DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/54**

Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark. Phase 1, report no. 3

Upper Cretaceous chalk and Paleocene limestone distribution and properties

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DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

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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. 3. It presents the existing knowledge about the geological properties and the subsurface distribution of the Upper Cretaceous and Paleocene chalk, marl, and limestones sedimentary deposits constituting the Chalk Group.

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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. 3: Udbredelsen og egenskaber af Øvre Kridt og Palæocæne kalksten (Upper Cretaceous chalk and Paleocene limestone distribution and properties)

I dybder ned til 500 meter består den danske undergrund i stort omfang af kalksten, der blev aflejret i sen Kridt og Danien tidsperioderne. Aflejringerne refereres samlet til som ”Chalk Group” (Kalkgruppen). Kalkstenen i Kalkgruppen er en finkornet sedimentær bjergart, der består af skalfragmenter fra kalkskallede nannofossiler, hovedsageligt kokkospherer, samt mindre mængder af foraminiferer og fragmenter af makrofossiler. Nogle intervaller indeholder en del lermineraler, som hovedsageligt består af smectit og illite.

Den øvre del af Kalkgruppen, som kendes fra undergrunden i danske landområder, er inddelt i fire formationer: Møns Klint Formationen (Maastrichtien), Mandehoved Formationen (Campanien), Stevns Klint Formationen (Nedre-Mellem Danien) og København Kalk Formationen (Øvre Danien). Disse formationer er underinddelt i led, baseret på litologiske forskelle, herunder intervaller med varierende indhold af ler og lermineraler.

Toppen af Kalkgruppen findes stedvis blotlagt i terrænoverfladen, men er oftest begravet til dybder varierende fra nogle få ti-tal af meter til flere hundrede meter, hvor den er kortlagt i undergrunden baseret på seismiske data og nogle få dybe boringer. Tykkelsen af Kalkgruppen overstiger 500 meter i størstedelen af landet og kan lokalt i det Danske Bassin opnå en tykkelse på mere end 2000 meter (i den nordligste del af Sjælland).

Kalksten findes i de fleste områder af Danmark i tykkelser på flere hundrede meter i lagserien over 500 meters dybde og vil derfor i de fleste tilfælde udgøre en stor del af den samlede geologiske barriere for et slutdepot, der placeres i 500 meters dybde. I tilfælde af at slutdepotet placeres i kalksten eller mergel, vil sedimenter fra Kalkgruppen således udgøre både værtsbjergarten og den overliggende barrierebjergart.

De øverste 0-50 meter af Kalkgruppen er generelt meget detaljeret beskrevet, både fra lokale naturlige blotninger i terrænet, kalkstensbrud og fra grundvandsboringer, idet den øverste del af kalkstenen udgør magasiner for grundvandsindvinding i store dele af landet. Herudover er kalkstenen i den øverste del af Kalkgruppen også gennemboret i forbindelse med geotekniske undersøgelser forud for anlægsarbejder så som metroen i København samt større broer og tunneller. Informationer fra de dybere dele af Kalkgruppen er indsamlet i forbindelse med olie og gas efterforskningsboringer samt nogle få geotermiske og geovidenskabelige boringer. Erslev boringerne i Erslev salthorst, og Stevns boringerne, er de eneste dybe boringer, der er udført med henblik på specifikt at indsamle information om egenskaberne af dybereliggende kalksten, og data herfra er således værdifulde i relation til det geologiske slutdepotprojekt.

Eksisterende detaljeret kortlægning af forkastninger og frakturer i kalksten er begrænset, da der kun findes sparsomme dybe seismiske data for landområderne, der er indsamlet med henblik på kortlægning af Kalkgruppen. En undtagelse er Københavnsområdet, hvor nogle få markante strukturelle elementer er detaljeret beskrevet, men kun til dybder på omkring 100 meter.

De øverste 0-20 meter af Kalkgruppen er karakteriseret af forskellige grader af subglacial deformation i form af knusning og sprækkedannelse. Sprækker forekommer både horisontalt og vertikalt udstrakte. I dybere dele af kalken ses også stedvis tegn på tidligere sprækker, men de synes at være lukkede på nuværende tidspunkt. De hydrauliske egenskaber af matrixen i Kalkgruppen er sjældent beskrevet på dybder under 20-50 meter, idet meget få borekerner er indsamlet fra større dybder. Der eksisterer således kun sparsomme informationer om de petrofysiske egenskaber. De tilgængelige data viser, at der er et konsistent fald i matrix porøsitet og permeabilitet med stigende dybde på grund af øget kompaktion og cementeringsprocesser, der resulterer i opløsning og genudfældning af kalcit. Tilstedeværelsen af ler (mergel) resulterer i højere grad af kompaktion og dermed lavere porøsiteter og permeabiliteter sammenlignet med rene kalksten på samme dybde. Den faldende permeabilitet med dybden synes at være relateret til både generel kompaktion, men også til et højere lerindhold i den nedre del. Cementering relateret til calcit genudfældning begynder typisk ved dybder på 1100 meter.

Kalkstenen er generelt over-kompakteret, idet store mægtigheder af Paleogene sedimenter tidligere har overlejret den, og efterfølgende er fjernet under perioder med opløft og erosion i Neogen tid. I stevnsområdet er det på grundlag af hastighedsdata og porøsiteter i kalken estimeret, at området har været begravet 500-700 meter dybere end i dag, og derfor er ”over-kompakteret” i forhold til hvad der kan forventes i de nuværende begravelsesdybder. Det betyder, at i nogen områder er kalkstenen hårdere og mere kompetent, end forventet ud fra den nuværende begravelsesdybde.

Kalkens hydrauliske konduktivitet på dybder større end 20-50 meter er kun beskrevet fra nogle få lokaliteter, idet kun enkelte dybe boringer er blevet testet. Et eksempel er fra den kalksten, der findes overlejret Mors saltdomen, og som er gennemboret i Erslev-boringerne. Resultaterne af intervaltest i Erslev-boringerne viser et fald fra 1-4 mD (milliDarcy) i de øverste 240 meter til 0,02-0,06 mD i 400-500 meters dybde. På grund af de særlige strukturelle og geomekaniske forhold, der eksisterer på toppen af en saltstruktur og deres indflydelse på sprække-permeabiliteten, er det usikkert, hvorvidt disse data er repræsentative for kalksten andre steder i den danske undergrund. Et indirekte estimat af vertikal transport fra dybe dele af Kalkgruppen i et strukturelt set ukompliceret område er publiceret fra Stevns-1 boringen.

Estimatet er baseret på salinitetsprofiler og temperaturmålinger. Resultaterne tyder på, at diffusion er den dominerende vertikale transportmekanisme for opløste stoffer på større dybder, og at der ikke foregår strømning via sprækker.

Mulig transport af radioaktive nuklider i kalksten kan bremses på grund af sorption eller ved udfældning af radionuklider med kalcit, men effektiviteten afhænger både af typen af nuklider og geokemien af porevand /grundvand samt den specifikke geokemiske sammensætning af bjergarten. Små mængder af ler, sulfid og jernoxider, som også findes i kalksten, kan have sorptionsegenskaber, som for nogle nuklider vil være af større betydning for den faktiske sorption, end udfældning med kalcitmineraler i kalken. Der eksisterer kun få studier af sorptionskapaciteten for kalksten i den danske undergrund, og det er vigtigt at få mere specifik viden om interaktionen mellem den potentielle værts- og barrierebjergart og nukliderne i det radioaktive affald for fremadrettet bedre at kunne evaluere sorptionskapaciteten, og dermed værts- og barrieregenskaberne af den danske kalksten.

1. Introduction

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

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

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

1.1 Guidelines for identification of deep geological repository sites

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

"*To identify and map layers of low-permeable rock types that are sufficiently thick (more than 100 meters) and which have a continuous lateral extension (several km*^{2}*) throughout the entire study area. The rock body should also be sufficiently homogeneous and represent no significant discontinuities like fractures and faults. Furthermore, the rocks should be as mineralogical homogeneous and uniform as possible. The geological conditions should be stable in the short term as well as in the long term.*"

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

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

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

1.2 The deep geological repository project

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.

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2. Geological setting

The Cretaceous chalk and Danian limestone sediments are covered by Cenozoic deposits. The Cenozoic section in Denmark varies in thickness from 0 meter to more than 400 meters. In some regions around Limfjorden in Jylland, Djursland, and Stevns, the cover is thinner than 10 metersand locally in these areas chalk and limestone crop out on the ground surface (i.e. Pedersen & Petersen 2002, Jakobsen et al. 2013, Jakobsen & Pedersen 2013).

The chalk and limestone formations of Upper Cretaceous-Danian age are referred to the Chalk Group (Lieberkind et al. 1982). The Chalk Group has a significant thickness and occurs at 500 meters depth in most parts of Denmark overlying older sediments of Jurassic and Lower Cretaceous age (Figs 1, 2 & 3).

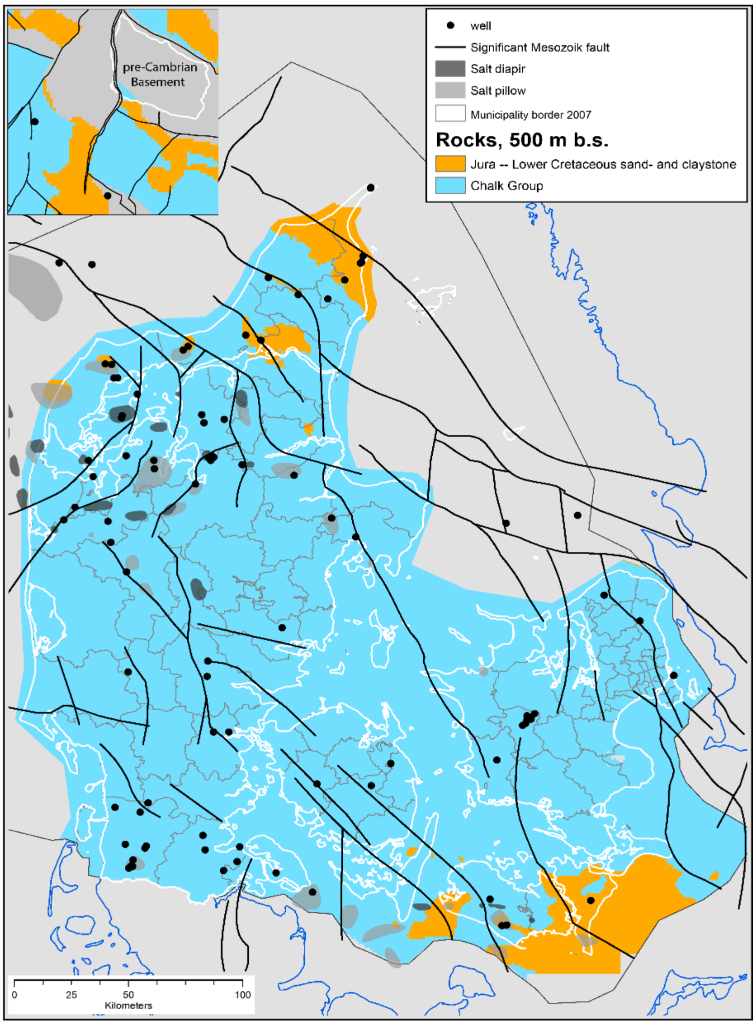


Figure 1. *The distribution of the Chalk Group at 500 metersbelow ground surface.*

Figur 1. *Udbredelsen af Kalkgruppen i 500 m's dybde under terrænoverfladen.*

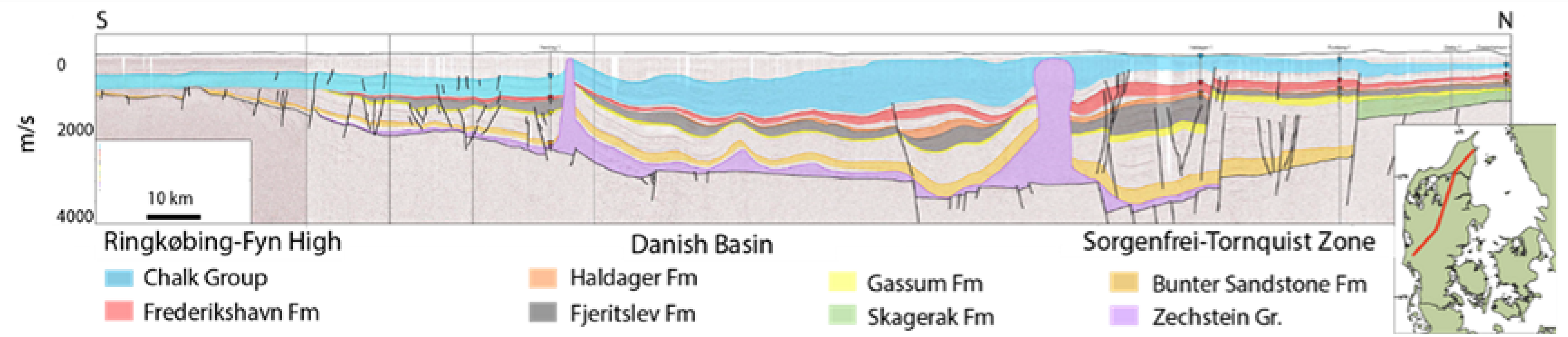


Figure 2. N – S cross-section from Frederikshavn to Blåvandshuk showing the thickness variations of the Chalk Group that overlies Lower Cretaceous and older formations (modified from https://data.geus.dk/geoterm/).

Figur 2. N-S geologisk profil der viser tykkelsesvariationer i Chalk Group, som overlejrer Nedre kridt og ældre formationer (modificeret fra https://data.geus.dk/geoterm/).
N-S fra Frederikshavn til Blåvandshuk som viser tykkelsen af kalkgruppen.

The Chalk Group is deposited in the Norwegian-Danish Basin and also in the North-German Basin located south of the Ringkøbing-Fyn High (Figure 3). It comprises Danian limestone of calcarenite, calcareous mudstone and bryozoan limestone (Figure 4) and Cretaceous chalk consisting mainly of a fine grained coccolithic matrix.

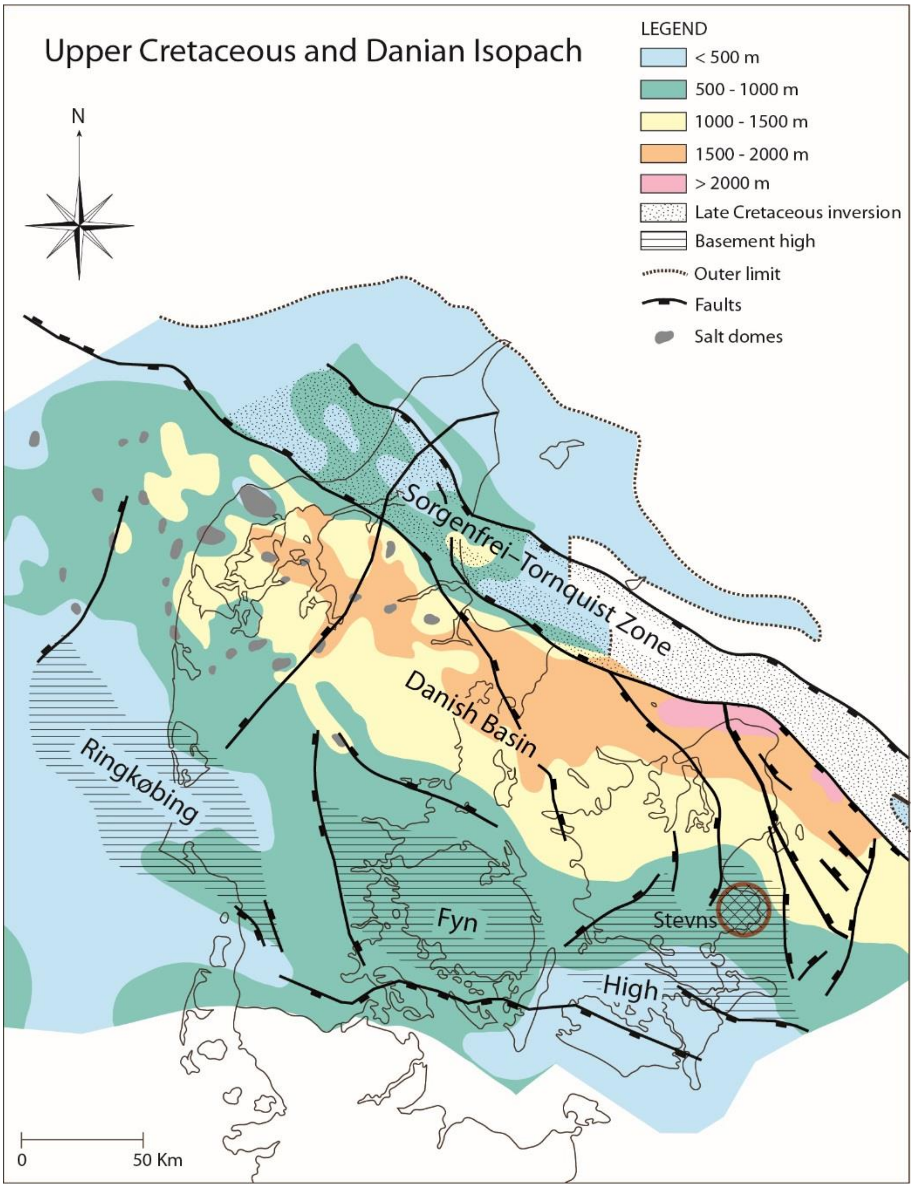


Figure 3. *Isopach map of the Chalk Group in Denmark (Japsen 1998, Larsen et al. 2014).*

Figur 3. *Tykkelseskort af Kalkgruppen i Danmark (Japsen 1998, Larsen et al. 2014).*

The Sorgenfrei-Tornquist zone (also referred to as the Fennoscandian Border Zone in literature (i.e. Liboriussen et al. 1987, Thomsen 1995)) is a significant and complex tectonic zone defining the border between the stable Fennoscandian-Baltic Shield and the metastable Norwegian-Danish Basin. The Sorgenfrei-Tornquist Zone is delineated by large faults and the area has a long and complex tectonic history (Liboriussen et al. 1987, Norling & Bergstrøm 1987, Vejbæk & Britze 1994, Erlstrøm et al. 1997). The overall tectonic fault pattern was established in Paleozoic time. During Paleozoic and Mesozoic time basins developed southwest of the Sorgenfrei-Tornquist Zone. During the late Cretaceous and early Cenozioc dextral transpressional stresses induced inversion in the Sorgenfrei-Tornquist Zone. In late Cretaceous large amounts of chalk deposited in the Norwegian-Danish Basin as well as Danian limestone. The thickest deposits are Upper Cretaceous chalk with the depocenter against the Fennoscandian Border Zone in north Zealand and the depocenter for the Danian Limestone is in Central Jylland. The total thickness of the Maastrichtian and Danian limestone varies from about 500 metersin southern Jylland to more than 2000 metersadjacent to the Sorgenfrei-Tornquist Zone.

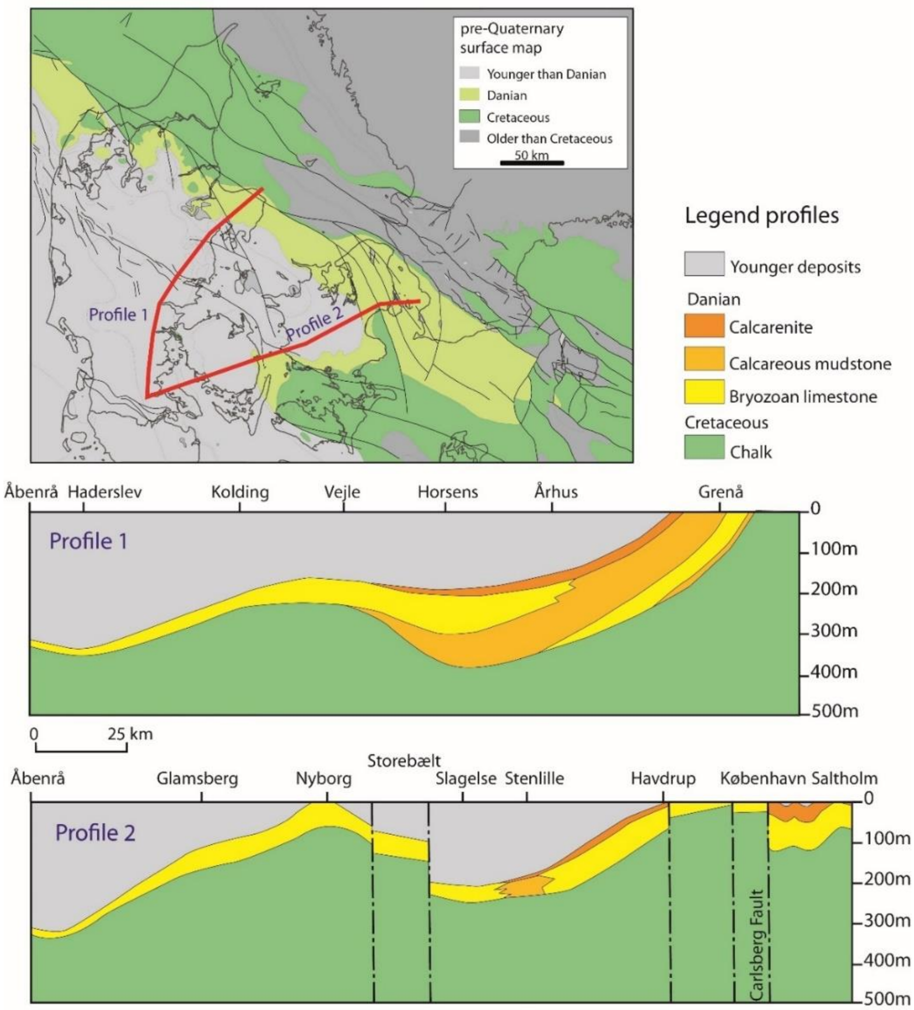


Figure 4. *Two conceptual sections showing the distribution of the limestone and chalk deposits in Denmark. Note that the thickness of the Danian Limestone is larger in central Jylland and calcareous mudstone is predominantly present in the western part of Denmark. (Profile 1 after Thomsen 1995. Profile 2 compiled after Fallesen 1995, Foged et al. 1995, Gravesen 1994, Kelstrup 1995, Klitten 2003, Mielby & Sandersen 2005, Nielsen & Japsen 1991, Pedersen 2001 and Stenestad 1976).*

Figur 4. *To konceptuelle tværsnit der viser tykkelsesfordelingen af forskellige kalksten i Danmark. Tykkelsen af Danian Limestone er størst i det centrale Jylland ligesom og slamkalk (calcareous mudstone) forekommer primært i den vestlige del af Danmark. (Profil 1 efter Thomsen 1995. Profil 2 er sammenstillet efter Fallesen 1995, Foged et al. 1995, Gravesen 1994, Kelstrup 1995, Klitten 2003, Mielby & Sandersen 2005, Nielsen & Japsen 1991, Pedersen 2001 og Stenestad 1976).*

3. Lithology and Stratigraphy of the chalk package

The chalk package comprises Danian limestone consisting of calcarenite, calcareous mudstone and bryozoan limestone (Figure 4) and Cretaceous chalk consisting mainly of a fine grained coccolithic matrix.

3.1 Cretaceous chalk

The Maastrichtian chalk crops out on the pre-Quaternary surface in the northern part of Jylland and in the southern and eastern parts of Sjælland and Møn in the Baltic area (Figure 4). The thickness of Cretaceous chalk deposits is at least 450 meters on Stevns (Surlyk et al. 2013) and more than 2000 meters in North Sjælland adjacent to the Sorgenfrei-Tornquist Zone (Figure 3).

In the Central Graben in the North Sea the Chalk Group is divided into 6 log units labelled Chalk 1 Unit to Chalk 6 Unit. Chalk 1 Unit to Chalk 5 Unit are of Cretaceous age and Chalk 6 Unit is Danian (Lower Paleocene) (Lieberkind et al. 1982).

Within the Danish Basin the upper 450 meters of the Cretaceous chalk has formally been defined as the Mandehoved Formation (Campanian) and Møns Klint Formation (Maastrichtian) primarily based on the Stevns-1 borehole (Surlyk et al. 2013) (Figure 5). The chalk immediately below Møns Klint Formation is not formally named, but it consists mainly of pure chalk (Surlyk et al. 2013).

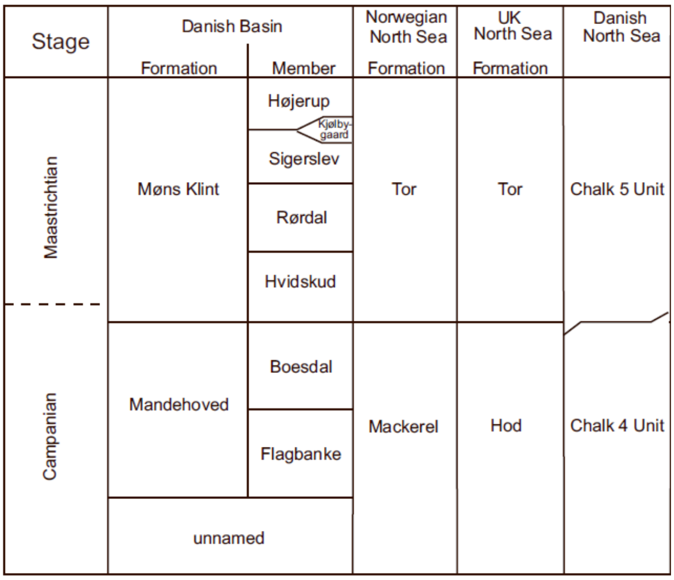


Figure 5. *Lithostratigraphy of the Campanian and Maastrichtian in the Danish Basin and the North Sea (Modified from Surlyk et al. 2013).*

Figur 5. *Lithostratigrafi af Campanien og Maastrichtian i det Danske Bassin og Nordsøen (modificeret efter Surlyk et al. 2013).*

The Campanian Mandehoved Fm is subdivided into Flagbanke Member and Boesdal Member. The Flagbanke Member is about 45 meters thick in the Stevns-1 core and consists of alternating meter-thick beds of chalk and thinner marly chalk with centimeter thick marl layers. The Boesdal Member is 85 meters thick in the Stevns-1 core and consists of alternating decimeter to meter thick beds of chalk, marly chalk and marl (Figure 6).

Figure 6. *Part of Boesdal Member in Stevns-1 core, with alternating chalk, marly chalk and marl (dark grey layes).*

Figur 6. *Dele af Boesdal Member i Stevns-1 kernen med vekslende lag af kalk, lerholdig kalk og mergel (de mørkegrå lag).*

The Maastrichtian Møns Klint Formation is subdivided into Hvidskud Mb, Rørdal Mb, Sigerslev Mb, Kjølbygaard Mb and Højerup Mb.

The Hvidskud Member is 204 meters thick in the Stevns-1 core and it is the thickest member of the Møns Klint Fm. It comprises alternating beds of white chalk and light grey marly chalk. The Rørdal Member (Surlyk et al. 2010) is exposed at the Rørdal quarry in Aalborg (Figure 7), and it is present in cores from boreholes south of Aalborg, Karlstrup-1, Stevns-1 and Stevns-2 (Nielsen & Jørgensen 2008, Surlyk et al. 2010). It is 9 meters thick at Rørdal and 29 to 36 meters thick in the boreholes on eastern Sjælland. The Rørdal Member is separating groundwater reservoirs within the chalk, if it is not too affected by faulting (Nielsen & Jørgensen 2008).

Figure 7. *The Rørdal Member, showing interbedded dark layers of marl, exposed in the Rørdal quarry Aalborg (foto: Erik Thomsen).*

Figur 7. *Rørdal Member der indeholder mørke lag af mergel, blotlagt i Rørdal bruddet, Aalborg (foto: Erik Thomsen).*

The Sigerslev Member is 61 meters thick in the Stevns-1 core, and the upper part is exposed in the coastal cliff at Stevns and in the Sigerslev quarry (Figure 8). It consists of white chalk, with few marl layers, and bands of flint nodules.

The Kjølbygård Member is 35 cm at the type section and is present in Northern Jylland and in wells in the Danish basin in Tune-1 and Tuba-13. The member was described as a thin marl bed with thin laminae of slightly contorted chalk.

The Højerup Member has a total of 2.2 meters in the Stevns-1 core. It is a bryozoan chalk wackestone with a significantly larger grain size than the underlying members. Flint occur as nodule bands.

Figure 8. *Sigerslev Formation exposed in the Sigerslev quarry at Stevns.*

Figur 8. *Sigerslev Formationen blotlagt i Sigerslev bruddet på Stevns.*

3.2 Danian limestone

The Danian crops out on the pre-Quaternary surface in a belt across Jylland and on Sjælland (Figure 4). The Danian limestone consists of several limestone types as bryozoan limestone, coral limestone, calcareous mudstone and calcarenite limestone, (Jakobsen et al. 2016, Thomsen 1995). The youngest unit is the often hard and massive limestone (København Kalk Formation; Stenestad 1976) (Figure 9).

The early and middle Danian bryozoan limestone was formally defined as the Stevns Klint Formation by Surlyk et al. (2006). It usually contains 20 to 45 % bryozoan fragments, but it might also appear as mudstone or calcarenite where only few bryozoans are present. Usually the bryozoan limestone is deposited in mounds (Figure 10), which are strongly asymmetric in the lower part and less asymmetric upwards (Nielsen et al. 2009, Galsgård et al. 2014). Flint occurs occasionally in high amounts in some distinct limestone layers. Lenses of coral limestone occur within the bryozoan limestone. The thickness of the bryozoan limestone is from 53m to 63m in the København area (Stenestad 1976). The bryozoan limestone is generally more indurated than Cretaceous chalk and it varies from not indurated (H1) to strongly indurated (H4). The indurated and strongly indurated limestone is calcite cemented.

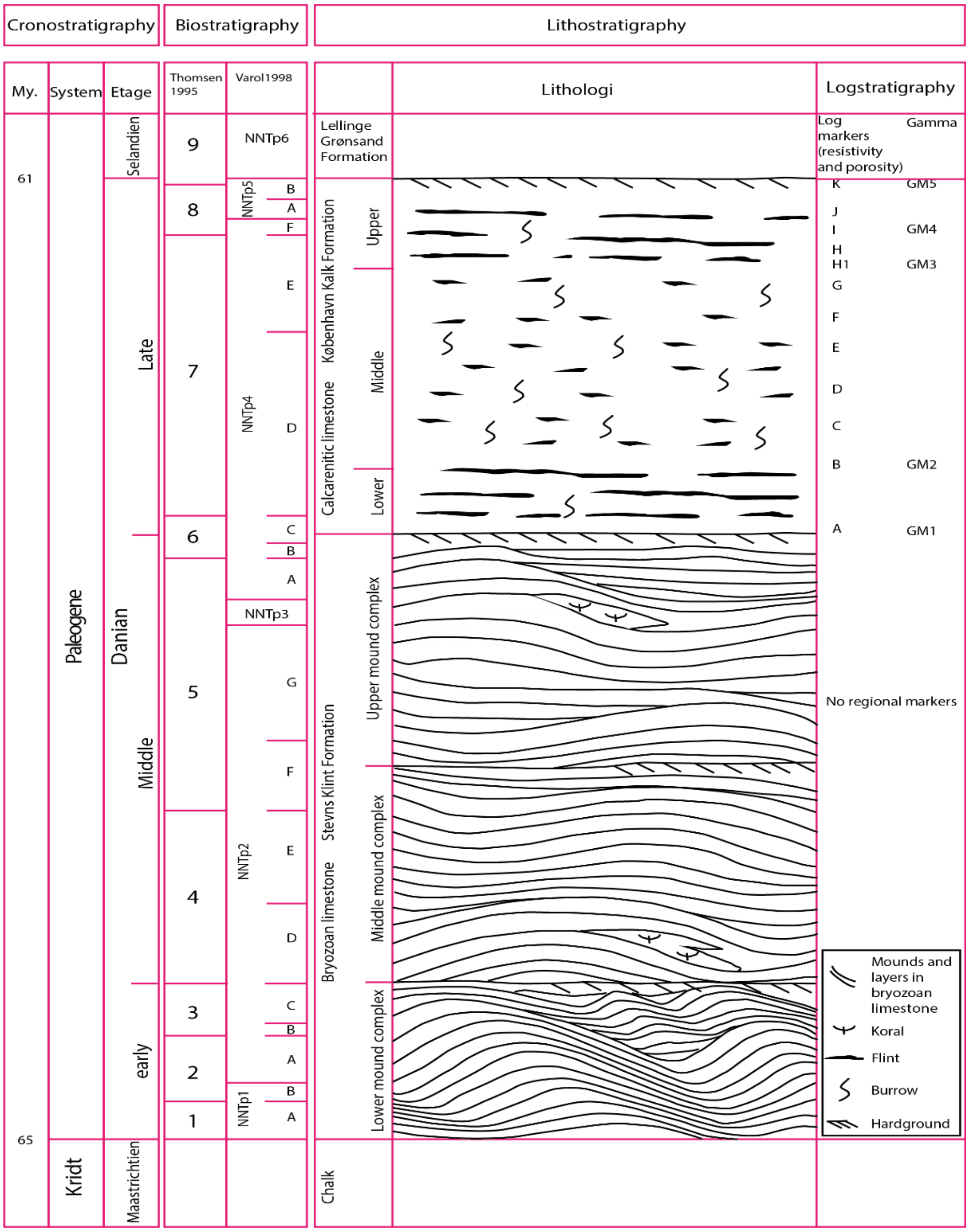


Figure. 9. *Lithostratigraphy of the Danian in eastern Denmark (from Galsgård et al. 2014).*

Figur. 9. *Lithostratigrafi af Danien in det østlige Danmark (fra Galsgård et al. 2014).*

Figure 10. *Assymetric mounds in the lower part of Stevns Klint Formation. Maastrichtian chalk in the lowermost part of the cliff, representing Sigerslev Member and Højerup Member. (Foto: T. Damholt).*

Figur 10. *Asymmetrisk bankestruktur i den nedre del af Stevns Klint Formation. Maastrichtien kalk i den nederste del af klinten repræsenterer Højerup Member og Sigerslev Member. (Foto: T. Damholt).*

Coral limestone is very limited in distribution and is mainly known from the Faxe quarry on southern Sjælland where it has been formally defined as the Faxe Formation (Lauridsen et al. 2012). It is associated with bryozoan limestone and it also occurs as smaller lenses within the bryozoan limestone as can be seen in the Limhamn quarry in Malmø, Sweden and in excavations in Øresund from the construction of the Öresund bridge (Jakobsen 1997, Jakobsen et al. 1997). Coral limestone consists of fragments of coral branches with a micritic matrix. The corals are often dissolved, resulting in a highly indurated micrite with pipe-like macropores. Coral limestone is a very pure limestone, nearly free of chert.

Danian calcareous mudstone is a white or light greyish fine-grained chalk where about 50% of the particles are less than 5 µm (Thomsen 1995). The Danian mudstone resembles the Cretaceous chalk but is has a larger fraction of silt size grains, and it contains up to 30% flint. The Danian mudstone is usually not indurated. The occurrence of the Danian mudstone is mainly in the western part of the Norwegian-Danish basin, in Jylland (Figure 11).

Figure 11. *Danian calcareous mudstone in a quarry at Dalby Over.*

Figur 11. *Danien kalk muddersten (kaldet slamkalk) i kalkbrud ved Dalby Over.*

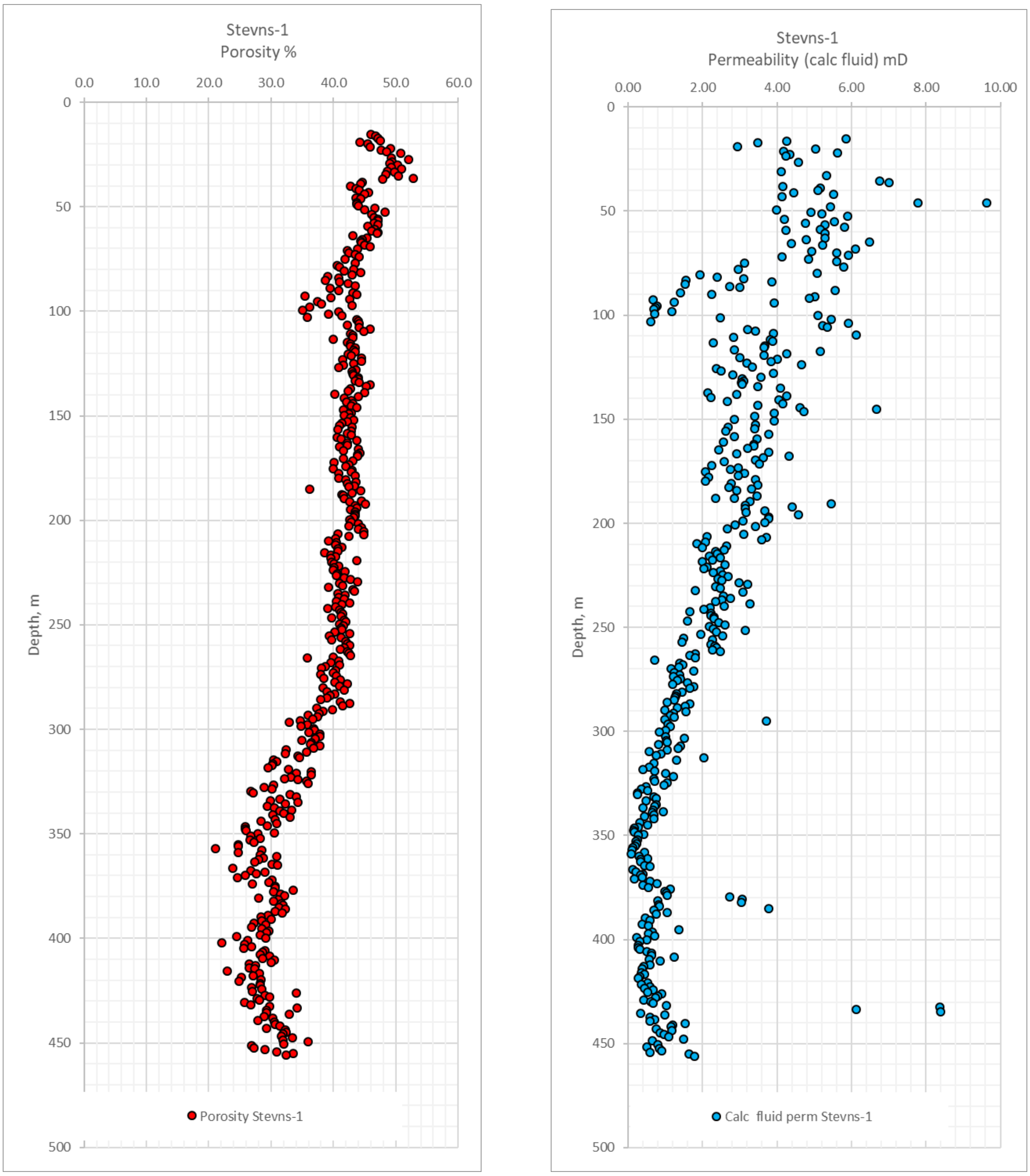
The København Limestone Formation is of late Danian age. It is a sandy and silty carbonate mudstone and was formally defined by Stenestad (1976). It has a sub-horizontal layering with pronounced flint layers parallel to the layering (Figs 9, 12). A characteristic log-stratigraphy has been established in the København area (Klitten et al. 1995, Olsen & Nielsen 2002). The København Limestone Formation is subdivided into a lower, middle and upper part, where the upper and lower parts are characterized by having abundant and thicker highly indurated limestone beds than the middle part. The thickness of the København Limestone Formation is 40 to 45 meters in the Copenhagen area.

Figure 12. *København Limestone Formation overlying Stevns Klint Formation in the Limhamn quarry, Malmø, Sweden.*

Figur 12. *København Kalk Formation overlejrer Stevns Klint Formationen i Limhamn bruddet, Malmø, Sverige.*

4. Diagenesis and strength of marl and limestone

The chalk generally has a decreasing porosity and permeability with depth, and increasing strength and induration (Jensen 2007, Knudsen & Jakobsen 2008 and Knudsen et al. 2010), (Figure 13).



A B

Figure 13. *Core data from the Stevns-1 well. The porosity* ***(A)*** *and permeability* ***(B)*** *values are based on plug data. The measured gas permeability has been recalculated to a proxy for fluid permeability (Mortensen et al. 1998).*

Figur 13 (forrige side). *Porøsitet* ***(A)*** *og permeabilitet* ***(B)*** *målt på kernemateriale fra Stevns-1 boringen. De målte gas-permeabiliteter er omregnet til fluid permeabilitet (Mortensen et al. 1998).*

The reason for the downward decrease in porosity and permeability is that the calcite dissolve at grain contacts because of the weight of the overburden (pressure solution) and then subsequently precipitate in the pore space. This process is estimated to begin when the burial depth exceeds ca. 1100 meters (Fabricius et al., 2008). The assumed amount of sediments removed by erosion at Stevns during the Tertiary is ca. 600 – 700 meters (Japsen 1992, 1993, 1998, 2017, Japsen & Bidstrup 1999, Japsen et al. 2007), therefore pressure solution should be found at depths below ca. 400 meters at Stevns.

4.1 Induration

The induration of the chalk is assessed in the Stevns-1 core (Knudsen & Jakobsen 2008) according to Larsen et al. (1988) using a five-level scale:
H1: Loose material. H2: Weakly indurated. The material can be scratched with a fingernail. H3: Indurated. The material cannot be scratched with a finger nail, but with knife. H4: Strongly indurated. The material can be scratched with knife, but grains cannot be loosened. H5: Very strongly indurated. Material cannot be scratched with knife.

The general trend is that the chalk gets more indurated with depth. The chalk has an induration of H2 down to 265 meters below surface. From 265 to 340 meters below surface the chalk is slightly harder, and the induration is assessed to about H2.5. Below 340 meters the induration is assessed to be H3 (Knudsen & Jakobsen 2008). This is in good agreement with the Sonic velocity log of the well (Figure15).

4.2 Rock strength

In Stevns-1 rock-mechanical testing was conducted on drill-core samples. It shows that there is a general increase in Unconfined Compression Strength (UCS) with depth (Figure 14). Below 300 meters the strength exceeds 10 MPa for the chalk and it is generally above 20 MPa in the depth interval between 300 and 500 meters. This increase in rock strength is also reflected in the increase in sonic velocity, which increases at ca. 300 meters in Stevns-1 (Fig 15).

The stability of the Chalk, if a cavern or tunnel were to be constructed, was described in Stevns-1 well (Knudsen & Jakobsen 2008) using the Q-system (Barton et al. 1994). The Q-values increases with depth. However, the stability is reduced in the presence of marl layers.

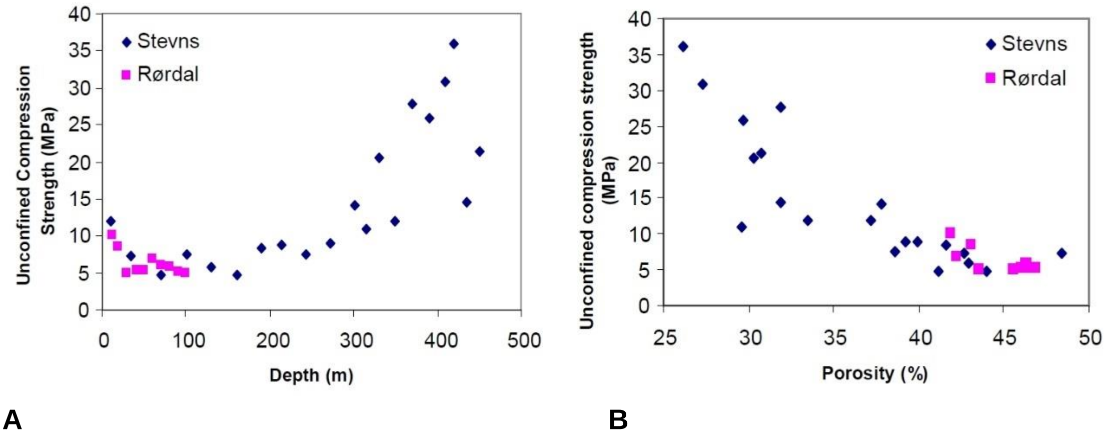


__Figure 14__. Unconfined Compression Strength (UCS) plotted against depth __(A)__ and porosity __(B)__ for the Stevns-1 and Rørdal wells (From Knudsen et al. 2010).

__Figur 14__ . Unconfined Compression Strength (UCS) plottet imod dybde __(A)__ og porøsitet __(B)__ for Stevns-1 og Rørdal boringerne (Fra Knudsen et al. 2010).

4.3 The marl

The marl-rich intervals within the Maastrichtian occur in the Rørdal Member and Boesdal Member, which can be recognised due to high values on the gamma ray log from the Stevns-1 well (Figure 15). The marl within the Rørdal Member is dominated by smectite and quartz with some illite and minor Analcime (Ahlborn 2008, Surlyk et al. 2010).

The Rørdal and Boesdal Members can be correlated from the Stevns-1 well across eastern Sjælland (Figure 16) and across Denmark to the western part of Jylland (Knudsen et al. 2010) (Figure 17). The deep wells also show indications of marl rich intervals at lower levels than Boesdal Member.

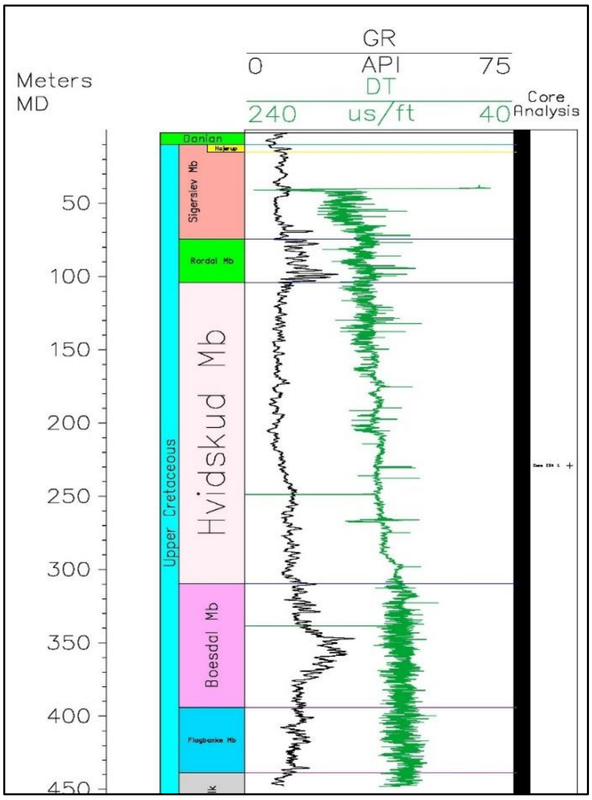


Figure 15. *Stevns-1 well gamma log (black) and sonic log (green). Increased gamma values in Rørdal (lightgreen) and Boesdal Members indicate increasing clay content. (From Kristensen et al. 2017).*

Figur 15. *Stevns-1 boring gammalog (sort) og sonic log (lydhastighed) (grøn). Høje værdier på gamma-loggen i Rørdal Member lysegrøn) og Boesdal Member (lyserød) afspejler et forøget lerindhold. (From Kristensen et al. 2017).*

Reflection seismic data from Stevns indicate a higher clay content at a depth of 610 meters (Nielsen et al. 2011). Marl-rich intervals within the chalk, at deeper levels than the Boesdal Formation, is also seen as high gamma readings in i.e. Stenlille-6, Hobro-1 and Mors-1 wells (Figure 17).

For comparison is shown similar panels for other wells with information on the deeper chalk package (Figs 18, 19).

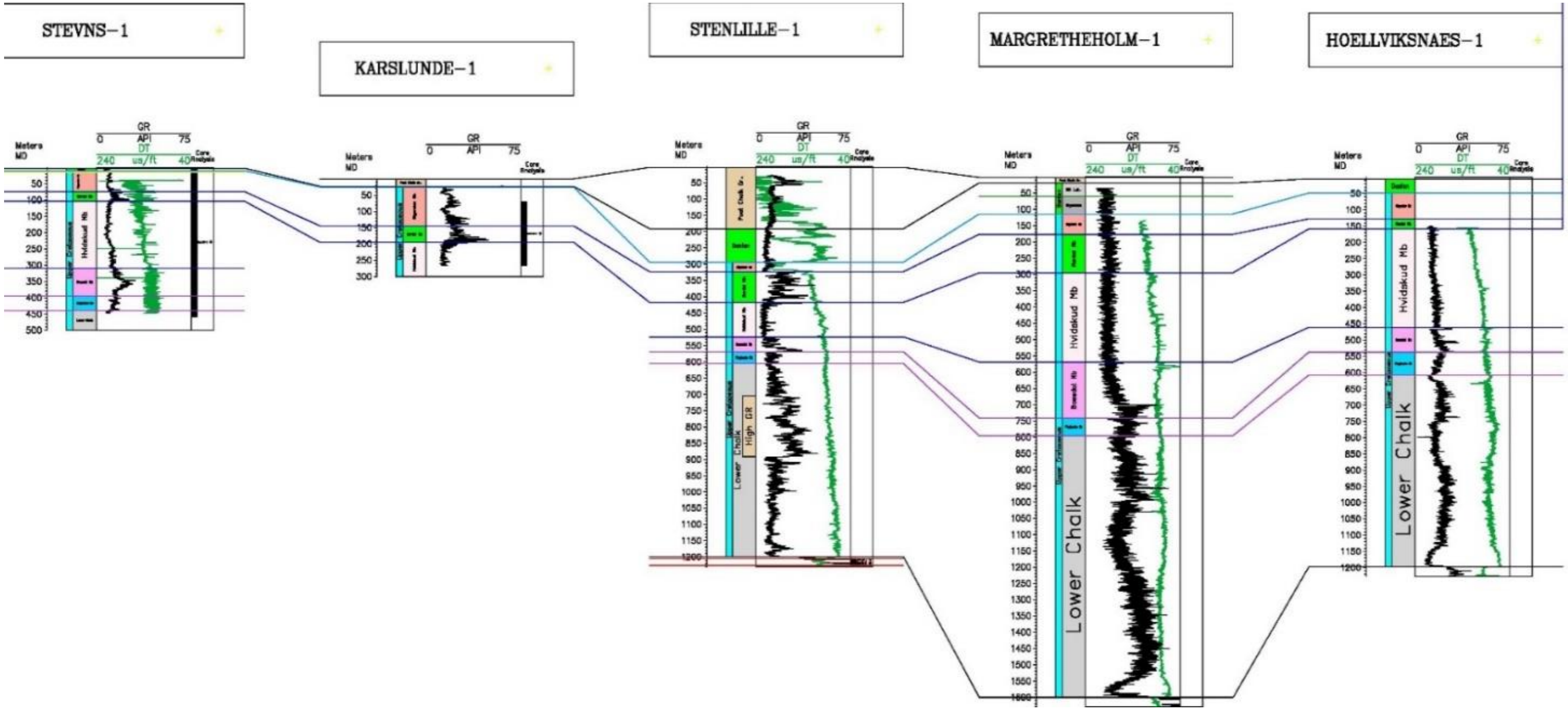


Figure 16. Well panel with gamma log (black) and sonic log (green). The gamma ray reflecting the clay content shows increased values in the Rørdal Member (lightgreen intervals) and the Boesdal Member (pink intervals). (From Kristensen et al. 2017).

Figur 16. Brøndpanel for øst Sjælland med gammalog (sort) og soniclog (grøn). Gamma- loggen afspejler forøget ler indhold i Rørdal Member (lysegrønne intervaller) og Boesdal Member (lyserøde intervaller). (From Kristensen et al. 2017).

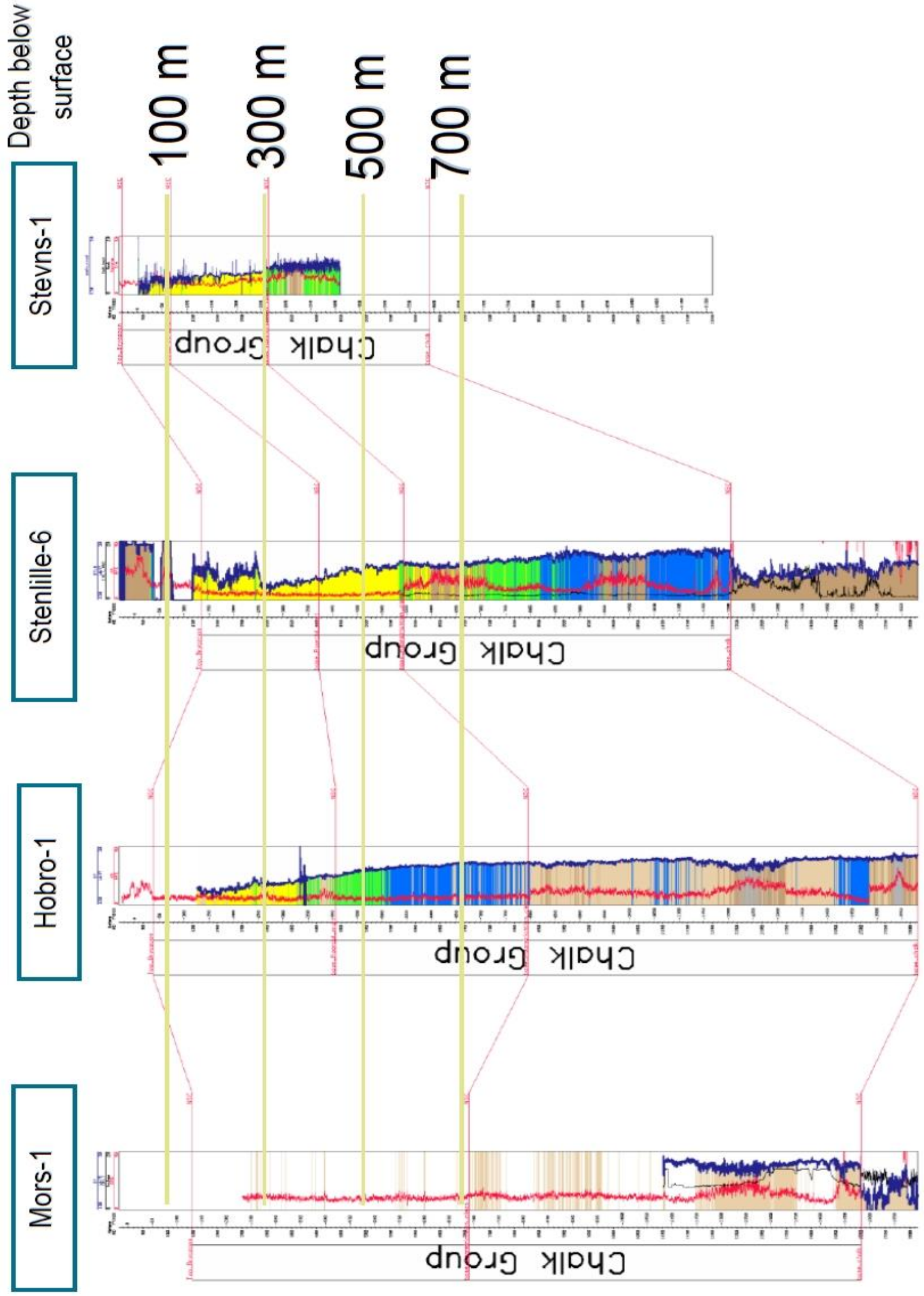


Figure 17. *Log panel across Denmark (Knudsen et al. 2010): Sonic (blue) and gamma (red) logs from Mors-1, Hobro-1, Stenlille-6 and Stevns-1. Lithology legend: Light to dark brown colors reflects impure chalk with high to very high γ-values.*

Color interval for clean chalk (low gamma-values) is based on sonic curve:
Yellow: >107 msec/feet, (slow sonic velocity – soft chalk (H1)).
Green 88 to 107 msec/feet (faster sonic velocity – slightly indurated chalk (H2)).
Blue < 88 msec/feet. (fast sonic velocity - indurated chalk (H3)).

Figur 17 (forrige side). *Log panel hen over Danmark (Knudsen et al. 2010): Soniclogs (blå) og gammalogs (rød) fra Mors-1, Hobro-1, Stenlille-6 og Stevns-1. Lithologi legende: Lys- til mørkebrune farver indikerer uren kalk med høje til meget høje gamma-værdier. Farveinterval for ren kalk (lave gamma-værdier) er baseret på sonic loggen:*
Gul: >107 msec/feet, (langsom sonic hastighed – blød kalk (H1)).
Grøn 88 to 107 msec/feet (hurtigere sonic hastighed – delvist hærdnet kalk (H2)).
Blå < 88 msec/feet (hurtig sonic hastighed – hærdnet kalk (H3)).

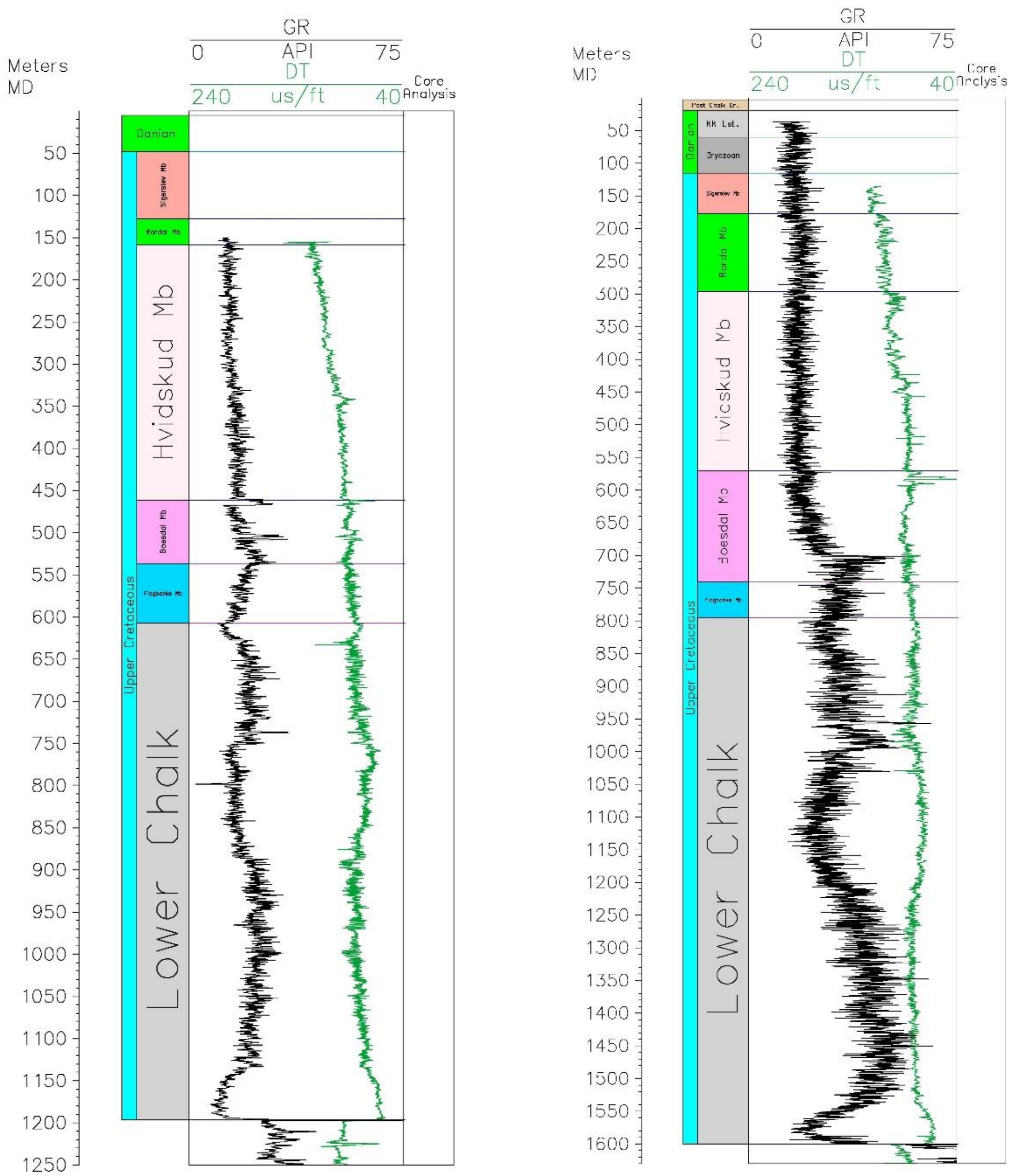


Figure 18. *Well panels for Margretheholm-1 (left) and Hölviksnäs-1 (right). (From Kristensen et al. 2017).*

Figur 18. *Brøndpaneler for Margretheholm-1 (venstre panel) og Hölviksnäs-1 (højre panel). (From Kristensen et al. 2017).*

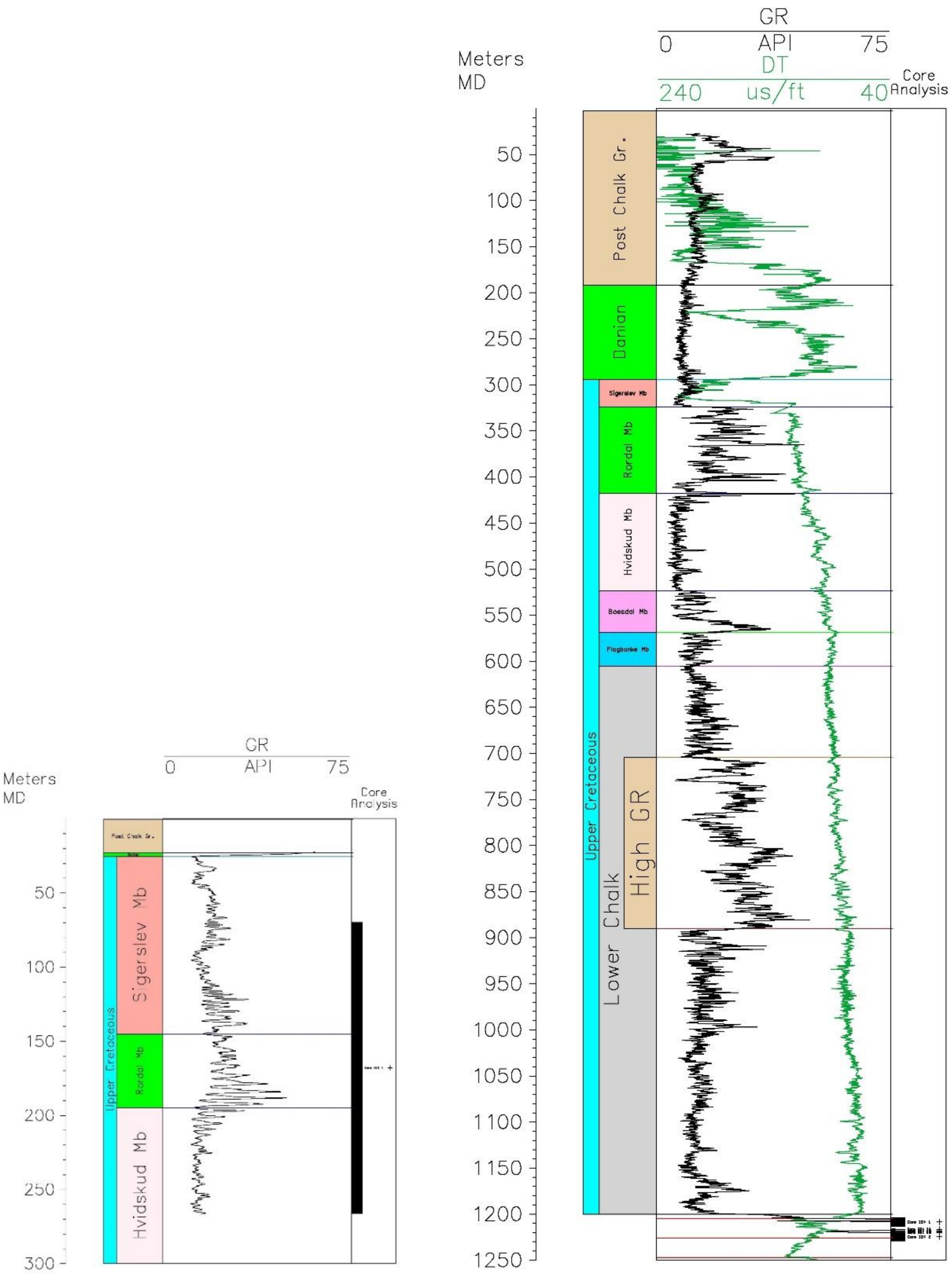


Figure 19. *Well panels for Karlslunde-1 (left) and Stenlille-1 (right). (From Kristensen et al. 2017).*

Figur 19. *Brøndpaneler for Karlslunde-1 (venstre panel) og Stenlille-1 (højre panel). (From Kristensen et al. 2017).*

5. Faults and fractures

5.1 Faults

Several large faults occur within the Sorgenfrei-Tornquist Zone (Figure 3), intersecting the Chalk Group (Liboriussen et al. 1987). From the Sorgenfrei-Tornquist Zone a number of faults continues into the Norwegian-Danish Basin. In some areas the lateral extent of the chalk and limestone units is structurally controlled, seen as termination of units against faults. An example is seen at the Carlsberg Fault which is the most pronounced tectonic feature in the subsurface of København (Jakobsen & Klitten 1997). The SE–NW striking Carlsberg Fault separates the København Kalk Formation from the Stevns Klint Formation (Figure 20). The fault is one of a number of relay faults related to the Sorgenfrei-Tornquist Wrench Fault Zone. The Carlsberg Fault has been interpreted as a negative flower structure with off-set between 50–100 meters of the hanging-wall block down to the NE (Fallesen 1995, Jakobsen et al. 2002). The Carlsberg fault may still be active as terrain movements across the fault have been detected recently (Jakobsen et al. 2013) and neo-tectonic faulting of the Quaternary cover is seen (Kammann et al. 2016).

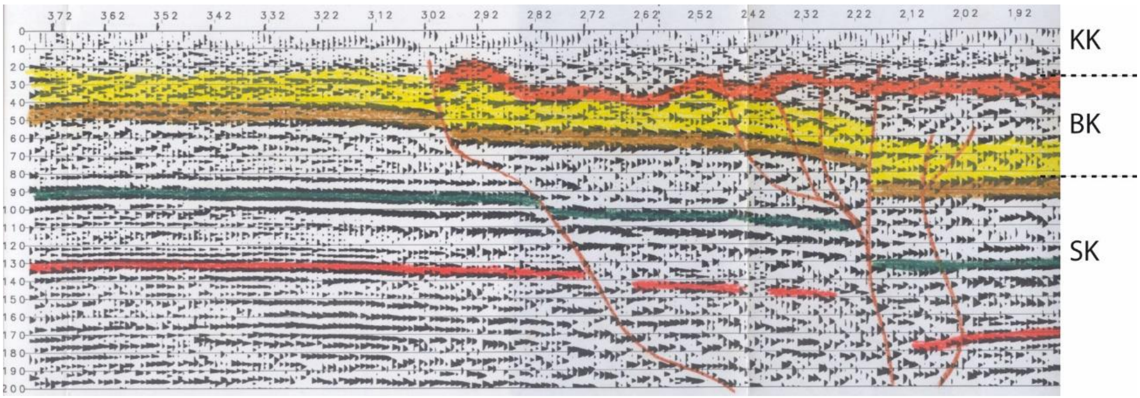


Figure 20. *Seismic section across the Carlsberg Fault on Amager (exit 19 on E20)(From Fallesen 1995). KK=København Kalk Formation, BK=Bryozoan Limestone, SK=Chalk, Upper Maastrichtian.*

Figur 20. *Seismisk section hen over Carlsberg Forkastningen på Amager (afkørsel 19 på E20) (From Fallesen 1995). KK=København Kalk Formation, BK=Bryozokalk, SK=Kalk, Øvre Maastrichtian.*

In the Aalborg region the mapping of the Rørdal Member as part of the groundwater mapping, showed that the member has been subjected to faulting, as it is found at varying levels in the area (Nielsen & Jørgensen 2008). Furthermore, the high-lying chalk is dissected by straight, incised valleys, within the pre-Quaternary surface, with incisions up to about 110 m, varying from 60 meters a.s.l. to 50 meters b.s.l. This relief (Figure 21) is caused by uplift of the chalk in the Sorgenfrei-Tornquist Zone, due to tectonic movements which created a complex fault pattern. These faults and associated fracture zones create weakness zones, which subsequently have been eroded. Fracture patterns have been mapped in detail in the Aalborg region (Jakobsen & Madsen 1996).

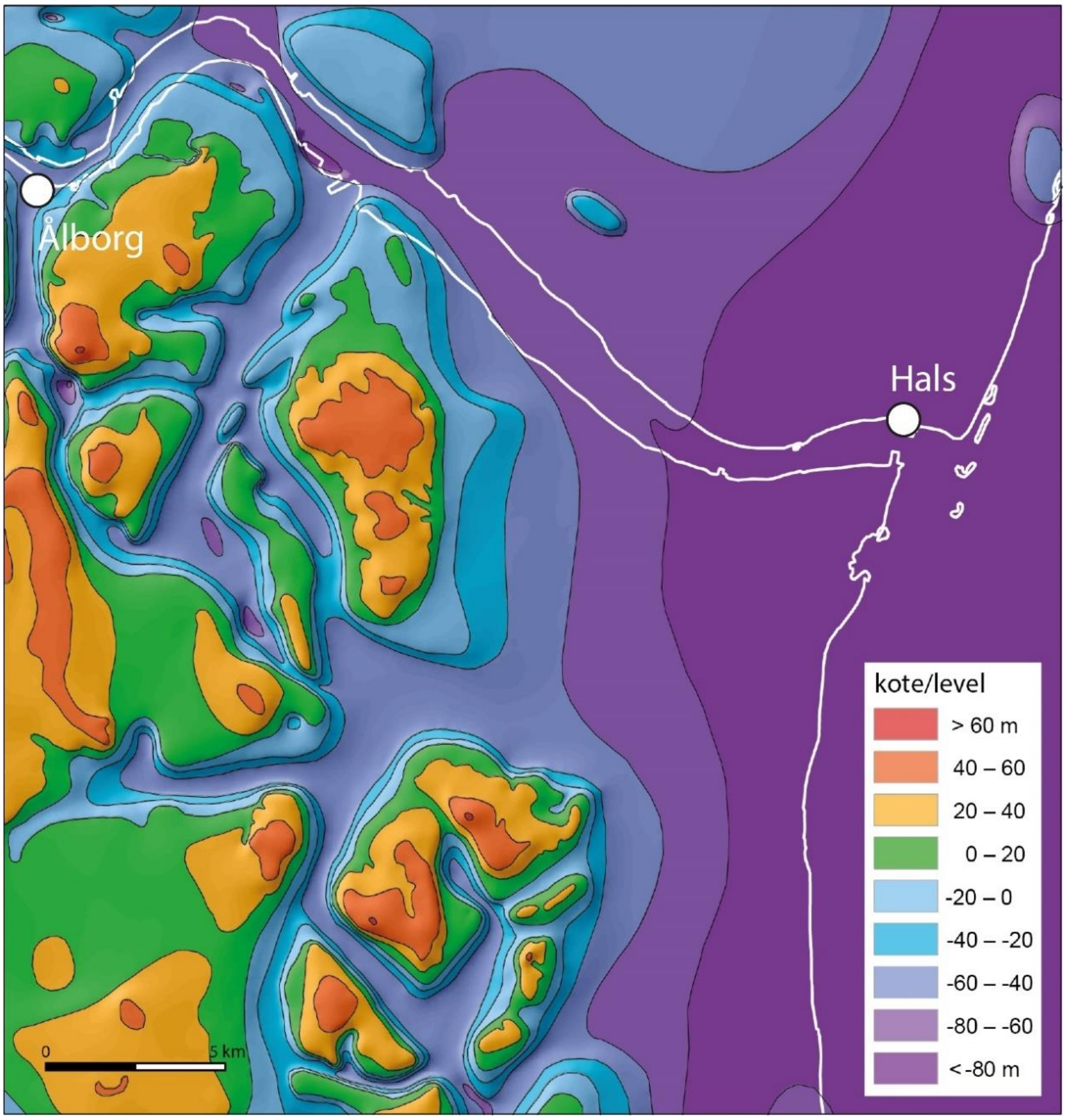


***Figure 21.** Topography of the pre-Quaternary surface in the Aalborg region, north Jylland (from Jakobsen & Pedersen 2013). The incisions in the pre-Quaternary surface are located above weakness zones related to faulting and with the same orientation as faults in the area within the Sorgenfrei-Tornquist Zone; E-W, NW-SE and NE-SW.*

***Figur 21.** Topography af præ-Kvartær overfladen i Aalborg området, Nordjylland (from Jakobsen & Pedersen 2013). Nedskæringerne i Prækvartær overfladen findes langs svagheds-zoner over større forkastninger orienteret parallelt med Sorgenfrei-Tornquist Zonen; Ø-V, NV-SØ, og NØ-SV.*

Just north of Mariager Fjord, a SkyTEM survey was performed (GERDA) (Figure 22). The survey revealed a fault, where a till layer has been down faulted. This has been interpreted as one of a number of faults in the region (Jakobsen et al. 2013). In the fault zone, the saltwater, with a lower resistivity, has emerged to a much higher level as the surroundings, indicating a much higher conductivity.

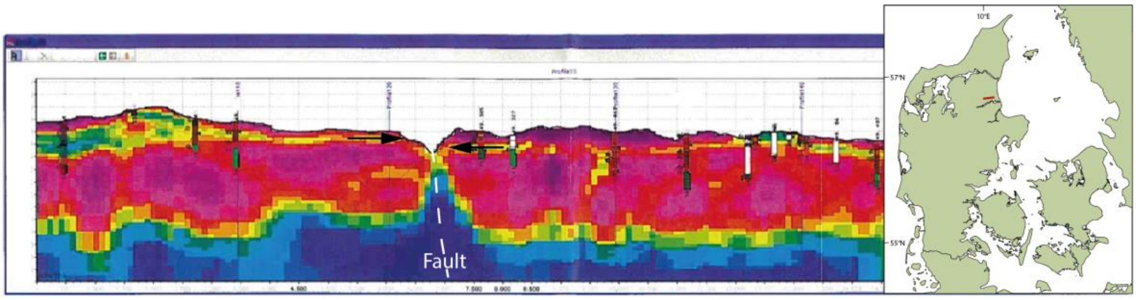


Figure 22. *East to West oriented SkyTEM survey just north of Mariager Fjord (GERDA) showing electrical conductivity. Note the thin yellow unit marked with arrows, with relatively high electrical conductivity, is displaced downwards on the eastern side, which is interpreted to indicate the presence of a fault. The blue colours have high electrical conductivity, and it outlines the salty groundwater, which at the interpreted fault is intruding to a higher level.*

Figur 22. *Øst-vest orienteret SkyTEM survey nord for Mariager Fjord (GERDA) som viser elektrisk konduktivitet. Bemærk den gule enhed markeret med pile, med relative høj elektrisk konduktivitet, der mod øst er lavereliggende, hvilket tyder på forsætning langs en forkastning. Den blå farve viser områder med høj elektrisk konduktivitet og markerer grundvand med høj salinitet. På profilet ses at det salte vand forekommer relativt højt, og tæt på terrænoverfladen i den tolkede forkastningszone.*

5.2 Fractures

Chalk and limestone display varying degrees of fracturing. Generally, fractures can be divided into 3 different types (Figs 23, 24 and 25):

- Vertical fractures, typically of tectonic origin
- Horizontal fractures, typically generated by unloading (glaciers, Neogene erosion)
- Crushed chalk, typically caused by glaciers.

Figure 23. *Vertical fractures in the København Limestone Formation in a temporary exposed outcrop in København.*

Figur 23. *Lodrette sprækker i København kalk Formationen observeret i en midlertidig blotning i København.*

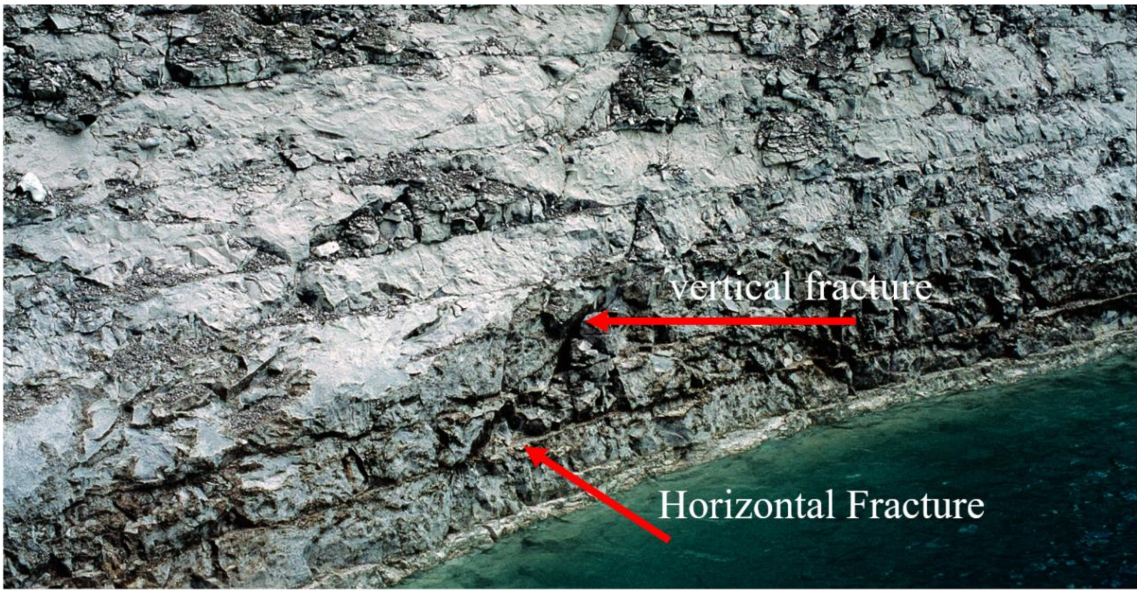


Figure 24. *Vertical and horizontal fractures in the Sigerslev Member, Sigerslev quarry. Section approximately 1.5 meters high.*

Figur 24. *Lodrette og vandrette sprækker i Sigerslev Member, Sigerslev kalkbrud. Profilet ca. 1,5 meter højt.*

Vertical fractures are grouped into fracture set after their orientation. Important parameters concerning conductivity is number of fracture set, spacing, aperture, size and connectivity.

In the Layered København Limestone Formation, horizontal fractures are usually seen between layers with different induration. In the bryozoan limestone the fractures follow the layering as well, giving them an undulating shape.

Figure 25. *Closely spaced vertical fractures in Stevns Klint Formation, in a temporary exposed excavation in Sydhavnsgade, Copenhagen, situated close to the Carlsberg Fault. Compass for scale.*

Figur 25. *Tætliggende lodrette sprækker i Stevns Klint Formationen, i en midlertidig udgravning i Sydhavnsgade, København, nær Carlsberg Forkastningen. Kompas til skala.*

The Carlsberg fault has locally a large impact on the hydraulic characteristics of the limestone in form of an increased hydraulic conductivity due to a dense network of fractures as seen in Figure 25 (Blem 2002, Markussen 2002). Anisotropic fracture-controlled water flow is also seen in the chalk in general. At Stevns there is a pronounced preferential flow controlled by fractures in the otherwise homogeneous chalk (Rosenbom & Jakobsen 2005) (Fig 26). The image was made at temperatures below 0^{o}C, and the water flowing into the quarry is outlined with colours indicating the warmest areas (white at level A and green at level B). The image clearly shows that water inflow is mainly from the north, and is very limited from west, indicating a strong preferential and anisotropic fracture flow.

The top of the chalk or limestone is very often crushed and densely fractured by subglacial deformation, generated during the advance of a glacier (Figure 27). The glacial deformation is mostly seen within the upper 10 meters of the limestone. The number of horizontal fractures were measured at the Sigerslev quarry (Figure 28). Just below the glacial till the number of fractures is very high, however it decreases rapidly downwards through the upper 10 m, and become rather constant further down, however still decreasing slightly with depth.

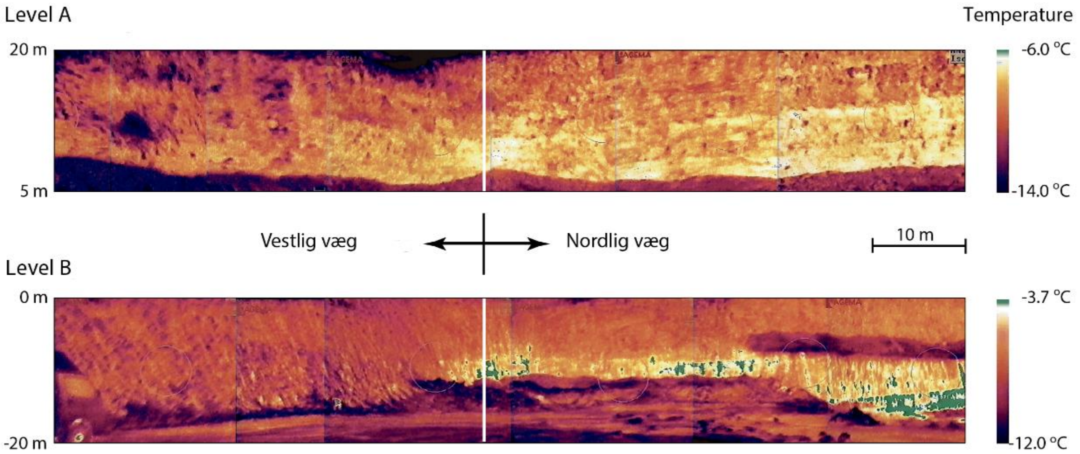


Figure 26. *Thermography image of the northern and western walls in the Sigerslev chalk quarry at Stevns. The image was made at temperatures below* 0^{o}*C, and the water flowing into the quarry has colours indicating the warmest areas (white at level A; green at level B).*

Figur 26. *Termografisk billede af nordlige og vestlige vægge i Sigerslev kalkbrud ved Stevns. Billedet blev optaget ved lufttemperaturer under* 0^{o}*C, og vandtilstrømning (ca.* 8^{o}*C) ind i bruddet ses som de varmeste områder (hvide farver på niveau A og grøn på niveau B).*

Figure 27. *Glacially crushed/brecciated and fractured København Limestone Formation at Limhamn, Sweden (Jakobsen 1994).*

Figur 27. *Glacialt knust og opsprækket København Kalk Formation ved Limhamn, Sverige (Jakobsen 1994).*

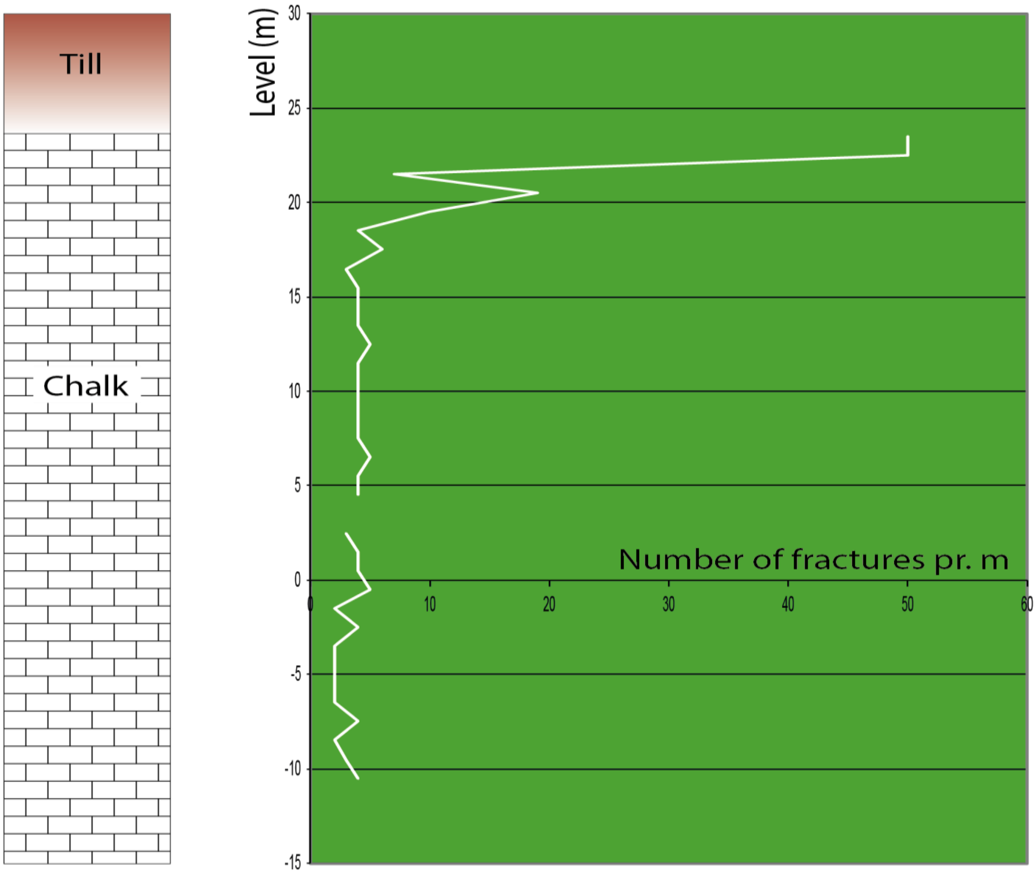


Figure 28. *Number of horizontal fractures per meter with depth, measured in Sigerslev quarry, Stevns.*

Figur 28. *Antal horisontale sprækker pr. meter for stigende dybde, målt i Sigerslev bruddet, Stevns.*

5.3 General observations on fractures

- In general fractures generated from subglacial deformation are very common at terrain surface and decrease rapidly in number downwards to depths of around 10 meters
- Intense fracturing is observed at deeper levels near major faults related to the Sorgenfrei-Tornquist zone (tectonically induced).

6. Hydraulic characterization of the chalk/limestone

When characterizing the hydraulic properties of groundwater reservoirs, the following parameters are used:

- Hydraulic conductivity (K) in m/sec
- Permeability (k) in mD (milliDarcy)
- Transmissivity (T) in m^2/sec

The hydraulic conductivity (K) is the flowability of a liquid in a porous medium, and it depends on both the properties of the aquifer and the liquid. The hydraulic conductivity is thus defined as the amount of water that, within a given time, can be transported through a given cross-sectional area with a hydraulic gradient of one. Hydraulic conductivity is usually given in the unit m/s.

Permeability (k) has the dimension of area (e.g. m^2), but is normally given in the unit of mD (milliDarcy) or Darcy, a unit commonly used in laboratories and in the oil/gas industry. Throughout this report the conductivity will be given in both m/s and in the mD unit systems.

In the included studies it is assumed that conductivity K of $1*10^{-8}$ m/s is equal to 1 mD.

The core plug permeabilities reported in many studies have been measured with gas permeameter. To enable comparison to the hydraulic test results the values have been converted to fluid permeability with the relationship established between gas permeability and Klinkenberg corrected permeability (common proxy for true fluid permeability): $k(Klink)= 0.52*k(gas)^{1.083}$ (Mortensen et al. 1998).

For core plugs, the orientation is usually horizontal, i.e. plugs drilled from the side of the core. In formations that are heterogeneous at small scale, e.g. having stylolites or thin clay laminae, the vertical permeability may be lower by orders of magnitude, thus not being represented by the values derived from horizontal plugs. Thus, permeability should always be measured on vertical plugs as well.

Transmissivity (T) means the ability to transport water per unit of time through a certain aquifer thickness (carrying capacity). The transmissivity is thus defined as the product of the hydraulic conductivity and the thickness of the water-saturated zone in the aquifer and is indicated in m^2/s. Transmissivity is usually determined by prolonged test pumping.

6.1 Hydraulic conditions in the chalk/limestone package

The data background includes 1) core material from wells, 2) outcrop material from surface, and 3) hydraulic tests in wells at variable depths.

The wells with available data are listed in Table 1, they are shown on the map (Figure 29) and in the well panel (Figure 30) from west to east across the Danish onshore area.
Most of the data have been collected in connection with studies on groundwater flow and transport and mainly focussing on production of water from the uppermost 50-100 meters.

The retardation of flow and the sealing properties of the chalk have therefore not been studied at the same detail, which significantly limits the interpretation of seal capacity of the chalk.

Table 1. *List of wells with data from core material or hydraulic tests in the chalk/limestone sequence. Data from hydraulic tests from depths at 500 meters is available only from the ES1-ES4 wells.*

Tabel 1. *Liste over boringer med data fra kerne materiale eller hydrauliske test i kalkpakken. Data fra hydrauliske test fra 500 meters dybde findes kun fra ES1-ES4 boringerne.*

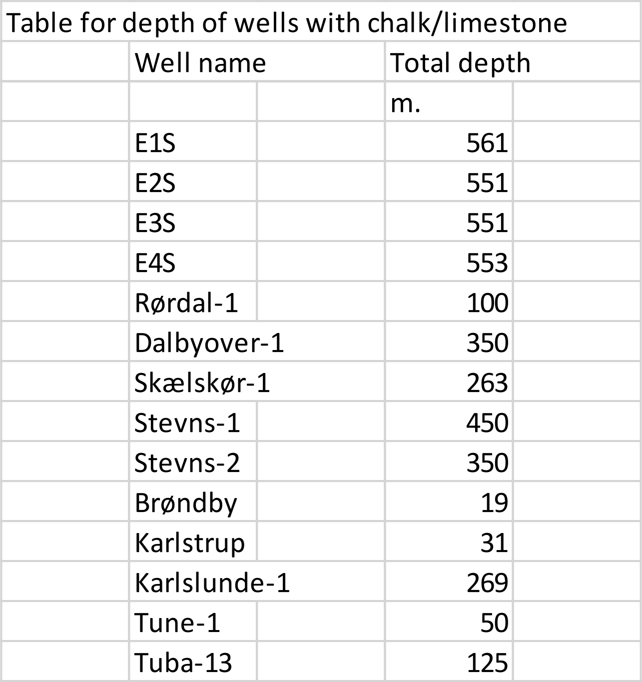


Table for depth of wells with chalk/limestone

Well name	Total depth
	m.
E1S	561
E2S	551
E3S	551
E4S	553
Rørdal-1	100
Dalbyover-1	350
Skælskør-1	263
Stevns-1	450
Stevns-2	350
Brøndby	19
Karlstrup	31
Karlslunde-1	269
Tune-1	50
Tuba-13	125

Figure 29. *Map showing the wells and outcrops with data available for the present study.*

Figur 29. *Kort der viser placering af boringer og blotninger hvorfra data er tilgængelige.*

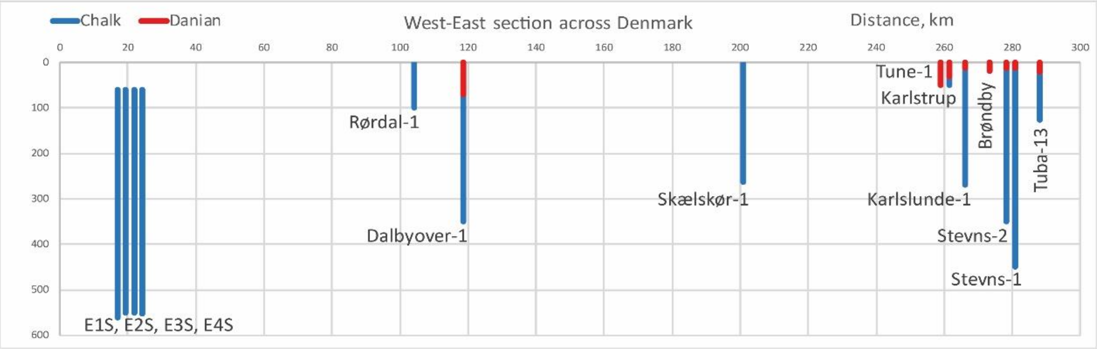


Figure 30. *Well panel showing the depths of the chalk/limestone where data have been available for the present study.*

Figur 30. *Brøndpanel som viser, hvor data er tilgængelige fra den gennemborede kalkpakke.*

6.2 Regional variation in hydraulic properties

Regionally, the hydraulic characteristics of the chalk and limestone vary considerably. In the areas important for water supply from the chalk and limestone, all dominant bedded rock types have visible open fracture zones at 0.5 to 1m intervals in the uppermost few tens of meters of the sequence. Along the eastern coastline of Sjælland, one or two highly permeable zones of horizontal fractures occur at 30-70 meters depth likely caused by rebound effects after glacial compression followed by unloading upon melting of the Weichselian ice shield. The same fracture patterns have been reported from the Aalborg region (Nielsen and Jørgensen 2008). The formation of horizontal fractures may be associated with the removal of overburden and stress relief processes. Consequently, bedding fractures may be expected to be more numerous, more laterally extensive and have larger apertures at relatively shallow depths (Bloomfield, 1999, Bonnesen et al. 2009).

Groundwater flow anomalies at surface and shallow depths have been noted with a few exotic examples of karst development in areas where the carbonates occur close to the ground surface (Nilsson & Gravesen 2018).

6.3 Transmissivity in the upper 50–100 meters of chalk

Transmissivity data and pumping test data from the JUPITER database have been used to calculate the transmissivity distribution in the upper 50-100 meters of the chalk/limestone sequence as input to the National Water Resources Model (DK model) in 500x500 meter grids. The information on transmissivity values in chalk is compiled from about 7500 screened sections in JUPITER. The distribution of estimated transmissivity values as shown in Figure 31 has been interpolated in ArcGIS using a top2rater method (Stisen et al., 2019).

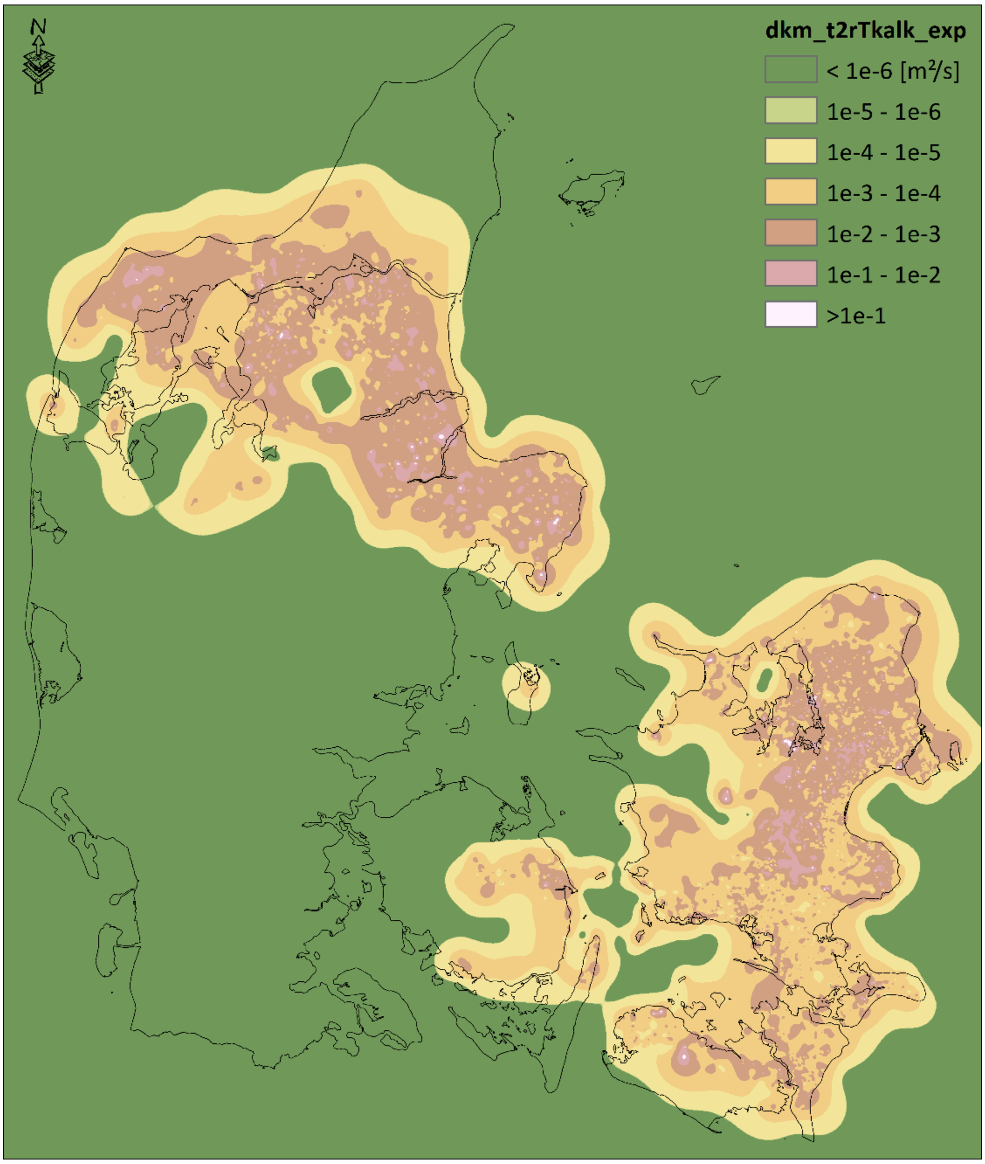


Figure 31. *Transmissivity in chalk/limestone in Denmark for the upper 50-100 meters layer in the Danish "National Vandressource Model" (DK-model 2019).*

Figur 31. *Transmissiviteten i kalksten i Danmark i de øvre 50-100 meter lag i den "Nationale Vandressource Model" (DK-model 2019)*

6.4 Petrophysical properties of the chalk/limestone package

The hydraulic behaviour of chalk, limestones and marl is controlled by the matrix properties and the presence of open fractures. The amount of open fractures fully determines the potential for extracting groundwater which is generally restricted to the upper 50 meters of the chalk/limestone formations. This is due to the glacial deformation history with fracturing of the upper layer, whereas deeper levels were left relatively undisturbed.

6.5 Data availability

Only few detailed investigations of porosity and hydraulic conductivity have been carried out in the deeper parts of the chalk and limestone sediments that are of interest here. The matrix properties have been sampled and analysed extensively in wells, where drill cores are available and where formations are exposed at surface or in quarries.

The knowledge about the subsurface chalk and limestone in central Copenhagen was early on explored in the TUBA-13 well in connection with planning of the subway train tunnels. In 1967-1972 several boreholes were drilled in Copenhagen, the majority of which include strata of Danian age. The geological results from the cores retrieved from these drillings have been published by Stenestad (1976). One of the cores, TUBA 13, penetrated strata of Selandian, Danian and Upper Maastrichtian age and provided the first information about the deeper levels of the formations in the Copenhagen area (Nielsen 1976).

The wells Stevns-1 and Stevns-2 were drilled as scientific wells during 2005, reaching depths of 450 and 350 meters. The oldest strata recovered were dated as Late Campanian (Stemmerik et al. 2006, Surlyk et al. 2013). Outcrops at Stevns have supplied data for the uppermost parts of the sequence for both the Danian bryozoan limestones and the uppermost Maastrichtian chalk (Frykman 2001).

- The well Skælskør-1 (263 meters total depth) penetrated down into Late Campanian limestone (Thibault et al. 2015).
- The well Rørdal-1 (100 meters total depth) penetrates into the Upper Campanian limestones at 74 meters depth (Harlou et al. 2016).
- The well Dalbyover-1 penetrates a special lithology in the Danian of lime mudstone which is specific for this central part of the Danish Basin. This lime mudstone has a thickness of more than 60 meters in the well.
- The well Karlslunde-1 (DGU nr. 207.3850) penetrates to a total depth of 269 meters in the Maastrichtian chalk (Larsen et al. 2006).
- For investigating the sealing properties of the chalk overlying the Mors Salt Dome, 4 wells (E1S, E2S, E3S, E4S) were drilled to a depth of 550 meters b.s., and a summary was reported (Gosk et al 1981).

6.5.1 Matrix porosity and permeability of chalk and limestone

Matrix investigations have been carried out in two main material sources: 1) outcrops or shallow pits of different formations and 2) core material from wells drilled through various parts of the sequence.

From shallow pits and construction sites there are data available in the Copenhagen area as part of the metro tunnel construction (GEO 2014) and in the Karlstrup chalk quarry (Jakobsen et al. 1993; Brettmann et al. 1993). These investigations show, based on plug matrix measurements, that the Cretaceous chalk in these shallow burial settings is soft and friable with a matrix porosity of 35-50% and Danian limestone contains alternating hard and soft layers and has a porosity of 10-35% (Figure 32). The hydraulic conductivity of the carbonate matrix rocks varies by orders of magnitude between $1*10^{-6}$ and $1*10^{-10}$ m/s (0.01-100 mD).

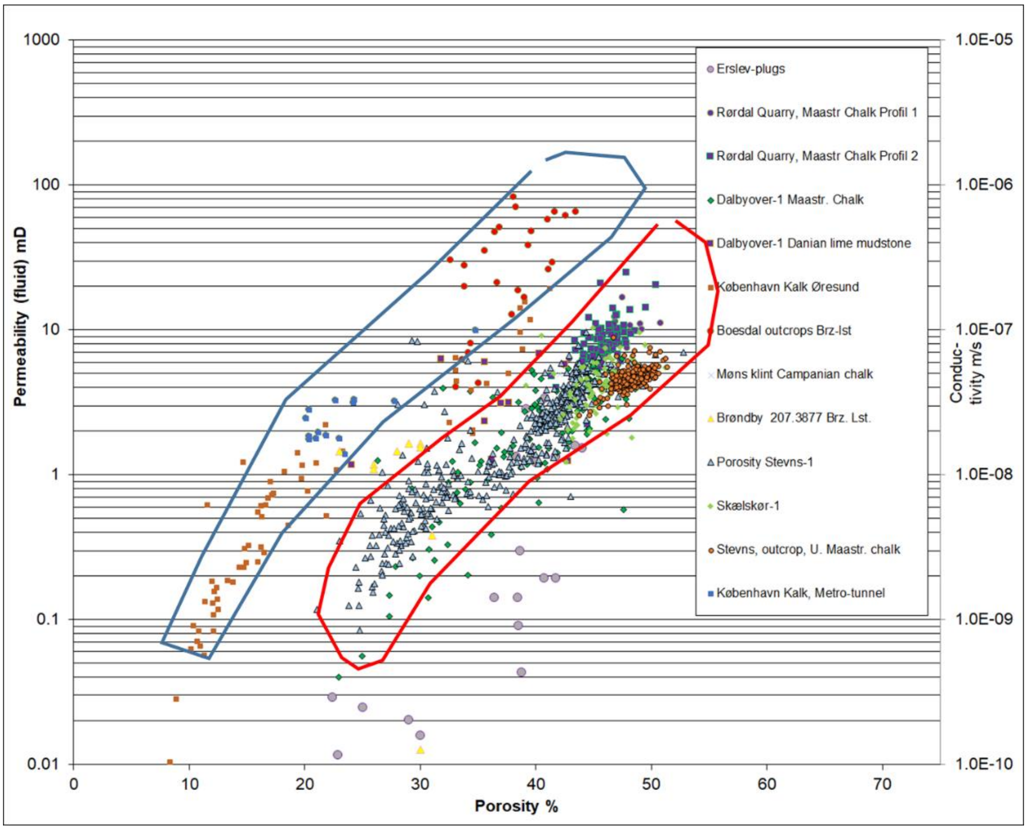


***Figure 32**. Crossplot of the porosity and permeability from different formations.*

***Figur 32.** Figuren viser relationen mellem porøsitet og permeabilitet for de forskellige dele af kalkpakken og illustrerer opdelingen i to hovedpopulationer der knytter sig til henholdsvis Danien kalksten/bryozokalk (blå) samt til den mere finkornede kridtbjergart (rød) med mindre permeabiliteter.*

The porosity and permeability data clearly show two main populations that can be linked to either the Danian limestones/bryozoan limestones, or to the finer grained and less permeable chalk or lime mudstones. The separation of the data from the Erslev wells at even lower permeabilities is probably due to diagenetic effects linked to the location immediately above a saltdome induced structure.

The correlation of lower porosities with lower permeabilities for the chalk family is due to compaction and minor cementation. For the limestones the similar trend is caused by more pervasive cementation processes linked to the specific lithology originally containing higher fractions of material with unstable mineralogy (aragonite, Hi-Mg-calcite and silica) which were dissolved and subsequently precipitated as cement in certain layers in the rock formations at relatively shallow burial.

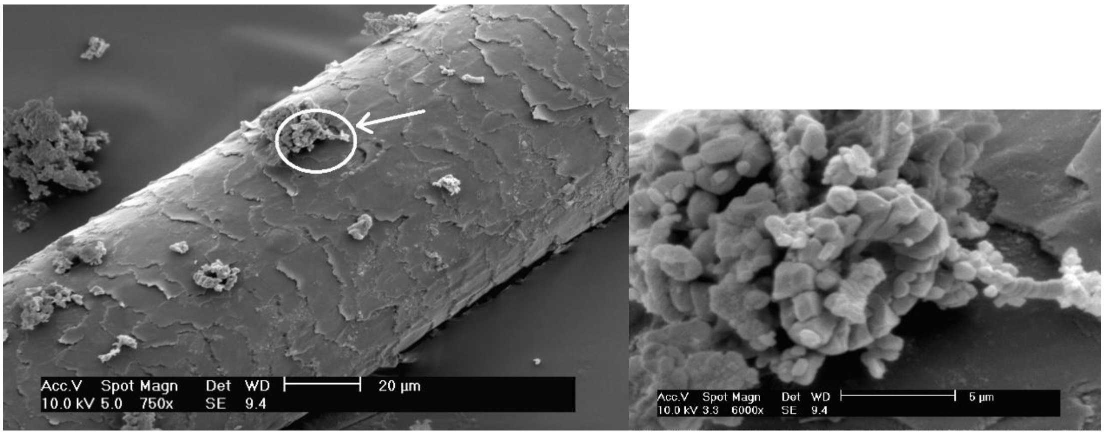


***Figure 33.** A single coccolith sitting on a human hair to illustrate the very small grainsize of the matrix particles in a typical chalk lithology. Close-up to the right.*

***Figur 33.** En enkelt coccolith på et menneske hår (til venstre), for illustration af den meget lille kornstørrelse af matrix partikler i en typisk kridtbjergart og nærbillede af coccolithen til højre.*

Chalk is a fine-grained, sedimentary rock composed primarily of skeletal debris from calcareous nannofossils, mainly coccoliths, with minor contributions from foraminifera, calcispheres and macrofossil fragments. Coccoliths range in size from 2 to 15 µm (Figs 33, 34).

In the living algal organism, a number of coccoliths interlock to form a spherical or ellipsoid external shell, the coccosphere. Normally the coccosphere will fall apart during the sedimentation stage, or due to subsequent bioturbation, but occasionally coccospheres from robust coccolith species survive in the sediment. Each coccolith is composed of a number of calcite crystals of varying sizes (0.2–3 µm) and shapes. When a coccolith disintegrates the elements are released as chalk particles (Figure 34).

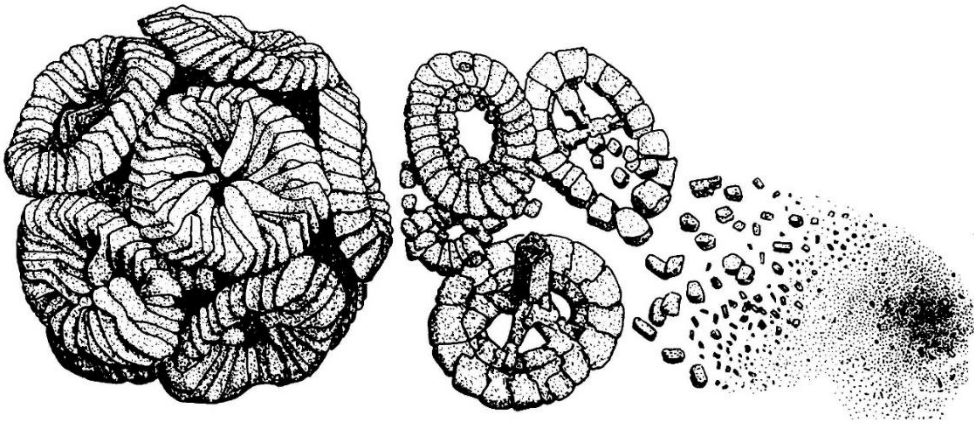
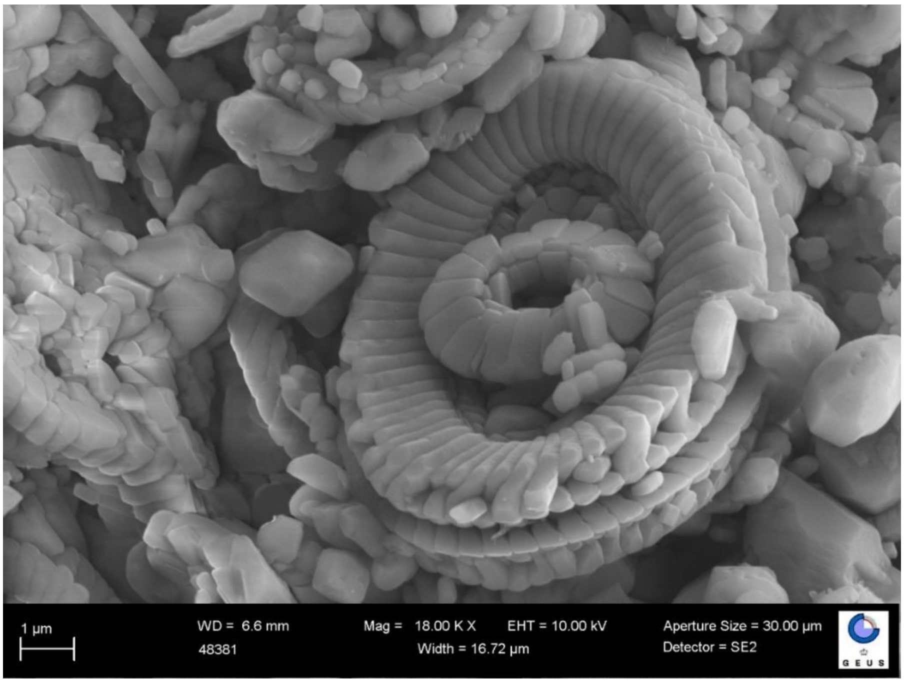


***Figure 34.** The gradual disintegration of a coccosphere into chalk matrix material. From Bromley (1979).*

***Figur 34.** Illustration af den gradvise nedbrydning af coccosphærer til kalk matrix materiale (Fra Bromley 1979).*



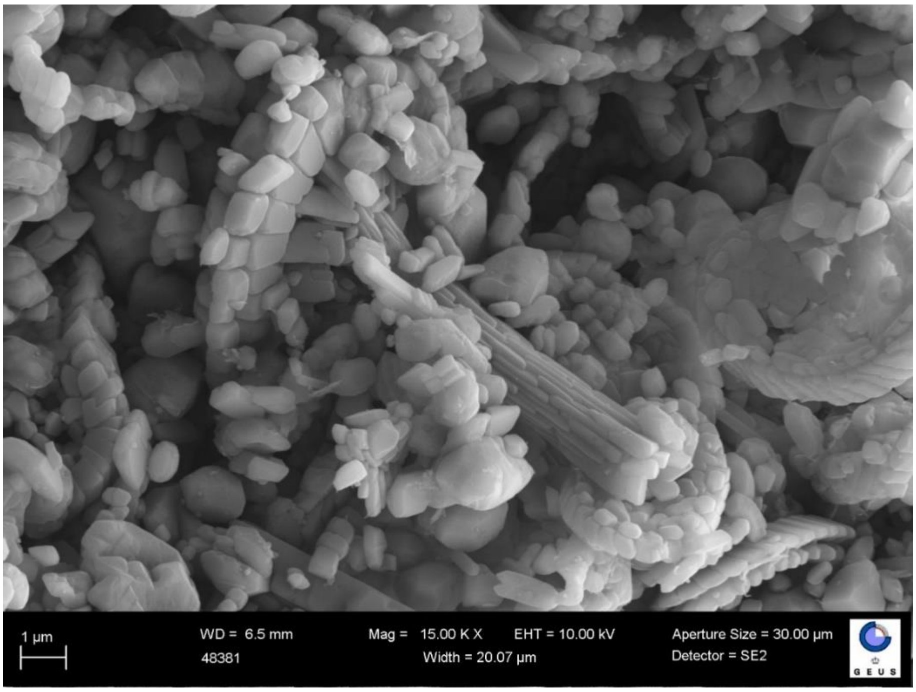


***Figure 35**. Photos of well preserved coccoliths, some with slight diagenetic overgrowth, and micron-sized particles forming the matrix. From the uppermost Maastrichtian chalk, Stevns Quarry.*

***Figur 35.** Fotos af velbevarede coccolither, nogle med diagenetisk overvoksninger, og mikrometer størrelse partikler, der udgør matrix. Fra det yngste Maastrichtien fra Stevns Kridtbrud.*

The typical chalk is composed of varying proportions of intact coccoliths, coccolith fragments and single coccolith elements (particles) (Figure 35) mixed with subordinate amounts of microfossils and macrofossil fragments.

6.5.2 Hydraulic properties (matrix and fractures) of the chalk

Very few measurements have been reported on fracture hydraulic conductivity from Danish investigations on hydraulic properties in chalk and limestone. The available data for this is summarized in the chapters below. The hydrogeology of the deeper parts of the chalk section in Denmark (>100 meters) is not well known, and the only area contributing with information about hydraulic properties of the chalk formations at depth is the Mors island in Northern Jylland (Gosk, 1981). These results are reported and discussed in a later chapter.

6.5.3 Investigations in the Greater Copenhagen area

The water supply in the Copenhagen area is based exclusively on local and regional groundwater aquifers at depths down to 100 m, and since the abstraction rate is larger than the sustainable resource, protection of the groundwater resource is crucial. Primarily glacial meltwater sand and Danian limestones are used for abstraction. In lithostratigraphic terms, the Danian limestones belong to the Stevns Klint and København Limestone Formations (Bryozoan Limestone unit and København Limestone).

No well tests have been conducted in the interval 400–800 meters and the amount of natural fractures is very limited for chalk found deeper than 300 m, thus the effective permeability of the chalk is unknown, but probably very low (Kristensen et al., 2017).

An analysis of 124 flow-logs conducted both in chalk and Danian limestones indicates that the major part of the influx of fresh water into the boreholes takes place in the upper 5–10 m, i.e. just below the base of the Quaternary. Throughout the Danian limestone formations, several levels with water influx are encountered. In the underlying chalk, being of Maastrichtian and Campanian age, the number of influx levels and the amount of influx decreases. Deeper than c. 70 meters below base Danian, only very limited influx occurs (Bonnesen et al. 2009, Larsen et al. 2006). The transition zone between fresh and salt groundwater is typically located at the base of the Danian limestones or at an internal marl layer a few meters down into the chalk. Exceptionally salty groundwater has entered higher stratigraphic levels in coastal areas and fault zone areas (Klitten et al. 2006). Thus, the chalk in general holds only limited groundwater resources.

It is important to note that the National Water Resources Model for Denmark (usually called DK-model) has a focus on the hydrological conditions in the uppermost layers that are of importance for groundwater extraction. The model was developed by the Geological Survey of Denmark and Greenland to advance the assessment of groundwater quantitative status accounting for interactions with surface water and anthropogenic changes, such as extraction strategies and land use, as well as climate change.

The model offers an overall 3D representation of the hydrological circle in the study area down to about 100 meters below mean sea level and can therefore contribute with input regarding flow in the freshwater zone. However, the scale and the scope the DK-model makes it a generalised model for water balance estimations and therefore results in some limitations e.g. for layers deeper than 100 meters and in the representation of the very local hydrology at specific fault zones etc.

The Tune-1 well (DGU Nr. 207.3841) south of Copenhagen has been used for a conceptual model (Kjøller et al. 2006) for the hydraulics in the uppermost 50 meters based on investigations for a master-project at M&R DTU (Madsen, 2003). Flow-logs, optical televiewer data for fracture densities and pumping tests are included for the interpretation. The Danian limestone is divided into three zones (Figure 36). Uppermost zone 1 is 26.7 meters thick and supplies 37% of the inflowing water. The zone has an average bulk hydraulic conductivity of $1.9*10^{-5}$ m/s (1900 mD= 1.9 Darcy). Below is a thin but very conductive layer (Zone 2) of 4.7 meters thickness taking 55% of the inflow and average bulk hydraulic conductivity of $1.6*10^{-4}$ m/s (16000 mD = 16 Darcy). At the bottom of the formation is a 18.7 meters thick layer (Zone 3) taking 4% of the water inflow and average bulk hydraulic conductivity of $3.0*10^{-6}$ m/s (300 mD). The remaining 4% of inflow water is coming from the underlying chalk formation having very low conductivity. It is therefore ignored in the conceptual model applied for this specific case study, but it is indicated to have conductivity around $1.2*10^{-7}$ m/s (12 mD), which is comparable to previously reported matrix permeabilities in the uppermost chalk layers. Similar interpretations have been made from the Karlstrup area (Jakobsen 1991).

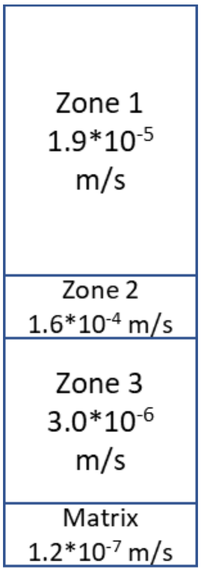


Figure 36. *Conceptual hydraulic model layers for the Danian Limestones at the Tune-1 well showing the conductivity in the various zones. Combined thickness of the upper 3 layers is 40 meters. (Modified from Kjøller et al. 2006, illustration is based on data from Madsen, 2003).*

Figur 36. *Konceptuel hydraulisk model for lag i Danian kalken i Tune-1 boringen, der viser konduktivitet i de forskellige zoner. Den samlede tykkelsen af de øverste 3 lag i modellen er 40 meter (modificeret fra Kjøller et al. 2006, illustrationen er baseret på data fra Madsen, 2003).*

6.5.4 Hydraulic parameters from deep well tests on Mors, North Jylland

Extensive hydraulic testing was carried out in wells in the 500 meters thick chalk package directly overlying the salt dome in a project investigating the potential for a storage facility for radioactive waste in a saltdome on the island of Mors in Northern Jylland.

The results from the Mors project where the chalk was penetrated and analysed also with hydraulic testing are summarized for in-situ transmissivity (Specific reports listed in section 9.1). The chalk package is situated on top of the Mors salt dome and might therefore have other structural characteristics than in other less deformed areas. The investigated area is situated above the concave part of the dome. If the halokinesis is stronger on the edge than in the centre of the dome, compressive force with a horizontal component may exist, giving rise to closure of the fractures. For detailed discussion of this subject see the original geological report (Gosk et al., 1981).

To investigate the sealing properties of the chalk overlying the Mors Salt Dome, 4 wells were drilled to a depth of 550 meters b.m.s. (below mean sea level), two on each drill site, in between the two deep test wells Erslev-1 and Erslev-2 that were drilled into the salt formation. The hydrogeological wells were numbered E1S, E2S, E3S and E4S. The summary here is based on the main report of the study (Gosk et al 1981).

The penetrated formations consist of clay, sand and gravel of Quaternary age to depth about 60 meters b.m.s. Below these depths the Upper Cretaceous formations consist of chalk and limestone of very fine-grained calcium carbonate of biogenetic origin with dominance of coccoliths and smaller amounts of foraminifera and other pelagic organisms. The upper part of the chalk formation is white, soft and friable. Below 350-400 meters b.m.s. the hardness increases. Marly layers or zones appear with increasing frequency downwards. The porosity varies between 45% in the upper part to about 15% at the bottom. Fractures have been detected from cores and impression packer tests as well as from log interpretations. The whole penetrated sequence comprises faults.

A physical recording of a few possibly open fractures from a depth of around 275 meters was reported (Andersen et al. 1981). The fractures were observed as an imprint in the rubber sleeve from a packer test tool and were estimated to have a dip of approximately 20 degrees.

Laboratory measurements of permeability and porosity on core plugs of the chalk formation from the wells E1-2-3-4S were carried out by DGU, Risø and Institute of Geological Sciences Wallingford, England. The core plug permeabilities are measured with gas permeameter and the values have been converted to fluid permeability with an empirical relation (Mortensen 1998) to enable comparison to the hydraulic test results (Figure 37).

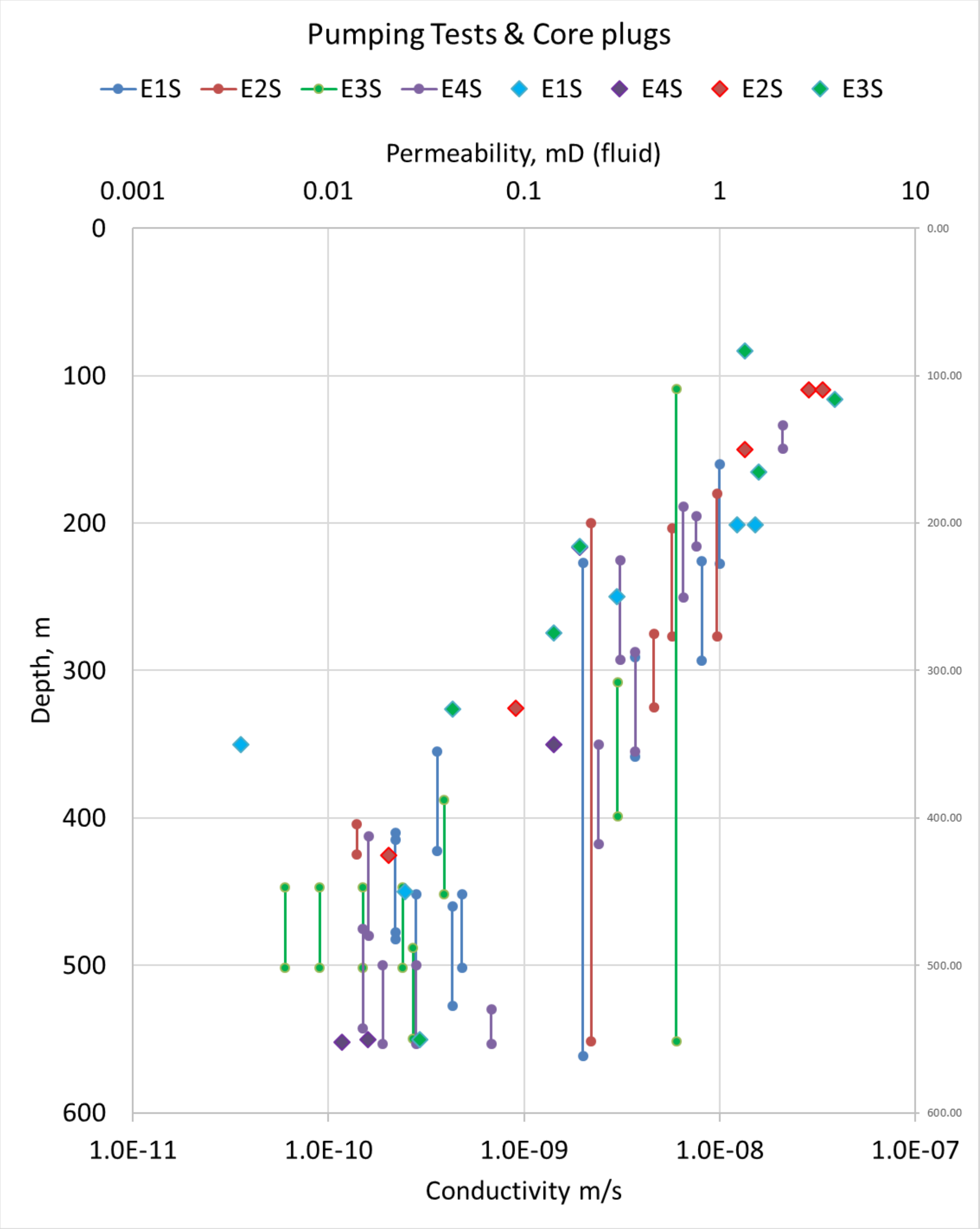


Figure 37. *Figure showing comparison of the matrix measured permeabilities from core material from the Erslev wells and pumping test interpretations of interval permeabilities. The core measured gas permeabilities have been converted to fluid permeability for this comparison. Permeability of 1 mD equals a conductivity of 1*10*$^{-8}$ *m/sec.*

Figur 37. *Sammenligning af matrix målte permeabiliteter fra kerne materiale fra Erslev boringerne og interval permeabiliteter tolkede fra pumpetest. De kerne målte gas permeabiliteter er blevet omregnet til væske permeabilitet til denne sammenligning. En permeabilitet på 1 mD svarer til en konduktivitet 1*10*$^{-8}$ *m/sec.*

The similarity in permeability levels for matrix measurements and pumping tests indicates that fractures play a very limited role in the inflow to the wells during test pumping. The permeability of 1 mD is equal to conductivity $1*10^{-8}$ m/sec.

6.5.5 Conclusions on the Erslev study on hydraulic parameters in chalk

The chalk package is situated on top of the Mors salt dome, and this structural setting may have resulted in a higher number of fractures compared to chalk in less deformed areas. However, the fractures in the chalk/limestone section, observed from cores, impression packers and geophysical logs do not seem to contribute significantly to the transmissivity (permeability times thickness) of the tested intervals, despite of the fact that the fracture-flow normally is the dominating part of the total flow in a low-permeable fractured formation. Therefore, the fractures seem to be closed.

The relatively large intervals tested (generally 50 meters) do not allow detection of fracture flow in the borehole. However, the labelled slug test, which gives more detailed information about the permeability distribution of the formation, should be able to detect a significant fracture flow, but an indication of such phenomena is not found. (A labelled slug test was run in E1S only).

The hydraulic conductivity values calculated from pumping tests have been controlled by using different methods of calculations by comparison with results from laboratory measurements, and a number of alternative, hydraulic in-situ testing methods (labelled slug test, injection tests and slug tests).

Various processes which may have caused the closure of the fractures have been considered, i.e. mud invasion during drilling, collapse of fracture due to drop in pressure produced by pumping, natural cementation or clay fill and lateral compression of the formation above the concave part of the salt dome caused by halokinetic movements. Based on the hydraulic tests only, the lateral compression seems to give the most reliable explanation for the closing of the fractures and the low permeability of the chalk in all 4 wells drilled on top of the Mors salt dome.

6.6 Conductivity interpreted from the freshwater/saltwater interface

A study of the salinity profile in selected representative wells through the chalk package was used to interpret the amount of vertical fluid exchange through the chalk (Bonnesen et al. 2009). The investigations outline the freshwater zone and the transition into the connate water salinities at deeper levels (Figure 38). It therefore also shows that groundwater interests are restricted to the uppermost 50-100 meters.

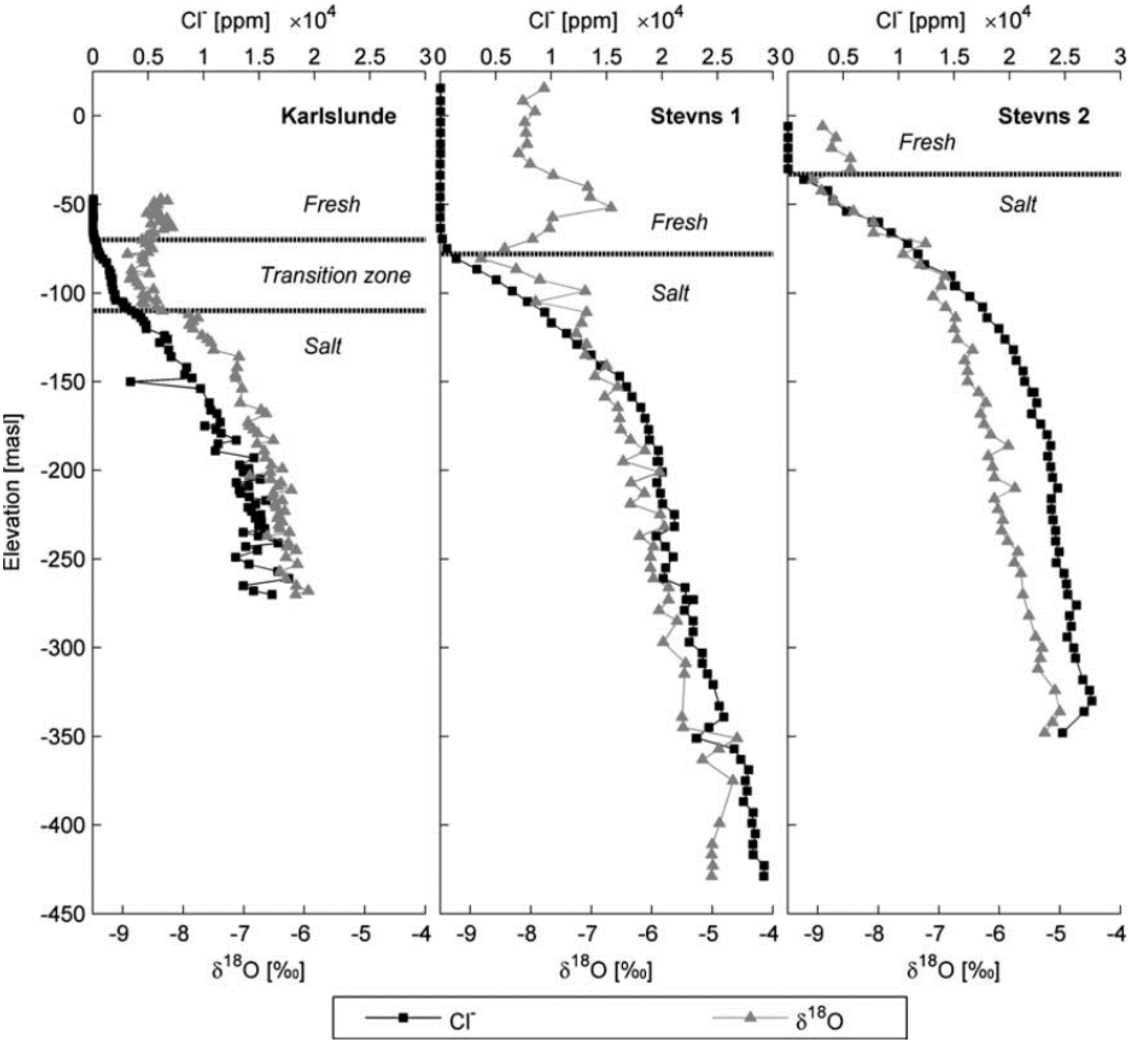


Figure 38. *Depth profiles of chloride and δ18O porewater concentration for three different wells (From Bonnesen et al. 2009).*

Figur 38. *Eksempel på ændringer i klorid indhold og isotop sammensætning ved stigende dybder i tre forskellige boringer (Fra Bonnesen et al. 2009).*

Fluid temperature logging in the studied boreholes indicates upward flow across the chalk-marl layers, and these flows have been verified by heat-pulse measurements. In Stevns-1, indications of upward groundwater flow were observed in a section from 410 to 190 meters b.g.s. (below ground surface) and across a chalk-marl section at 100 meters b.g.s. (Figure 39). Vertical hydraulic heads were measured in this borehole using a packer system, and the largest gradient was 0.14 measured over the chalk-marl layers that are found at depths of 300 meters b.g.s. Using a hydraulic conductivity of the chalk-marl layer of $1*10^{-9}$ m/s (equal to 0.1 mD) and compared to clean matrix chalk permeabilities of 0.5-1.5 mD, this corresponds to a vertical upward particle velocity in the order of a few cm per year. The pressure difference detected in layers below and above the marly layers even at the deep levels in Stevns-1 points to that no fracture flow is present to cause equilibration of the natural pressure differences.

An assessment of the implication of this advective transport of solute compared to diffusive transport can be done using the Peclet number (Bear 1972; Appelo and Postma 2005). A diffusive spreading of a solvent is typically in the order of 25 cm/year (Appelo and Postma 2005) and solute transport in the chalk and chalk-marl layers must therefore predominantly take place by diffusion.

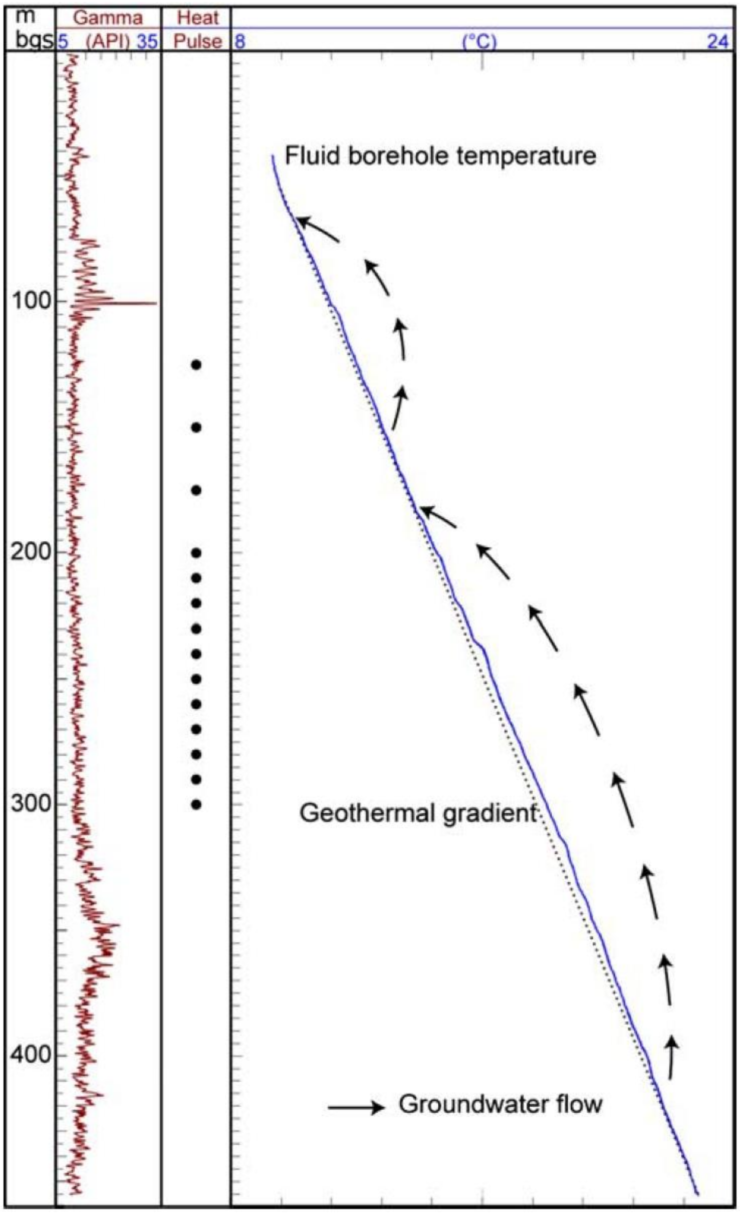


__Figure 39.__ Natural gamma radiation and fluid temperature in Stevns-1 borehole. Variations from the geothermal gradient indicate sections with an upward flow in the open borehole. The arrows illustrate in and out flow zones. Depths with heat pulse measurements are also indicated.

__Figur 39.__ Naturlig gamma-stråling og fluid temperatur i Stevns-1 borehul. Lokale variationer fra den geo-thermale gradient viser sektioner med opadgående strømning. Pilene illustrerer strømning i de forskellige zoner. Varme puls målinger i forskellige dybder er også vist.

6.6.1 Other studies

As mentioned in the previous chapters the amount of data on the presence of fractures and their effects on flow in deeper levels in the chalk/limestone sequence in Denmark is very limited. Therefore, we have included references and summaries of results from studies in other areas where similar lithologies occur.

6.6.2 Examples on flow in U.K. chalk formations

Investigations both in field tests and laboratory measurements on chalk in the U.K. (Price et al., 1977, Price et al. 1982, Price 1987) have shown that high permeability in the chalk lithology is related to fractures and secondary porosity. The interstitial (matrix) permeability of the chalk is very low, in the order of $1*10^{-6}$ to $1*10^{-7}$ m/sec. (100 to 10 mD), and the total hydraulic conductivity 10-100 times higher (1-10 Darcy). These high values have been recorded down to depths of 70-80 meters. The matrix permeabilities reported are comparable to values in the Danian limestones in the Danish aquifers. The UK chalk aquifers are mainly developed in older carbonates than the Danish, i.e. dating from the Santonian, Coniacian and Turonian periods, but the lithologies are somewhat comparable to the wackestones of the Danish Danian carbonates.

Measurements made in the Candover Valley, Hants, using packer systems (Price et al. 1977, 1982) indicate hydraulic conductivity values ranging from 0.02 m/day (corresponding to $3*10^{-7}$ m/s, 30 mD) to more than 2 m/day ($3*10^{-5}$ m/s, 3000 mD), some of the highest permeabilities occurring in the Chalk rock. Measurements made during investigations for the proposed Channel Tunnel, ranged from less than $1*10^{-3}$ m/day (about $1*10^{-8}$ m/s, 1 mD) to more than 4 m/day (more than $6*10^{-5}$ m/s, 6000 mD). Similar investigations during tunnelling trials at Chinnor, gave conductivity values ranging from 0.07 m/day ($1*10^{-6}$ m/s, 100 mD) to 9.5 m/day ($1.5*10^{-4}$ m/s, 15000 mD) with a mean value of 1.3 m/day ($1.8*10^{-5}$ m/s, 1800 mD). The Chinnor investigations were at depths of less than 30 meters below ground level.

At significantly greater depths there is evidence that the primary fracture component decreases in importance. Investigations at S. Killingholme, S. Humberside, for the construction of caverns to store liquefied petroleum gas (LPG), showed that the chalk at cavern level (180-190 meters below ground level) is largely intact and the minor joints are closed by secondary calcite precipitations. Obvious near-vertical open joints are generally spaced several metres apart. At this depth the bulk of the chalk (which is in the lower part of the Middle Chalk and the top of the Lower Chalk corresponding to Cenomanian-Turonian) has in situ permeabilities of the order of 0.1 mD (less than $1*10^{-9}$ m/s). In zones where joints are concentrated, the permeability is of the order of 1000 mD ($1*10^{-5}$ m/s).

6.6.3 Permeability in chalk oil/gas fields in the North Sea

Because there are very few data available for onshore locations, one example from an offshore hydrocarbon reservoir is included here to supplement the view on the variations.
An example of reported bulk permeability from a hydrocarbon reservoir, mainly attributed to a fracture system is from the Ekofisk Field in the Norwegian sector. Here test permeabilities

up to $1.5*10^{-6}$ m/sec. (150 mD) is reported (Brown 1987). Fracturing is a general phenomenon in this field and a map of permeabilities from 1 to more than 80 mD ($8*10^{-7}$ m/s) shows a distribution of permeabilities corresponding to structural deformation and fracture intensity (Brown 1987). In most settings the hydrocarbon-filled chalk reservoirs are on top of salt induced domal structures, and might therefore still be in a tensional regime, promoting some of the fractures to be in an open state. It should be noted that the difference in burial depth and diagenesis between the shallow chalk and the offshore example can limit the comparative value. Also, in many cases the chalk forms efficient seals for hydrocarbon accumulations.

6.7 Porosity and permeability depth trends

The compaction and cementation processes have modified the primary high porosity of the various carbonates. The effect of these processes is a general decrease of porosity with depth but also depending on the primary lithology, grainsize, mineralogy, clay content. Intervals with high clay content are more easily compacted resulting in lower porosity and permeability compared to chalk and limestone without clay at same burial depths. Plot of porosity versus depth from different wells show overall decreasing porosity with depth (Figure 40). A decrease with depth is also obvious for the matrix permeability and for the well tests available from the Erslev wells (Figure 41).

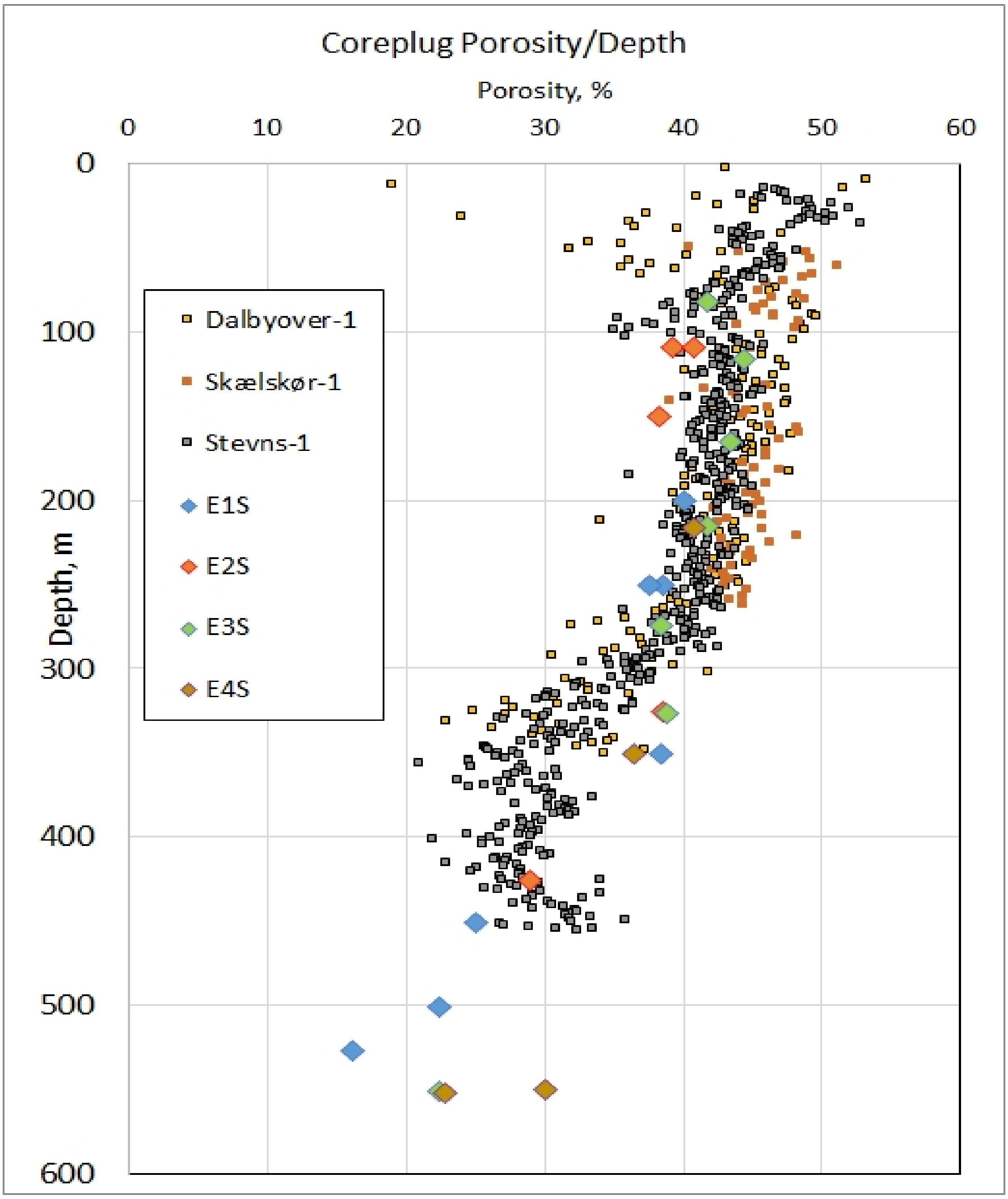


Figure 40. *Porosity/depth trend for core measurements in selected wells is shown. The deviation towards low porosity at around 100 meters depth in the Stevns-1 well is caused by high clay content (marl) in the chalk at this level.*

Figur 40. *Porøsitet mod dybde vist for kerne målte data fra udvalgte boringer. De lave porøsitetsværdier ved ca. 100 meter i Stevns-1 skyldes tilstedeværelse af ler (mergel) i dette niveau.*

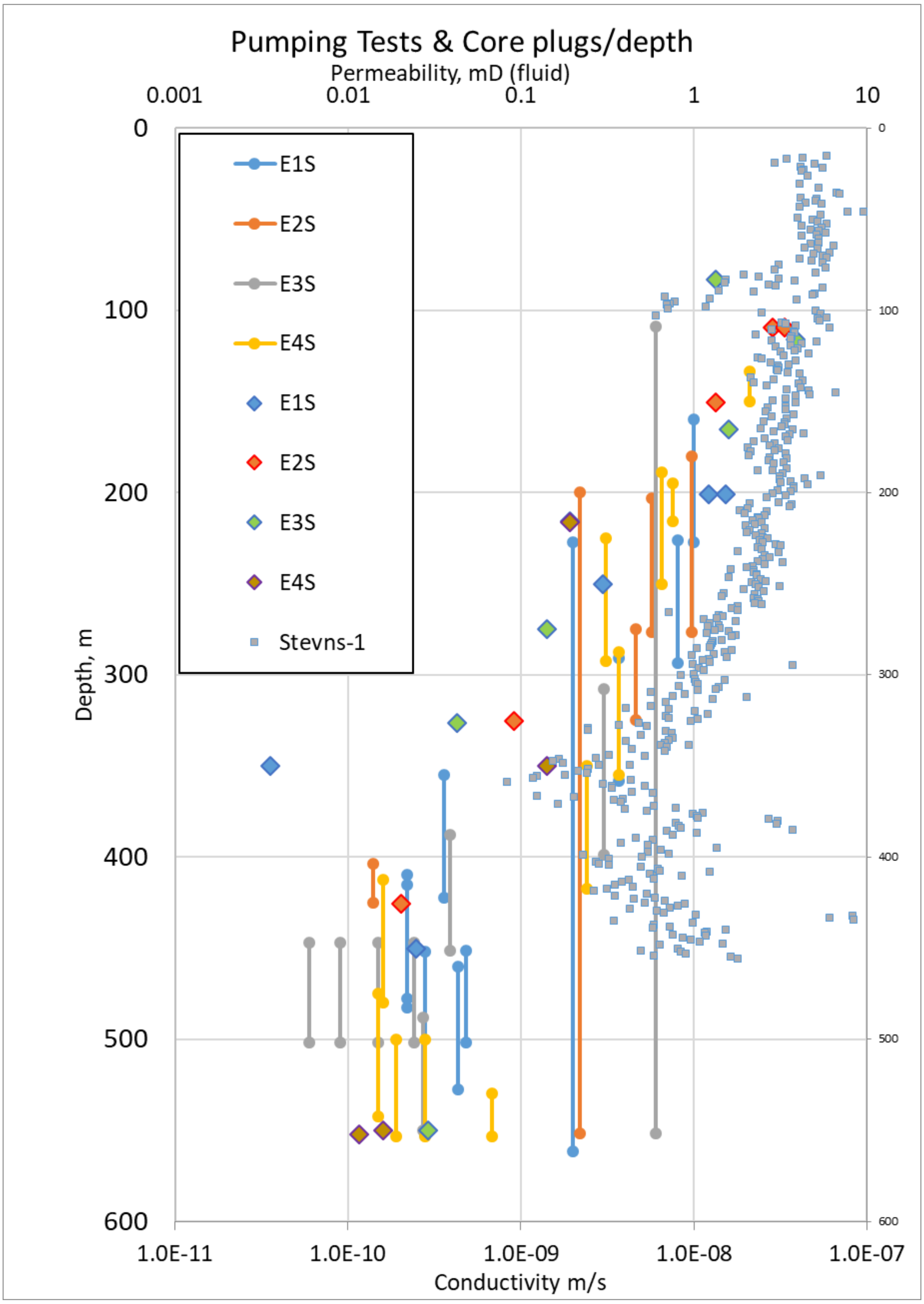


Figure 41. *Permeability with depth including data from both the Erslev wells and the Stevns-1 well. The deviation towards low permeability at around 100 meters depth in the Stevns-1 well is caused by a high clay content in the chalk at that level.*

Figur 41. *Sammenligning af permeabilitet mod dybde for Erslev boringerne og Stevns-1 boringen. Afvigelse mod lav permeabilitet ved ca. 100 meters dybde for Stevns-1 data skyldes ler-indhold i dette niveau.*

7. Transport of radionuclides in chalk

There are only a few studies directly addressing the transport of radionuclides in Danish chalks.

Carlsen et al. (1981) used batch experiments and directly measured the relative transport velocity for some ions, known to occur in the Danish nuclear waste, in chalk core samples from the Erslev boreholes. It was found that there was a retardation of the cationic species Cs^+ (cesium(I)), Sr^{2+} (strontium(II)) , Co^{2+} (cobolt(II)) and Eu^{3+} (europium(III)), while the anionic species Cl^- (chloride) and TcO_4^- (pertechnetate) were not retarded compared to water moving through the material. Strontium was used to represent other group II elements such as barium and radium, and cobalt was assumed to behave similarly to other divalent metal ions e.g. iron and nickel. Europium was included as a reasonable representative for trivalent actinides such as americium (III) and plutonium (III). The retardation factor (R), meaning the transport time relative to water, can be estimated as $R \sim (1 + 4.2 \cdot K_D)$, K_D being the ratio between what is bound to the solids and what is dissolved in the water (the factor: 4.2 assumes a porosity of 0.3 and a bulk density of 1.8 g/cm^3). The mean K_D values determined by Carlsen et al. are shown in Table 2. The K_D values vary with the NaCl concentration, which is a simple illustration of the influence of other compounds present in the system. The whole concept of a K_D value is a highly simplified approach that does not take the effect of competing and complexing ions (including H^+/OH^- i.e. pH) into account.

Table 2. *Mean K_D values (Carlsen et al. 1981).*

Tabel 2: *K_D middelværdier (Carlsen et al. 1981).*

[NaCl]:	1M	5M
K_D(Eu)	4500	4800
K_D(Co^{2+})	31	27
K_D(Sr^{2+})	2.5	2.3
K_D(Cs+)	1.5	0.9

An example of this was the finding in the study of Carlsen et al. (1981), that the K_D value/retardation of the divalent cations was lower in the presence of EDTA, which forms strong complexes with especially divalent ions. Similarly, the presence of dissolved organic matter (DOC) or other complex forming ions could lower the retardation, but there are also examples of complexes that bind more strongly to the surfaces than the free ions.

Hubert et al. (2006) used an indirect approach where they studied the distribution of uranium (U) and thorium (Th) isotopes in a chalk aquifer system in France. Based on their measurements they derived retardation factors of 10-35 for U and 10,000-200,000 for Th.

Considering the relatively few studies of chalk, the literature on the sorption/co-precipitation of radionuclides on/with calcite, the main mineral in chalk, has been examined. It is worth noting that the small amounts of clay, sulfide and Fe-oxide minerals that are also present in the chalk may have sorption properties that for some ions will have greater importance for the actual sorption than the calcite in the chalk. It is therefore important to characterize the mineralogy of potential repository rocks to evaluate the sorption capacity for the nuclides in the radioactive waste.

When uranium is present in its oxidized state (U(VI) as uranyl ions, it forms a neutral complex with Ca^{2+} and CO_3^{2-} : $Ca_2UO_2(CO_3)_3^0$, increasing the mobility of U(VI) (Dong et al., 2005). This is supported by Stewart et al., 2010 who find that pH ~5 and a low Ca concentration is optimal for uranium sorption, as U(VI) is not bound in the complex.

In reduced form, actinides, such as thorium (Th), uranium(U), Neptunium (Np), plutonium (Pu) og americium (Am) have a relatively high tendency to be incorporated in calcite crystals, implying that their mobility will be limited in a calcite dominated rock such as chalk. In contrast, U(VI), Cs(I), Sr(II) and Ra(II) will have a much lower tendency to be incorporated in the calcite (Curti, 1999). Therefore, they would be expected to be more mobile in chalk, unless they sorb to other components in the chalk. This could be the explanation for the slightly elevated retardation seen for Sr(II) in the Carlsen et al. study on the Erslev samples. Lead (Pb) also has a tendency of being incorporated into calcite (Meece & Benninger, 1992).

The number of fractures in chalk seems to be very limited at depth, however, the transport of radionuclides with colloids, specifically bentonite colloids eroded from bentonite backfill, could be an issue if fractures are present in the repository rock. Tran et al. (2019) carried out a study using brackish water, which causes flocculation of the clay particles, and found that the net transport rate of U(VI) and Cs(I) was not affected by bentonite colloids, while Cerium(III), used as an analogue for reactive actinides in the reduced redox state, was effectively immobilized.

8. Summary

In Denmark, the Upper Cretaceous and Danian sediments of chalk, limestone, and marl are referred to as the Chalk Group which occurs widespread at 500 meters depth in the Danish subsurface. The thickness of the Chalk Group varies from several hundred meters in most areas to several kilometers in the Danish Basin in the central-northern part of Jylland and Nordsjælland. The depth to the top of the Chalk Group varies from ground level to a few tens of meters below terrain in large parts of Denmark and with a maximum depth around 1000 meters in Vestjylland. The chalk of the Chalk Group is to varying degree “over-compacted” relatively to the present burial depth due to erosion of significant amounts of Paleocene sediments that were removed during periods of uplift and erosion in the Neogene time.

Carbonates and marl from the Chalk Group are present in most of the Danish onshore subsurface in the depth interval from just below surface to more than 500 meters depth. Therefore, carbonates and/or marl will constitute a major part of the geological barriers either providing barriers in the ECZ or providing barriers both as the host rock and as the ECZ.

Sediments in the Danian limestone in the uppermost part of the Chalk Group are dominated by calcarenites, calcareous mudstones and bryozoan limestones whereas the Cretaceous chalk consists mainly of a fine-grained matrix of coccoliths. Some intervals, including the Rørdal and Boesdal Members, are argillaceous and referred to as marls comprising smectite clay, quartz, and minor amounts of illite and analcime.

Sediments in the uppermost 0-50 meters of the Chalk Group have been described in large detail both from outcrops occurring along coastal cliffs, from quarries, and from water wells and deep wells, as this interval comprise important reservoirs for abstraction of drinking water in large parts of Denmark. Geotechnical and geological information exist from investigations related to major engineering construction projects such as the metro in København and large bridges and tunnels. Detailed information on rock properties from deeper sections of the chalk section is sparse and unevenly distributed. Data on rock properties at depths around 500 meters exist from a few wells only including the Erslev wells drilled on top of a salt diapir in northern Jylland, and some wells drilled at Stevns for scientific purposes.

The uppermost 0-10 meters of the chalk is intensively fractured and crushed due to subglacial deformation. Fractures are both vertical and horizontal and where they form a well-connected fracture system, the chalk and limestones have a high hydraulic conductivity. Information from depths greater than 20-50 meters is sparse due to scarcity of drill cores and well logs. However, the available data show a consistent decrease in matrix porosity and permeability with increasing depth due to compaction, cementation, recrystallisation of calcite, and generally increasing amounts of clay in the lower parts of the Chalk Group.

Estimates of vertical transmissivity in the deeper parts of a representative, undisturbed section of chalk, exist from the Stevns-1 well. The estimates are based on salinity profiles and temperature logging. The results show that diffusion is the dominant vertical transport mode for solutes at deeper levels which will result in extremely slow transport of radionuclides that are not retarded in the repository. In sections with marl layers, it is observed that clay rich layers (marl) may have lower permeability/hydraulic conductivity than the pure chalk, and the marl may form vertical pressure and flow barriers.

Studies of retardation of specific elements in the calcite dominated chalk and in the associated clay minerals indicate a high potential for sustained adhesion (sorption), depending also on the nature of the nuclides and the groundwater geochemistry. Better knowledge about the sorption capacities of the Chalk Group is one of the requirements to the detailed geological investigations that are to be carried out in the next phase of the geological repository project.

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