et al., 2019).

It should be noted that no observations with the purpose to examine the groundwater table at 500 meters depth have been included in any groundwater monitoring program in Denmark.

5.3.3 Water supply based on groundwater conditions since 1850

The groundwater steady-state conditions that existed before the industrial era was interrupted around 1850 by anthropogenic impacts from initial groundwater pumping. Around this moment in time, the way in which drinking water was supplied to the largest Danish cities changed – thus, pumping surface water was replaced with using abstracted groundwater for drinking water purposes (Odense in 1851; Aalborg in 1854; Aabenraa in 1858; København in 1859). Aarhus first uses groundwater around 1920. In 1894 there were 27 towns with their own waterworks. Groundwater-based water supply developed rapidly in the period up to the 1920s, where the number of municipal waterworks had been increased to 70 plants in the cities and 1,200 plants in the countryside. In the early 1970s, the number had increased to a total of almost 6,000 waterworks, and in addition approximately 200,000 individual household wells in the countryside.

5.4 Relevant groundwater investigations in Denmark

This chapter summarizes the results from a rather sparse number of studies of deep groundwater systems in Denmark (Table 5.2). The groundwater investigations have been carried out to maximum depths of 450 meters; thus, no investigations have been conducted at the depth of interest for deep geological disposal around 500 meters: firstly, in relation to the non-existing scarcity of sustainable groundwater, there has been no need to do so; secondly, due to the likelihood that deep groundwater will contain high concentrations of chloride, it is not suitable for drinking water purposes. In general, there has been an acceptable water quality in the shallow groundwater resources until now. However, there are signs that particularly warm summers with low groundwater tables result in abstraction wells being drilled deeper and deeper, to provide enough groundwater of sufficient quality and quantity.

5.4.1 Sedimentary aquifers

Sand aquifers

To investigate pristine freshwater resources in Denmark, coastal aquifer studies have been carried out in sedimentary basins at depths up to 350 meters (Hinsby et al., 2001; Harrar et al., 2001; Sterckx et al., 2018). The area of southwestern Jylland was the focal point of the studies and, here, hydrochemical and isotope data showed that Miocene sand generally contains high-quality fresh groundwater of Holocene age and with no signs of human impact (see Figure 5.2). A sequence stratigraphic approach for mapping and prediction of sand distribution has been tested for the same area by Scharling et al. (2009). Comparison between the sequence stratigraphic approach and a traditional lithofacies model, based on sediment descriptions of borehole samples, indicated that the new method provides a more sound geological understanding – found to be essential when evaluating groundwater flow paths and the vulnerability of deep seated aquifers. As done in the study by Scharling et al. (2009), uncertainties in geological model structures and parameter estimations can be evaluated by using different geological model inputs to the groundwater model.

Buried valley aquifers

Inland groundwater aquifers down to depths of 200-400 meters located in sand-filled buried valleys are also an important groundwater resource in Denmark. The development of these glacial features is described thoroughly in Chapter 2. Often, the existence of buried valleys is not described explicitly in hydrogeological models (Henriksen et al., 2003). Seifert et al. (2008) have shown that buried valleys incised 300 meters into a sequence of pre-Quaternary sediments in Central Jylland can affect the groundwater flow down to significant depths. Two alternative conceptual models were produced to help quantify the effect that the buried valleys have on groundwater vulnerability. The location of recharge areas and the groundwater age distribution in the pre-Quaternary deep aquifers surrounding the buried valley were different for the two models, with significantly higher vulnerability when the valley was included in the model. Firstly, it is concluded that a buried valley may not always be detectable when calibrating a wrong conceptual model. Secondly, in order to obtain reliable results, a good geological model must be constructed. In relation to hydrological models, the use of alternative conceptual models is another well-known uncertainty assessment technique to address uncertainty in geological model structures, input data and parameter variables. It can be speculated whether deep buried valleys can influence the upward groundwater movement between the approximate target depths of 500 meters to the bottom of the – known at the present time – deepest buried valleys at 300-400 meters depth. Clarification of this potential relationship depends on further research.

Table 5.2. *Investigations of deep groundwater aquifer systems in Denmark.*

Tabel 5.2. *Danske undersøgelser af dybe grundvandsmagasiner.*

Depth(m)	Work done	Geology	Reference
250-300	Groundwater chemistry, isotopes, numerical modeling	Miocene sand aquifer	Hinsby et al. (2001); Harrar et al. (2001); Meyer et al. (2018)
0-300	Hydrostratigraphy, age dating, numerical modelling	Quaternary and Miocene deposits	Scharling et al. (2009)
0-300	Buried valleys, alternative conceptual models	Pre-Quaternary sediments	Seifert et al. (2008)
0-300	National water resources groundwater model (DK-model)	Quaternary and Pre-Quaternary deposits	Henriksen et al. (2003)
0-550	Compilation of hydraulic data	Chalk deposits (this study)	Frykman & Jakobsen (2020)
250-450	Salt/freshwater relation, diffusion, porewater chemistry	Chalk aquifer	Bonnesen et al. (2009)

Chalk aquifers

Upper Cretaceous chalk and Danian limestone aquifers from the upper 50-100 meters of the chalk and limestone layers (blue area in Figure 5.9) supply about a third of the drinking water for Denmark (Vangkilde-Pedersen et al., 2011). The blue area in Figure 5.9 delineates the Pre-Quaternary surface consisting of chalk and limestone with a 0-30 meters cover layer of glacial deposits. The chalk and limestone aquifers have fissured characteristics, formed by glaciotectonics in the upper 50 to 100 meters. In addition, it is speculated whether the fractures/fissures in the chalk aquifer have been karstified by recharging acid precipitation at places with a thin surficial layer of glacial deposits. Karst features in the landscape have been observed in areas where the pre-Quaternary surface of chalk lies near the terrain, allowing the development of sinkholes, karst springs, karst lakes and streams with disappearing water flow (Nilsson & Gravesen, 2018). The conceptual understanding of dynamic karst and fissured chalk, groundwater and stream interaction remains yet unexplored; both fracture/fissures and karst features need to be incorporated in relation to the hydrogeological parametrization of the National Water Resources Model (https://vandmodel.dk/), in which chalk and limestone are conceptualized without fracture flow and as non-karstic aquifers.

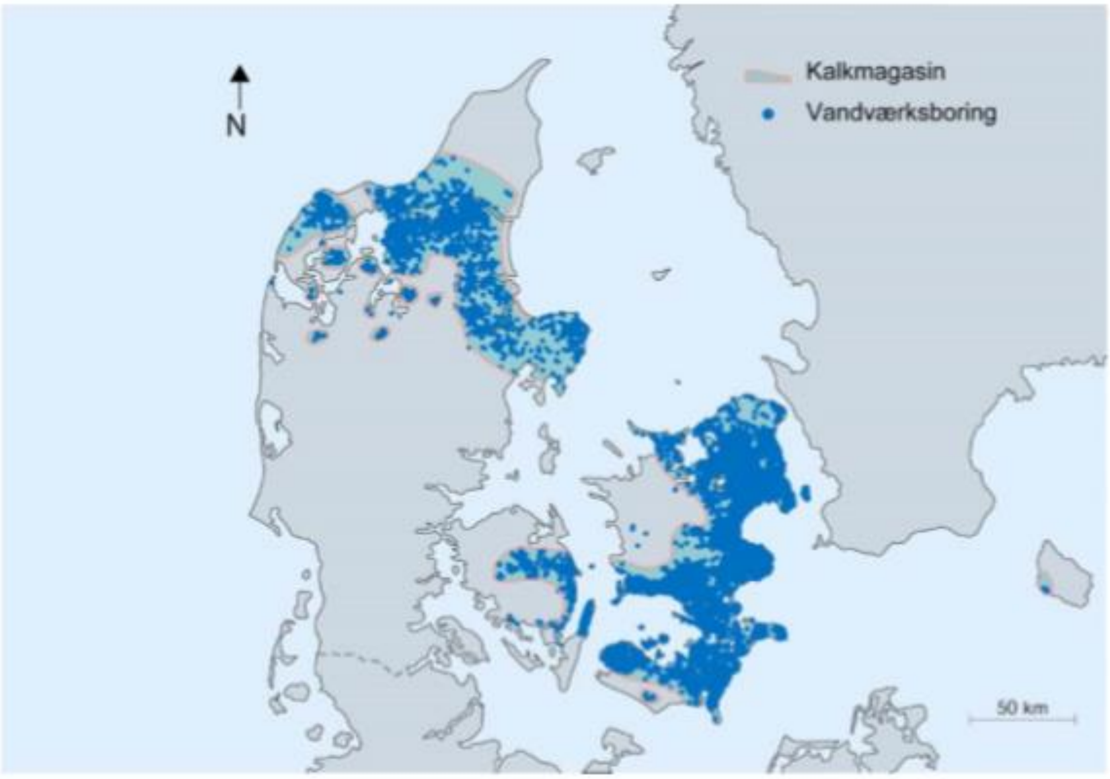


Figure 5.9. *Distribution of Chalk and Limestone freshwater aquifers and the locations of groundwater abstraction wells (blue dots). The light blue area is the zone with groundwater abstraction in the upper 50-100 meters of the chalk/limestone. Modified from Nygaard (1993).*

Figur 5.9. *Udbredelsen af kalkmagasiner og placeringen af vandforsyningsboringer der er boret i kalk. De lyseblå områder viser, hvor der indvindes grundvand fra de øverste 50-100 meter af kalken. Modificeret fra Nygaard (1993).*

5.4.2 Fractured bedrock aquifers

The groundwater aquifers at Bornholm occur in fractured bedrock, Quaternary sand and gravel in-fill in major fracture valleys on the Northern part of the island. Along the southern coast of Bornholm, Mesozoic and Paleozoic sediments host the groundwater aquifers. The sedimentary aquifers are the major groundwater resource on Bornholm. Figure 5.10 shows all wells in the JUPITER database where the bottom of the boreholes goes deeper than 100 meters. Most of the wells go down to depths of 100-150 m, and a few go deeper than 200 meters. Out of about 150, a hundred wells in total have reached the bedrock.

Preferential flow along groundwater seeping faces in fractured Precambrian bedrock has been observed along vertical walls in up to 100 meters deep open bedrock excavations on northern and western parts of Bornholm; water flows out of the exposed walls, mainly through the fractures. Figure 5.11 shows a south-north and east-west cross-section through at least the upper 90 meters of the fractured bedrock at northern Bornholm. Eight household wells were investigated using geophysical flow logging methods to obtain information about occurrence of horizontal fracture systems in the bedrock and relative inflow of groundwater along fractures in the wells. The logging showed that fracture systems occur at many depths down to at least 90 meters and “major” groundwater inflow occur in the bottom of most of the investigated household wells, which indicates that up to at least 90-metre-deep circulation of groundwater happens at northern Bornholm (Gravesen et al., 2014). ^{14}C groundwater dating of the groundwater inflow in the bottom of two household wells indicated older groundwater from 4,150 years BP (at 88 meters below surface) and from 1,450 years BP (at 68 meters below surface). The ^{14}C groundwater ages estimated support the current conceptual hydrogeological understanding of how groundwater recharges down to significant depths at Bornholm.

It may be speculated whether potential major water-bearing fracture systems occur at the repository depth of approximately 500 meters in northern Bornholm. An attempt to identify potential heterogeneities like groundwater-borne weathered fracture zones in the bedrocks at depths of more than 500 meters was made by acquisition of seismic data. Based on the data no major fracture zones or other discontinuities could be identified in the crystalline basement. More detailed descriptions of the seismic data are given in Gravesen et al. (2020).

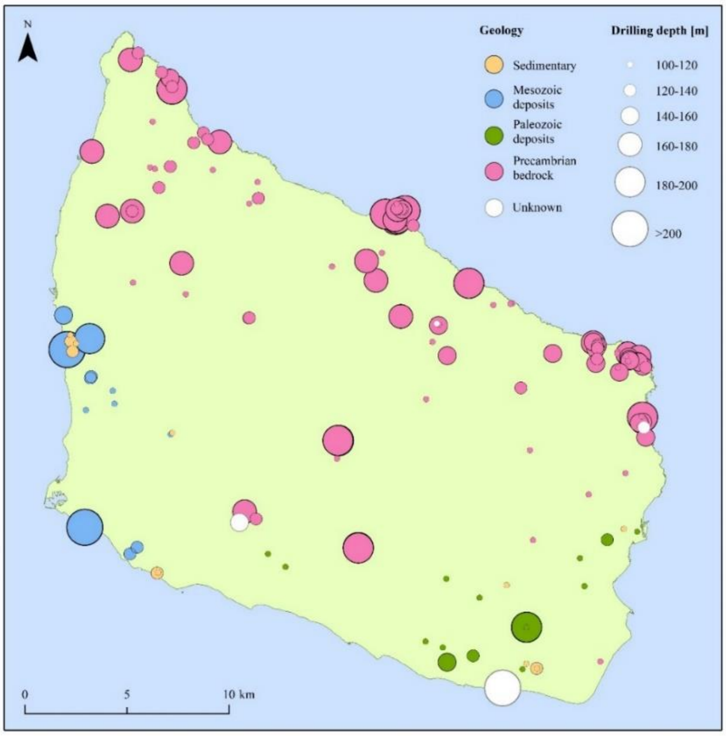


Figure 5.10. *Location of boreholes deeper than 100 meters at Bornholm. The geological time period of the rocks at the bottom of the borehole is indicated with colours.*

Figur 5.10. *Kort over boringer på Bornholm. Bjergartstypen, der optræder i bunden af boringerne, er vist med farver, pink viser boringer i grundfjeldet*

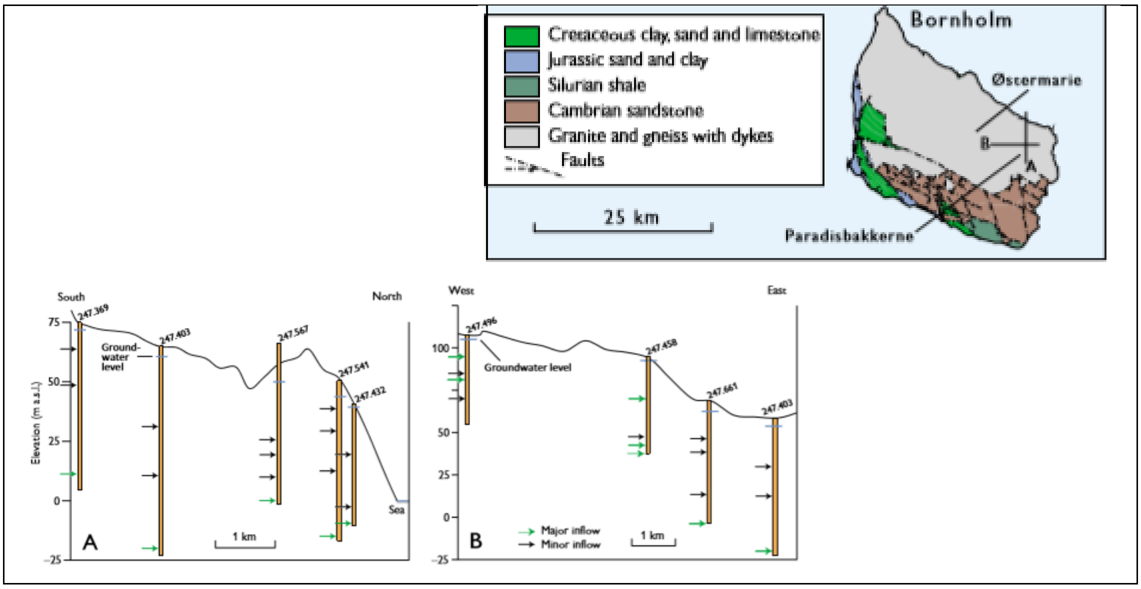


Figure 5.11. *Two cross-sections through logged boreholes. The location of the cross-sections is shown in the inserted map. From Gravesen et al. (2014).*

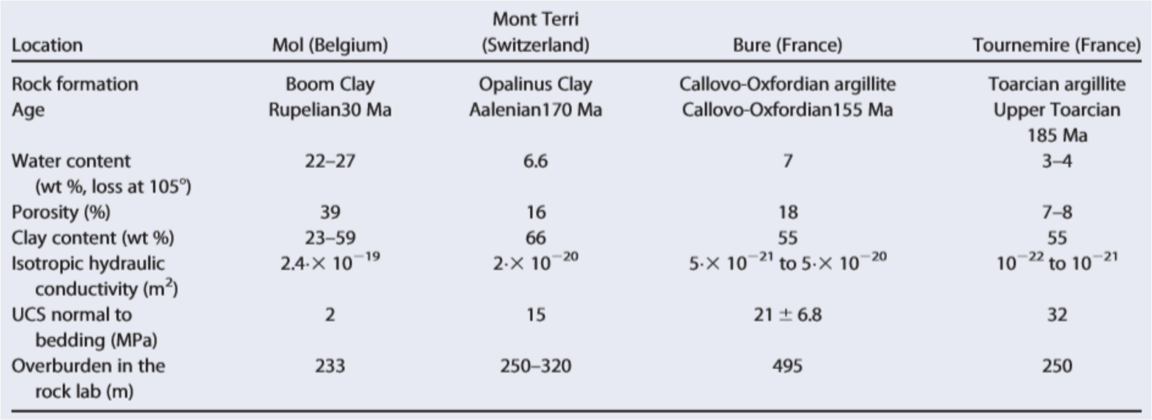
Figur 5.11 (forrige side). *To tværsnit med borehulsloggede husholdningsboringer på nordøst Bornholm. Placeringen af tværsnittene fremgår af det indsatte kort. Fra Gravesen et al. (2014).*

5.4.3 Pre-Quaternary Clay deposits

Pre-quaternary clay deposits of Tertiary or older clay rock types at 500 meters depth in Denmark have never been characterized in terms of hydraulic conditions. European experience from characterizing rock properties in soft clay and clay rocks is summarized in Table 5.3 (Tsang et al., 2015). Comparison of hydraulic and chemical methods for determining hydraulic conductivity and leakage rates from clay materials have been discussed by Neuzil (1994) and Battle-Aguilar et al. (2016). Groundwater flow characterization in Pre-Quaternary Clays at potential nuclear repository sites have been obtained in Belgium (Wemaere et al., 2008; Yu et al., 2011, 2013; Vis and Verweij, 2014), Switzerland (Rübel et al., 2002; Jacobs et al., 2017), France (Patriarche et al., 2004; Beaucaire et al., 2008), Netherlands (Verweij et al., 2016), Canada (Hendry & Wassenaar, 1999; Smith et al., 2016) and Japan (Nakata et al., 2018).

Table 5.3. *Summary of rock properties and in situ conditions of four European Underground Rock Laboratories located in clay (Tsang et al., 2015).*

Table 5.3. *Bjergartsegenskaber og in situ forhold i fire europæiske underjordiske laboratorier i ler (Tsang et al., 2015).*



Location	Mol (Belgium)	Mont Terri (Switzerland)	Bure (France)	Tournemire (France)
Rock formation	Boom Clay	Opalinus Clay	Callovo-Oxfordian argillite	Toarcian argillite
Age	Rupelian30 Ma	Aalenian170 Ma	Callovo-Oxfordian155 Ma	Upper Toarcian 185 Ma
Water content (wt %, loss at 105°)	22–27	6.6	7	3–4
Porosity (%)	39	16	18	7–8
Clay content (wt %)	23–59	66	55	55
Isotropic hydraulic conductivity (m^2)	$2.4 \cdot \times 10^{-19}$	$2 \cdot \times 10^{-20}$	$5 \cdot \times 10^{-21}$ to $5 \cdot \times 10^{-20}$	10^{-22} to 10^{-21}
UCS normal to bedding (MPa)	2	15	21 ± 6.8	32
Overburden in the rock lab (m)	233	250–320	495	250

5.5 Summary of groundwater flow to 500 meters depth

Chalk/limestone aquifers

Advective groundwater flow is restricted to the fractured upper parts of the chalk formation at 50 -100 meters depth. Diffusive transport is the predominant transport mechanism at the repository depth of 500 meters. Layers of marl are known to form local barriers due to very low hydraulic conductivity.

Fractured bedrock aquifers

Fracture flow occurs at the upper 100 meters of the fractured bedrock at northern Bornholm. For the time being, no knowledge exists about the potential existence of heterogeneities such as water bearing weathered fracture zones at depths of 100 to 500 meters below the surface at Bornholm.

Buried valleys

In the future, inland groundwater aquifers related to sand filled buried valleys at depths of 200-400 meters may be an important groundwater resource in Denmark. It can be speculated whether deep buried valleys can influence the upward groundwater movement between target depths of approximately 500 meters to the bottom of the – known at the present time – deepest buried valleys at 300-400 meters depth. In any case it is not a preferred situation with 300-400 meters of high porosity sand overlying the repository as no additional barrier is provided in the overburden.

Tertiary and Mesozoic clays

In Denmark, Pre-Quaternary clay deposits within sections of Tertiary or Mesozoic mudstones occurring at 500 meters depth in the Danish subsurface have not been characterized in terms of hydraulic conditions. Further research is necessary to clarify the groundwater flow and transport in these types of deposits in the Danish subsurface.

Monitoring of groundwater levels

Observations of deep-seated groundwater flow at 500 meters depth are scarce because the water is usually saline and thus not of interest for water abstraction. Data from such depths are not included in any groundwater monitoring program in Denmark.

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

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