DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2017/22

Examining the possibilities of establishing thermal storage in the chalk/limestone aquifer in the greater Copenhagen area

Phase 1 of project HTES (High Temperature Energy Storage)

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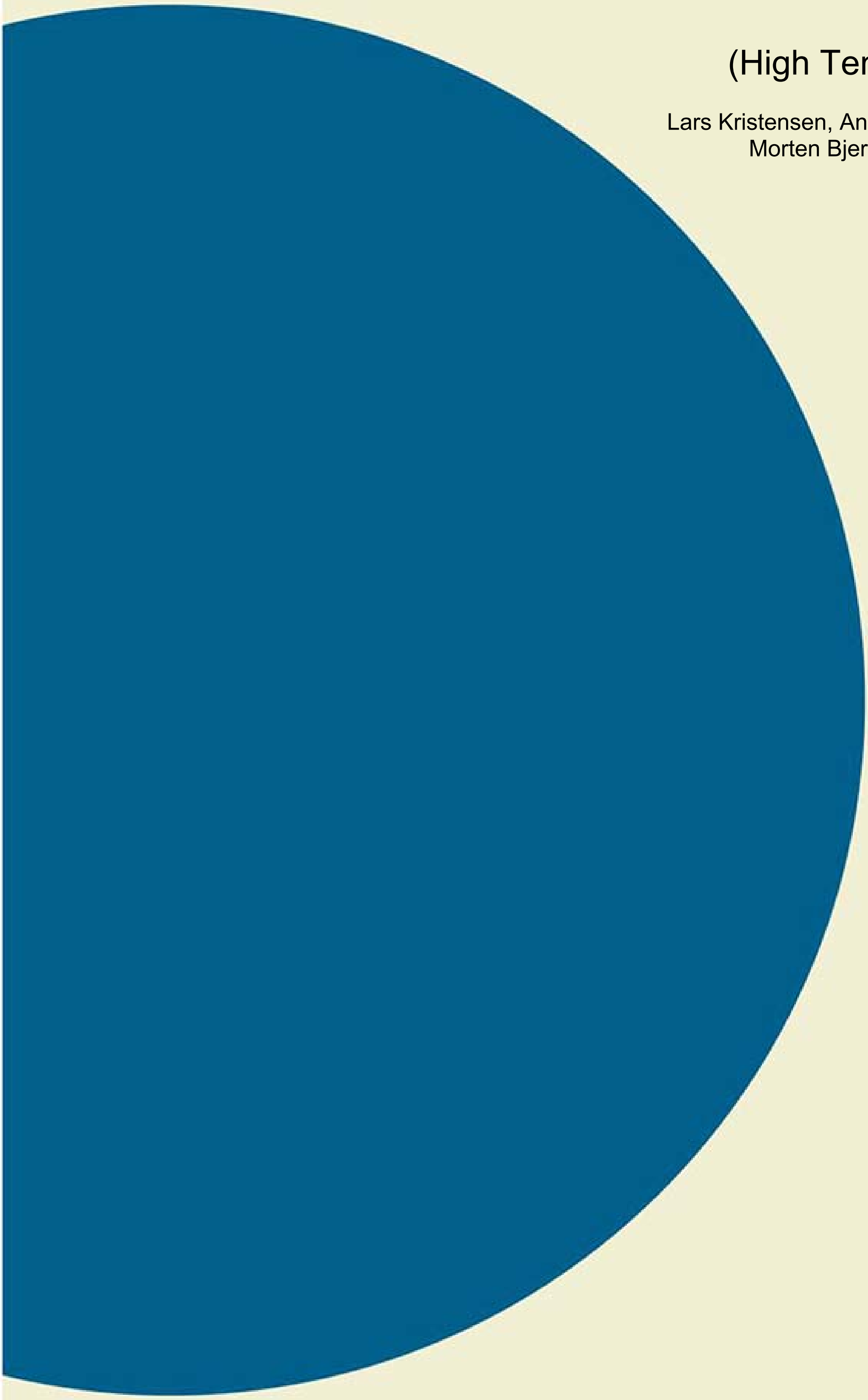

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF ENERGY, UTILITIES AND CLIMATE

G E U S

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Part of an EUDP Project (ID 64016-0014)

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GEUS

Contents

The geology of the storage zone is quite similar to the chalk that outcrops at Møns Klint:

Preface

The project 'HTES' (High Temperature Energy Storage) aims at demonstrating a new seasonal storage technology. The HTES project examines the possibilities of establishing thermal storage in the chalk/limestone aquifer within the greater Copenhagen area in the depth range 400–800 metres.

The project 'HTES' is founded by the 'Energy Technological Development and Demonstration Program', EUDP. The EUDP Project ID is 64016-0014 within the EUDP technology class "Smart grid and Systems".

The project 'HTES' consists of 4 work packages;

- WP 1. Review of existing knowledge of HTES and local subsurface data
- WP 2: Model simulation of the storage potential and possible effects on groundwater system
- WP 3: Well design
- WP 4: Project management

The purposes of WP1 and WP2 are:

1) To collect and review the existing data material, including:
    i) Geological data (primarily GEUS),
    ii) Geotechnical data (primarily DTU),
    iii) Geophysical data (primarily GEUS)
2) To set up a numerical groundwater and reservoir model.
3) To pin-point (map) possible sweet spots or prospects.
4) To set up a geological well prognosis with reservoir parameters for each prospect.

Project partners are Ross, GEUS, DTU, Geo, Awell, Ingeniør Huse and OE3i; see below:

The Geological Survey of Denmark and Greenland (GEUS) along with the Danish Technical University (DTU) carried out studies on the behaviour and parameters of the carbonate deposits as well as temperature, depository changes over time as the reservoir is charged and depleted. GEUS evaluated the stratigraphy of thick Chalk Group in an attempt to identify aquifer units and estimate their reservoir parameters. Furthermore, GEUS carried out flow simulations to address the storage potential and possible interaction between storage and groundwater zones. The modelling work is based on the Eclipse 100 reservoir simulator and the FEFLOW groundwater flow simulator. DTU focussed on the geotechnical aspects of the limestones and chalks.

Ross DK A/S provided knowledge of well engineering and management, and Geo ('Geoteknisk Institut') has drilling expertise, machinery and laboratory facilities specialised in testing and analysing geotechnical properties of chalk.

Awell Aps has the expertise in using modern water well drilling techniques. An appropriate business case, focusing on estimating economical production and injection rates, has been established in collaboration between the three companies Ingeniør Huse, Ross and Awell.

OE3i Aps has the systemic knowledge about production planning and optimisation for combined heat and power plants (CHP plants) and sun farms.

The project has assembled a project host group that provides the project group with an interface to the district heating system. The project host group has in-depth knowledge of heating supply, and can thus provide a substantial feedback on what can be adopted by the district heating companies.

The following GEUS employees participated in HTES work:
Lars Kristensen
Anders Mathiesen
Carsten Møller Nielsen
Morten Bjerager
Lars Henrik Nielsen
Claus Becher Ditlefsen
Ingelise Møller
Anders Juhl Kallesøe
Per Rasmussen
Torben Sonnenborg
Jette Halskov
Hans Jørgen Lorentzen
Troels Laier
Hanne Dahl Holmslykke
Emma Sheldon

Hanne Holmslykke and Troels Laier (geochemists) contributed to the work on geochemistry and on suggestions for water treatment prior to re-injection of water.
Emma Sheldon carried out the biostratigraphic analyses based on cuttings samples from the Margretheholm-1 well.

This extended project report deals with the results of the geological and geophysical assessments along with the outcome of reservoir modelling work as carried out by GEUS in WP 1 and WP 2 (Phase 1). The present report includes:

- ***A Danish and English summary/resumé.***
- ***An extended summary including general recommendations and conclusions; presented in Chapter 1.***
- ***Chapter 1 will also be published in the common EUDP project report (the latter report is prepared by the consortium of project partners, i.e. Ross, Ingeniør Huse, Awell, OE3i, DTU and GEUS).***
- ***A descriptive part to be used for documentation. This part discusses details and provides the basic information for phase 2 work (Chapters 2-8)***

GEUS, April 2018

G E U S

Energiteknologisk udvikling og demonstration

Abstract

GEUS reviewed existing literature on thermal energy storage and evaluated the available geophysical, geological, hydrological and reservoir data. Only little information about heat storage in chalks and limestones is published, however. The evaluation of the geophysical and geological data led to a better understanding of subsurface geology, including stratigraphy and location of fault systems. Our screening of the aquifer systems points out a number of water protection areas within the Copenhagen area, and this aspect has to be considered prior to pointing out well locations. The data compilation resulted in two geological well prognoses accompanied by reservoir parameters: a prognosis for the Vestforbrænding site and a site located within a fault zone associated with the Carlsberg Fault Zone. A key conclusion is that the storage chalk in itself is characterised by high porosity but very low matrix permeability.

Work on establishing two numerical groundwater and reservoir models is carried out. The objectives are to model heat and water transport, and to estimate potential production rates. The modelling runs point to rather low rates, unless using specific well configurations based on an array of wells, for example. Application of well stimulation technologies will surely enhance flow conditions, leading to enhanced productivity and higher rates. Supplementary work on well stimulation does not form part of Phase-1, but should be included in a forthcoming Phase-2. GEUS constructed a number of numerical and groundwater simulation models aiming at modelling a series of water injection and withdrawal scenarios are simulated using Eclipse 100 and FEFLOW. The presumed interaction between storage and groundwater zones is also considered, but the simulations carried out so far indicate, however, that there is no conflict between storage and groundwater interests. Most likely, the chalk package in between the groundwater and storage zones acts as a sort of seal that prevents upward fluid flow.

GEUS recommends stimulating the wells in order to increase the effective permeability of the chalk, as the challenge is to ensure and maintain reasonably high production and injection rates in a low permeability chalk reservoir. It is thus recommended to conduct a Phase-2 including the drilling of a pilot well with a sufficient data acquisition programme (logging, coring and testing). Phase-2 should also comprise core analysis and deployment of various well stimulation techniques, if appropriate. Water treatment should also be considered.

Dansk og engelsk resumé

GEUS har vurderet lagringspotentialet i kalken indenfor det Storkøbenhavnske område. Vurderingen er baseret på den eksisterende viden om undergrunden, bl.a. ud fra data fra boringer, kernemateriale, borehulsmålinger, seismiske data og litteratur af geologisk karakter. Kalken består af flere enheder med forskellig sammensætning og reservoiregenskaber, og GEUS vurderer, at den såkaldte Hvidskud Member vil være bedst egnet som lagerenhed. Denne enhed ligger i ca. 600 meters dybde, men dybden varierer på tværs af det Storkøbenhavnske område som følge af, at kalklagene har været udsat for forskellig grad af indsynkning, opløft og erosion.

Med henblik på at udpege egnede steder for etablering af et eventuelt lager, har GEUS har karakteriseret det enkelte kalklag med hensyn til fordeling af porøsitet, permeabilitet, temperatur og termiske egenskaber. Hvert lag betragtes som en strømningsenhed.

På baggrund af de geologiske og reservoirmæssige forhold har GEUS vurderet mulighederne for at etablere et termisk lager ved Vestforbrænding og i nogle kendte brudzoner (forkastningszoner). For hver prospekt-type har GEUS udarbejdet en prognose med forventede lagtykkelser og variation i reservoirparametre. De udførte undersøgelser og de opstillede prognoser peger på, at kalken kan anvendes som lagringsmedium, men de tilhørende produktions- og injektionsrater er vanskelige at prædiktere ud fra det foreliggende datamateriale, bl.a. på grund af et ringe kendskab til den effektive permeabilitet.

Permeabiliteten kan være høj i og omkring forkastningszoner, men der er knyttet særligt høje usikkerhedsfaktorer til genindvinding af det lagrede (varme) vand fra områder med forkastninger, bl.a. kan afkølingsgraden vise sig at være høj, og desuden er der mulighed for tab af det opmagasinerede vand. På den baggrund anbefaler GEUS, at der etableres et anlæg på en lokalitet, der ligger udenfor større brudzoner.

GEUS har opstillet en geologisk model for kalken samt udført en række reservoirsimuleringer af mulige strømnings- og temperaturforløb, herunder prædiktion af potentielle produktions- og injektionsrater. Der er i den forbindelse foretaget et 'følsomhedsstudie' samt simuleret forskellige løsningsmuligheder for at opnå øgede produktions- og injektionsrater.

Herudover har GEUS undersøgt, om de ændrede tryk- og strømningsforhold i lagerzonen påvirker grundvandszonen (0–250 m) i et vist omfang. De udførte simuleringer viser imidlertid, at der ikke er konflikt mellem lager- og grundvandsinteresser.

Da det foreliggende datamateriale er relativt sparsomt, anbefaler GEUS, at projektet fortsætter med en fase 2, der har til formål at tilvejebringe et mere nøjagtigt og omfattende datamateriale. I den forbindelse anbefales det, at der bores en pilot boring til 800 meter dybde, hvori der tages én eller flere kerner i den påtænkte lagerzone (400–800 m). Herudover bør der ubetinget foretages en produktionstest med henblik på at bestemme kalkens effektive permeabilitet, og desuden bør der udføres en række borehulsmålinger ved hjælp af sonder (logs).

Det anbefales endvidere at overveje anvendelse af brøndstimulering og at etablere et vandbehandlingsanlæg. Formålet med vandbehandlingen er at reducere omfanget af udfældninger i installationer og i selve reservoiret.

Engelsk resumé

GEUS evaluated and assessed the storage potential of the chalk section in the greater Copenhagen area. The work is based primarily on the existing knowledge of the subsurface, including data available from wells, core material, logs, seismic data and literature on geological aspects of the chalk. The chalk section is subdivided into a number of flow units that differ in terms of geological character and reservoir properties. The unit having the most favourable reservoir properties is the Lower Maastrichtian Hvidskud succession. This depth to the top of this unit is about 600 metres, but the depth varies across the study area due to basin character and post-depositional movements and erosion.

In order to pinpoint a series of localities suitable for thermal storage in the chalk section, GEUS characterised each flow unit with respect to the distribution of porosity, permeability, temperature and thermal properties. Based on this reservoir characterization and information about the geological aspects in general, GEUS assessed the possibilities of establishing a thermal storage at the Vestforbrænding site and at some of the major fault zones that displace the chalk layers, leading to creation of e.g. fractures.

For each prospect type, GEUS prepared a geological well prognosis including expected unit thicknesses and the variation in reservoir parameters. The prognoses and the geological investigations signify that the chalk section can be used for thermal storage, but it is rather difficult to predict reliable production and injection rates, because the present-day knowledge on variations in the effective permeability is poor.

GEUS has established a geological, a static and a dynamic reservoir model for the chalk section – and performed a series of simulations of the fluid flow, pressure and temperature development. These reservoir simulations include prediction of potential production and injection rates. In addition, GEUS conducted sensitivity studies with the objective to estimate the effect of varying the effective permeability parameter and to test the effect of applying well stimulation.

The injection of water into the surface leads to changes in the pressure distribution and affects flow conditions in the storage zone. There is a potential risk of interaction between storage and groundwater zones. The GEUS simulations carried out so far indicate, however, that there is no conflict between storage and groundwater interests.

GEUS recommends placing a coming thermal storage outside fault zones, because there is a risk that the injected water gets into contact with large volumes of cold sediment, meaning that withdrawal of hot water may not be possible.

The data material currently available is sparse, and GEUS therefore recommends introducing a Phase-2 working period. The objective of Phase-2 is to provide a more comprehensive and thorough dataset. GEUS recommends drilling a pilot well and acquiring essential data. The pilot well should be cored in the storage zone and GEUS recommends conducting a flow test aiming at determining chalk productivity and effective permeability. Logging of the well is essential for getting valuable information about the reservoir parameters.

GEUS also recommends considering well stimulation and water treatment. GEUS examined the possibilities of increasing potential production and injecting rates by setting up various reservoir simulation models that include stimulated wells. The purpose of water treatment is to prevent – or at least reduce – clogging, scaling and corrosion problems.

1. Extended summary

The **first phase** of project 'HTES' reviews the existing knowledge on thermal energy storage, evaluates relevant geological and geophysical data from the study area and sets up a numerical groundwater and reservoir model. This phase also includes an evaluation of information from geotechnical wells. The aim of the data compilation is to evaluate existing knowledge and data, and on this basis provide a geological well prognosis accompanied by reservoir parameters for a pilot well, complying with standard water well drilling equipment. Phase 1 also comprises work on searching for potential prospects (sweet spots) within the depth range 400–800 m, corresponding to the planned storage depth. At these depths, chalk dominates the lithology of the aquifer system.

Project 'HTES' utilizes information from a number of High-Temperature Aquifer Thermal Energy Storage systems located in Germany, France, Holland and England. Most commonly, these storage systems utilize sandstone aquifers, but the German plant at Dingofing involves storage of surplus energy in a Jurassic limestone aquifer at about 500 m depth. The idea behind the German storage system is very similar to the concept of the planned Danish HTES system: Hot water is injected into the aquifer via an injection well during the summer period, and the same well is used for producing the stored water during the winter period. During summertime, a separate production well supplies the necessary cold water and via a heat exchanger, the water is heated to up to 90°C (or the best operational temperature). Subsequently the water is injected into the aquifer (and stored). During wintertime, the production well is converted into an injector. In this way, the formation water circulates in a closed system, and no excess water is added (**Figure 1.1**).

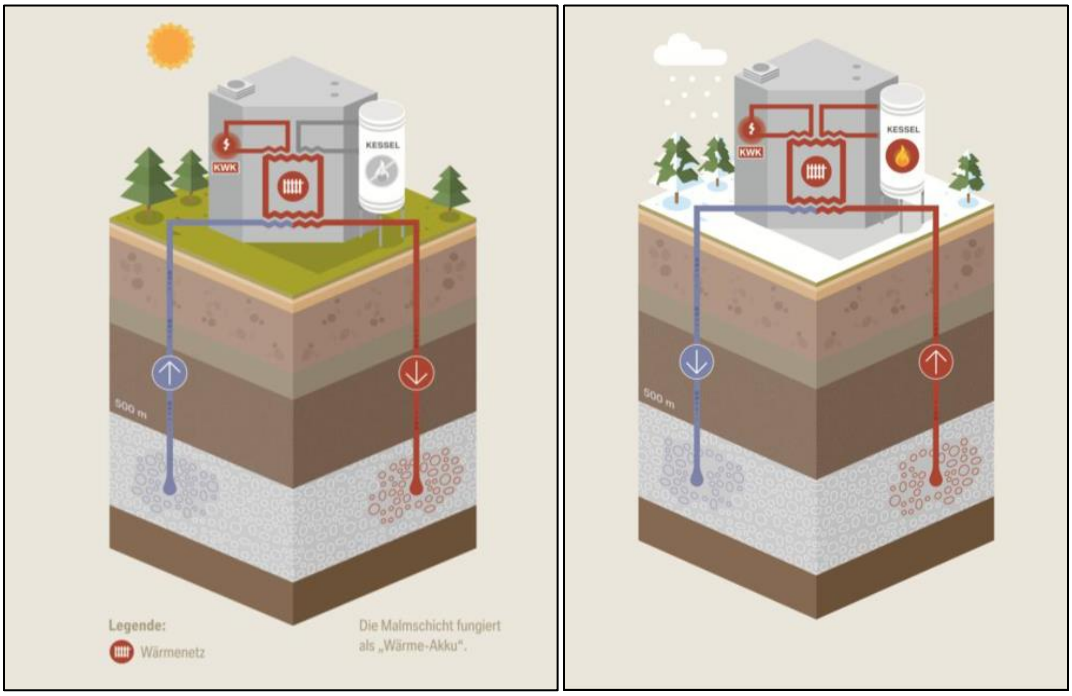


Figure 1.1: ***Summer*** *operation (left): Loading the storage via a 'Warm Well' (red). Injection of water that has been warmed-up via surplus energy from a combined heat and power plant system (CHP). The 'Cold Well' (blue) supply the formation water needed for running the system.* ***Winter*** *operation (right): Extraction of the injected hot water using the 'Warm Well'. The water is used as a heat source, e.g. for the district heating system. The cooled water is re-injected using the 'Cold Well'. The closed loop limits pressure and geochemical disturbances.*

1.1 Geology and reservoir characterization

A number of deep well are drilled within the greater Copenhagen area, and data from these wells show that the subsurface consists of an up to 2 km thick package of chalks and limestones. The Danian limestone section, which generally is relatively thin (c. 100 m), is overlain by a quite thin cover of sandy and clayey deposits (<100 m). The scheme below presents a stratigraphic subdivision relevant for this study (**Table 1.1**). Details are outlined in **Chapters 4 and 5**.

Table 1.1: Stratigraphic scheme of the

Upper Cretaceous – Quaternary in the Copenhagen area

Chronostratigraphy Geological age		Lithostratigraphy Reservoir units**	Local Member
Quaternary		Quaternary undiff.	
Paleocene	Selandian	Kerteminde Marl Fm Lellinge Greensand Fm	
Paleocene	Danian	København Limestone Fm	
		Bryozoan Limestone unit (Stevns Klint Fm)	
Late Cretaceous*	Maastrichtian	Sigerslev Mb	Højerup Mb
		Rørdal Mb	
		Hvidskud Mb	
	E. Maastrichtian–L. Campanian	Boesdal Mb	
	Late Campanian	Flagbanke Mb	
	L. Campanian–Cenomanian	Lower Chalk unit (informal)	High GR unit
	Santonian and older	-	

* In the Danish onshore area, the late Cretaceous chalks belong to the informal 'Chalk Group' (Nielsen and Japsen 1991). ** The nomenclature is based partly on information from Surlyk et al. (2006, 2013) and Stenestad (1976).

The limestone section consist of two key units in the study area: the 'København Limestone Formation' and the 'Bryozoan Limestone unit'. The København Limestone is composed predominantly of sand-size carbonate grains and limestone. The Bryozoan Limestone is dominated by bryozoan-rich limestone, occasionally with large amounts of clay-size and silt-size carbonate grains.

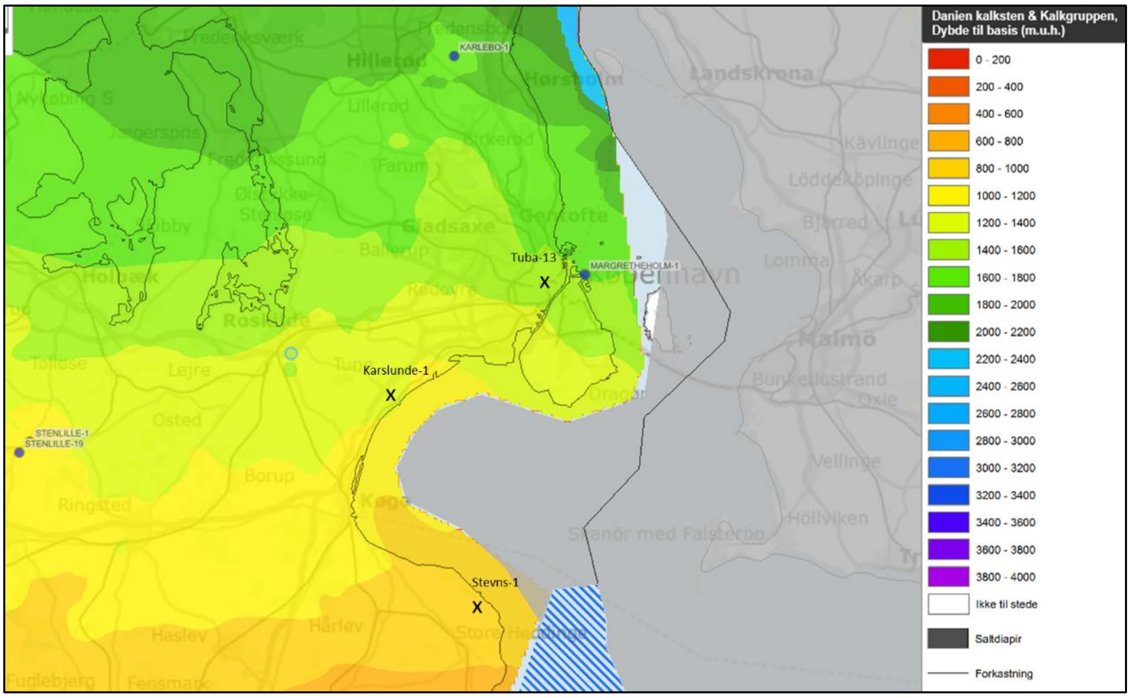
The planned storage zone is located primarily in the deeper buried Maastrichtian and Campanian chalks. Chalk is a white, soft carbonate rock; a form of limestone composed of calcite originating from shells of micro-organisms (coccoliths). Apart from the presence of chert nodules and small amounts of clay, the chalk is particularly homogenous, but the degree of cementation and the amount of natural fractures vary considerably with depth. In order to get additional information about the chalk in the central Copenhagen area, GEUS carried out a number of core analyses on the Tuba-13 drill core ("tunnelbane boring" located at Copenhagen Central Station).

The stratigraphy, lithology and reservoir parameters vary considerably within the study area, both vertically and horizontally – and this situation is a challenge for the geological assessment. The lithostratigraphic units are also considered flow units (reservoir units) and thus the unit subdivision is essential, both from a geological and reservoir technical point of view. The lithostratigraphic subdivision of the Upper Cretaceous chalk units into Sigerslev, Rørdal, Hvidskud, Boesdal and Flagbanke Members is based on outcrops and fully cored boreholes sections located largely at Stevns/Møn (cf. Surlyk et al. 2006, 2013). The GEUS subdivision of the drilled section in each well is based on log data supported by results of biostratigraphic analyses. GEUS screened 47 cuttings samples from the limestone and chalk sections in the Margretheholm-1 well and carried out both nannofossil and foraminfera analyses to support the stratigraphic subdivision (see also paragraph 4.2). The unit subdivision is also based on interpreted seismic data (**Chapter 3**).

The reservoir quality generally decreases with depth and with increasing clay content and diagenetic carbonate precipitation. **Overall, the Sigerslev and Hvidskud Members are considered the best reservoir units** due to a general clean chalk composition and relatively shallow burial. A general shallowing and thinning of the chalk units occurs towards the south, causing better reservoir quality of the individual units in this direction.

The national groundwater mapping program initiated by the Danish Government in 1999 resulted in a detailed description of Danish aquifers – and as part of the project, areas with *specific groundwater interests* as well as areas with *general groundwater interests* were pointed out. The major part of the greater Copenhagen area is assigned to the category: 'specific groundwater interests'. West of the central Copenhagen and on the southeast of Amager, areas with 'general groundwater interests' are designated. Only in the central harbour area and on western Amager a zone with limited groundwater interests is found. The hydro-geology of the Copenhagen area and our screening of groundwater aspects are outlined in detail in **Chapter 5** (in short in paragraph 1.1.2).

No cores are available from the chalk section within the depth range 400–800 m in the greater Copenhagen area, but core analysis from Stevns-1, Karslunde-1 and Tuba-13 give an indication of the matrix permeability, despite the cores are cut in the depth range 0–450 m. No well tests have been conducted in the interval 400–800 m and the amount of natural fractures is very limited for chalk found deeper than 300 m, meaning that the effective permeability of the reservoir chalk is not known. A map showing the **well locations** is inserted below. The coloured base map corresponds to a base chalk depth structure map (metres) available from the GEUS WebGIS portal. The map also gives an indication of the total thickness of the chalk and limestones sections.



The available conventional core analysis data makes it possible to establish a reliable porosity-permeability relationship (poro-perm plot), which form the basis of estimating the matrix permeability for a given porosity value. It is thus possible to relate a log-derived porosity to a matrix permeability estimate. The chalk matrix permeability is generally low or even very low, i.e. in the order of 1–10 mD.

Reservoir parameters that overall characterize the chalk of the planned storage zone - as well as reservoir parameters representative of chalks found outside the storage area - are listed below. The reservoir parameters characterizing the storage zone are estimated by GEUS on the basis of core analysis data from nearby wells and interpreted log data from deep wells located outside the planned storage area. The 'best reservoir zone' corresponds primarily to the Hvidskud Member (refer to **Table 1.1**).

Best reservoir zone at a specific site or well	Approx. Depth (m)	Approx. Porosity	Approx. matrix Permeability	Source
Møns Klint	0	42%	3–5 mD	Measured on core plug samples
Stevns-1	200	38–45%	3–8 mD	
Stenlille-1	500	24%	1 mD	Log interpretation
Planned storage zone	**600**	**30%**	**2 mD**	**GEUS assessment**

Remark: The effect of fracture presence and the effect of faulting on the permeability estimates will be discussed later. Note that the permeabilities listed above are matrix permeabilities.

The expected temperature in the storage zone is calculated on the basis of an average temperature gradient of 22°C/km; i.e. **Temperature (on avg.) = 8°C + 22°C/km x Depth[km].**

The temperature prediction is associated with some uncertainty, because the temperature gradient varies within the greater Copenhagen area as discussed in further detail in **Chapter 6.** With respect to conductivity, it has been assumed that the thermal conductivity of chalk/limestone is related to porosity as suggested by Balling et al. (1981). Similarly, a relationship between heat capacity and porosity is suggested.

1.1.1 Sandy chalk and thin sandstone beds

A sandy chalk section was encountered in the Margretheholm-1 well in the depth range *c.* 900–950 m, and this interval may form a potential storage section. It appears from the mud loss record that the sandy section is characterized by rather high permeability.

The storage and groundwater zones may interact, and GEUS has therefore screened the hydrogeological data available from study area. This process encompasses screening of the aquifer systems and the groundwater interests along with evaluation of flow-logs, existing groundwater maps and existing hydrogeological models including the DK model.

1.1.2 Hydrogeology

The water supply of the Copenhagen area is based exclusively on local and regional groundwater aquifers, 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).

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 under-lying chalk, being of Maastrichtian and Campanian age, the number of influx levels and the amount of influx decreases. Deeper than c. 70 m below base Danian, only very limited influx occurs (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 and fault zone areas (Klitten et al. 2006). Thus, the chalk in general holds only limited groundwater resources.

In 1996, GEUS started to develop a national water resources model, i.e. the DK model. The objective is to advance the quantitative assessment of the groundwater status. Furthermore, the purpose is to account for interactions with surface water and anthropogenic changes, such as groundwater extraction strategies and land use, as well as climate change. As part of the national groundwater mapping, the DK model has been updated with input from a number of local models. This is especially the case on Zealand, and the present screening of groundwater aspects reveals that almost all relevant data from the available models have been integrated into the national model. Thus, the DK model offers an overall 3D representation of the hydrological cycle in the study area down to about 100 m b. MSL. The DK model describes and outlines the flow in the fresh water zone in detail – though the scale and the scope the DK model also results in some limitations, e.g. in the representation of the very local hydrology at specific fault zones etc. The DK model has therefore contributed with input to the modelling work carried out as part of the present HTES project.

A few models compiled by private companies have not been available for this study. Marcussen (2002) compiled a map of the transmissivity in the limestone in Copenhagen from a large number of well tests. Considerable variations in the transmissivity are found, and zones with enhanced transmissivity appear to be related to the NW-SE trending structural elements in the area. Especially along the Carlsberg Fault zone, very high transmissivities are observed.

1.2 Conceptual model and prognosis for the Vestforbrændring site ('prospect')

Herein the quoted word '**prospect**' denotes a potential geothermal site (cf. heading above). The Vestforbrænding site is located in Glostrup/Ejby close to an intersection point between two seismic lines (**Figure 1.2).** The depth to the various surfaces and geological units can therefore be calculated with good confidence. A geological well prognosis accompanied by reservoir parameters is tabulated below (**Table 1.2**); observe that the København Limestone unit is not present at the Vestforbrænding site.

The Vestforbrænding site is located at an intersection between the two seismic lines HGS-001 and HGS-005. A seismic interpretation of these lines is outlined in detail in **Chapter 3**. This chapter also includes a map showing the location of HGS-001 and HGS-005 and other seismic lines.

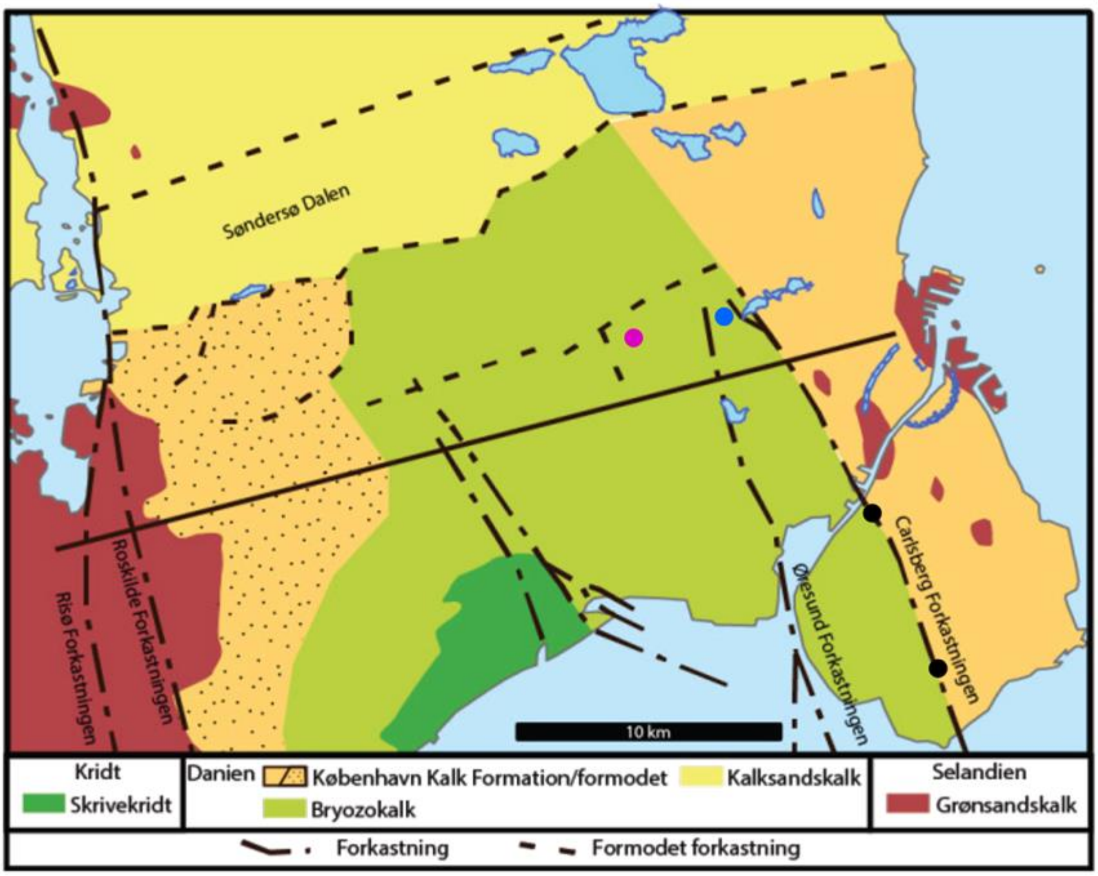


Figure 1.2: *Location of the Vestforbrænding site (pink dot), the faulted site at line HGS-001 (blue dot), and the Carlsberg Fault zone including two selected sites (black). These four sites are considered relevant for examining the possibilities of establishing thermal storage in the chalk section. The Vestforbrænding site is situated close to an intersection between two seismic lines (HGS-001 and HGS-005). On the Amager Island, a black dot indicates intersection between the Fault Zone and a seismic line. The figure also points out pronounced fault zones other than the Carlsberg Fault. In addition, the map provides an overview of the limestone and chalk types related to the pre-Quaternary surface (from Jakobsen et al., 2017). The ENE–WSW line refers to a cross-section (not shown).*

The planned storage depth (400–800 m) encompasses the Hvidskud, Boesdal and Flagbanke Members of Maastrichtian–Campanian age, and the rock-forming material of the storage zone corresponds probably to rather homogeneous chalk with a few natural fractures. The Danian is represented by bryozoan limestone with possible intercalations of chalk mudstone. The geological prognosis at Vestforbrænding is based on descriptions of samples from nearby shallow boreholes, seismic interpretation (Larsen 2016), and correlation with fully cored boreholes combined with information from petrophysical well-logs in the region. **Chapter 4** outlines the stratigraphic break down in further detail, and this Chapter also includes a description of the composition of each chalk Member.

The porosity and permeability vary with depth and member. Well data from Margretheholm-1, Stevns-1 and Karslunde-1 provide the reservoir parameters for the Hvidskud Member, whereas the reservoir parameters for the Boesdal/Hansa and Flagbanke Members are based on data from Margretheholm-1, Stevns-1 and Stenlille-1.

The site is situated at the boundary between areas with specific and general groundwater interests, and thus it must be ensured that deep storage in the chalk at this site does not affect the groundwater resource negatively. The groundwater aquifer at the Vestforbrænding site consists of Bryozoan Limestone, and the direction of the groundwater flow in the limestone aquifer is estimated to be from the NW. This observation is based on information from a hydraulic head map constructed by Region Hovedstaden in 2009.

Table 1.2: Well prognosis for the Vestforbrænding site (for location, see Figure 1.2)

Vest-		Top	Base	Thick	Top	Base	Por.	Matrix	Effective
forbrænding	**PROGNOSIS**	(mMD)	mMD	(m)	b.MSL	b.MSL	(%)	Permeability (mD)	
Quaternary	Quaternary undiff	0	12	12	-16	-4	N/A	N/A	N/A
DANIAN	København lst.	12	12	0	-4	-4	N/A	N/A	N/A
DANIAN	Bryozoan lst.	12	48	36	-4	32	38	30	100
MAASTR.	Sigerslev Mb	48	210	162	32	194	35	3	20
MAASTR.	Rørdal Mb	210	260	50	194	244	29	2	10
MAASTR.	Hvidskud Mb	260	560	300	244	544	26	2	10
MAASTR.	Boesdal/Hansa Mb	560	675	115	544	659	20	0.5	2.5
CAMP.	Flagbanke Mb	675	730	55	659	714	18	0.5	2.5
Cret.	Lower Chalk Unit	730	1200	470	714	1184	18	0.5	2.5

Vest-		Temperature	Thermal	vol.Heat	Rock
forbrænding	**PROGNOSIS,**	mid unit (*)	cond.	capacity	density
Glostrup, Ejby	**Cont.**	deg.C	(W/m/K)	(MJ/m3/K)	(g/cc)
Quaternary	Quaternary undiff	8.1	2	unknown	2.5
DANIAN	København lst.	8.3	N/A	N/A	N/A
DANIAN	Bryozoan lst.	8.7	1.69	2.9	2.6
MAASTR.	Sigerslev Mb	10.8	1.78	2.8	2.7
MAASTR.	Rørdal Mb	13.2	1.98	2.7	2.7
MAASTR.	Hvidskud Mb	17.0	2.08	2.6	2.7
MAASTR.	Boesdal/Hansa Mb	21.6	2.31	2.5	2.7
CAMP.	Flagbanke Mb	23.5	2.39	2.4	2.7
Cret.	Lower Chalk Unit	29.2			

(*) The temperature data listed in the well prognosis are based on an average temperature gradient of 22°C/km.

According to Japsen (1998), the Chalk Group experienced structural uplift in Neogene times, leading to creation of some fractures. Based on experiences from North Sea chalk and due to the uplift of the chalk within the Copenhagen area, the effective permeability is assumed to be about 5 times higher than the matrix permeability (**Table 1.2**), primarily due to fracture presence.

1.2.1 Reservoir simulation model for the Vestforbrænding site

GEUS conducted a number of reservoir simulations aiming at estimating volumes, potential production and injection rates together with an expected pressure and temperature development. The design and properties of the base case model utilized the geological well prognosis for the Vestforbrænding site and is described below.

The simulations were run with the Eclipse 100 reservoir simulator. Eclipse 100 is a state-of-the-art reservoir simulator widely used by the oil & gas industry. Several other reservoir simulators exist in the market, some developed for groundwater modelling and some developed for modelling oil and gas production. For modelling of geothermal operations as well as subsurface heat storage different simulators can be used. A comparison study of two simulators are presented in **Chapter 7** of the present report; The Eclipse 100 is compared to the groundwater modelling software FEFLOW. The geometry of the base case model builds on a gross area of 12 km x 12 km around the Vestforbrænding site – and vertically, the model is delineated by the tops and thicknesses listed in **Table 1.2**. The well configuration includes two vertical wells (HTES-1 and HTES-2) with a distance of 1 km. A lateral coarse grid of 200m x 200m is used globally, but the coarse grid has been refined around the wells: locally at wells 50m x 50m and very close to wells 10m x 10m. In the vertical direction the grid dimension ranges from 2 m to 40 m, with the finest grid size in the reservoir interval. With respect to reservoir properties, the permeabilities and porosities outlined in Table 1.2 are transferred to the simulation model, and used as input data. Information about thermal conductivities and heat capacities for chalks and limestones are obtained from Balling et al. (1981), cf. **Table 1.2.**

The presumed charging period is May–mid October. Formation water is extracted from a '**Cold Well**' (HTES-1) and then the water is heated up to 90℃ by means of excess heat and finally, the water is injected into the storage zone using another well that herein is named the '**Warm Well'** (HTES-2).

An intermission period of 14 days is introduced, and this period is considered sufficient for converting the wells from production to injection mode – and vice versa.

The presumed extraction period is November–mid April: The HTES-2 well is now converted into a production well. Accordingly, the stored and warm water is produced from HTES-2 and next, the energy is extracted using a heat exchanger that heats the circulating water of the district heating system. After passing the heat exchanger, the expected temperature of the cooled formation water is in the temperature range 20–40℃ (20℃ in case 1 and 40℃ in case 2). The cooled formation water is then re-injected into the subsurface using the HTES-1 well. In this way, the water in the system circulates and no extra water is needed.

Model set-up: The 'Warm Well' produces pre-heated, hot water from the storage zone, with an applied bottom hole pressure of 3 bar (drawdown constraint). The injection rate is controlled by a full voidage constraint, meaning that the produced and injected volumes are identical at reservoir conditions. With respect to both HTES-1 and HTES-2, the completion length is 400 m in the base case model, i.e. the well is fully open to the reservoir in the interval 400–800 m.

In the base case simulations, GEUS consider unstimulated wells drilled into the presumed storage reservoir in the chalk. Using the above parameters, the base case simulations point to an average injection rate of *c.* 600 m^3/day (~25 m^3/h), when the Warm Well (HTES-2) is in charge mode, and an average production rate of *c.* 800 m^3/day (~35 m^3/h), when the well is in production mode. Production and injection cycles in the HTES-2 well is illustrated in **Figure 1.3** during a four year period (2021–2025). The difference in rates for the production/injection mode for the well is caused by the viscosity dependency of temperature on the formation water. In charge mode (injection) the HTES-2 well is dependent on the volume of water that can be produced from the HTES-1 well (Cold Well). This situation is constrained by the maximum drawdown in the well and the fact that cold formation water is more difficult to produce than pre-heated formation water. In the reverse situation, when hot formation water is produced from the HTES-2 well, the cooled formation water is injected into the reservoir using the HTES-1 well, and in this case a relatively high injection pressure can be applied. The only constraint to the injection pressure is the formation fracture pressure (and pump efficiency).

The results of the reservoir simulations are summarised in **Table 1.3**. It appears from the table that the 'Mid case–High case' and the 'Low case–Mid case' ranges are quite large, signifying considerable uncertainties. When dealing with potential flow rates, the **most critical parameter is the effective permeability (K_{eff}).** Note that the rates listed below are based on production from one well only. The low, base and high case scenarios presumes 2½, 5 and 25 times higher permeability than the matrix permeability (K_{matrix}). The effective permeability is greater than the matrix permeability, primarily due to the presence of fractures in the chalk.

In addition, GEUS simulated potential production rates based on a well stimulation technique that includes completion with 8 or 16 artificial and sand-propped fractures. The distance between fractures is 50 m and 25 m, respectively. A well stimulation strategy based on intensive fracturing of an area close to the well bore (i.e. 100 m around the well) point to high production rates. The use of deviated wells will also lead to higher production rates compared to the base case scenario. Similar scenarios are set up and completed with respect to simulation of injection rates.

Table 1.3: Simulation cases

Simulation case *)	**Effective perm.**	**Prod. Rate (m^3/day)**	**Prod. Rate (m^3/h)**
Base case	$K_{eff} = 5 \cdot K_{matrix}$	800	35
Low case	$K_{eff} = 2½ \cdot K_{matrix}$	360	15
High case	$K_{eff} = 25 \cdot K_{matrix}$	2160	90
Well stimulation, 8 fractures	$K_{eff} = 5 \cdot K_{matrix;}$ 50m between fracs.	1200	50
Well stimulation, 16 fractures	$K_{eff} = 5 \cdot K_{matrix;}$ 25m between fracs	1680	70
Well stimulation: 100 m around well	$K_{eff} = 5 \cdot K_{matrix;}$ Well stimulation close to the well bore and $K_{eff} = 10 \cdot K_{matrix}$	3000	125
Deviated wells	30 deg. dev in res. sec. & $K_{eff} = 5 \cdot K_{matrix}$	1080	45

*) For the different simulation cases, the estimated heat return (efficiency) is in the range 75–85%.

Flow rates, which are significantly higher than the base case rate, may be obtained if:

- The storage system is based on an array of wells – and not just one well. A multi-well storage system will definitely increase the productivity considerably.
- Very long completion lengths are used (pumping intervals > e.g. 400m).
- Reservoir treatment is implemented, aiming at increasing the effective permeability, e.g. intensive fracturing of the chalk, acid stimulation, hydro-fracturing, application of fishbone or jetting techniques or other methods.
- The storage system is based on one and possibly shorter production well (e.g. 500 m) combined with one or two injection wells. The injection well(s) should be rather long and preferably also deviated.
- The pilot well is placed in an area with several fault-induced fractures.
- The storage system is based on horizontal or highly deviated wells.

The Vestforbrænding site is considered a high-risk ‘prospect’, as the matrix permeability is low and the effective permeability is not known. In addition, the distance to the nearest deep well (Margretheholm-1) is more than 10 km. Prior to drilling, further evaluation of the ‘prospect’ is recommended. This evaluation may include calculations on the effect of well stimulation and on the effect of loading the aquifer with hot water during the summer period and unloading during winter. Focus should be on one of the best reservoir zones, i.e. the Hvidskud Member, alternatively the Sigerslev Member. Despite further investigations, it may turn out that drilling and coring is the best way to test and evaluate the 'prospect'. A flow test is also definitively needed.

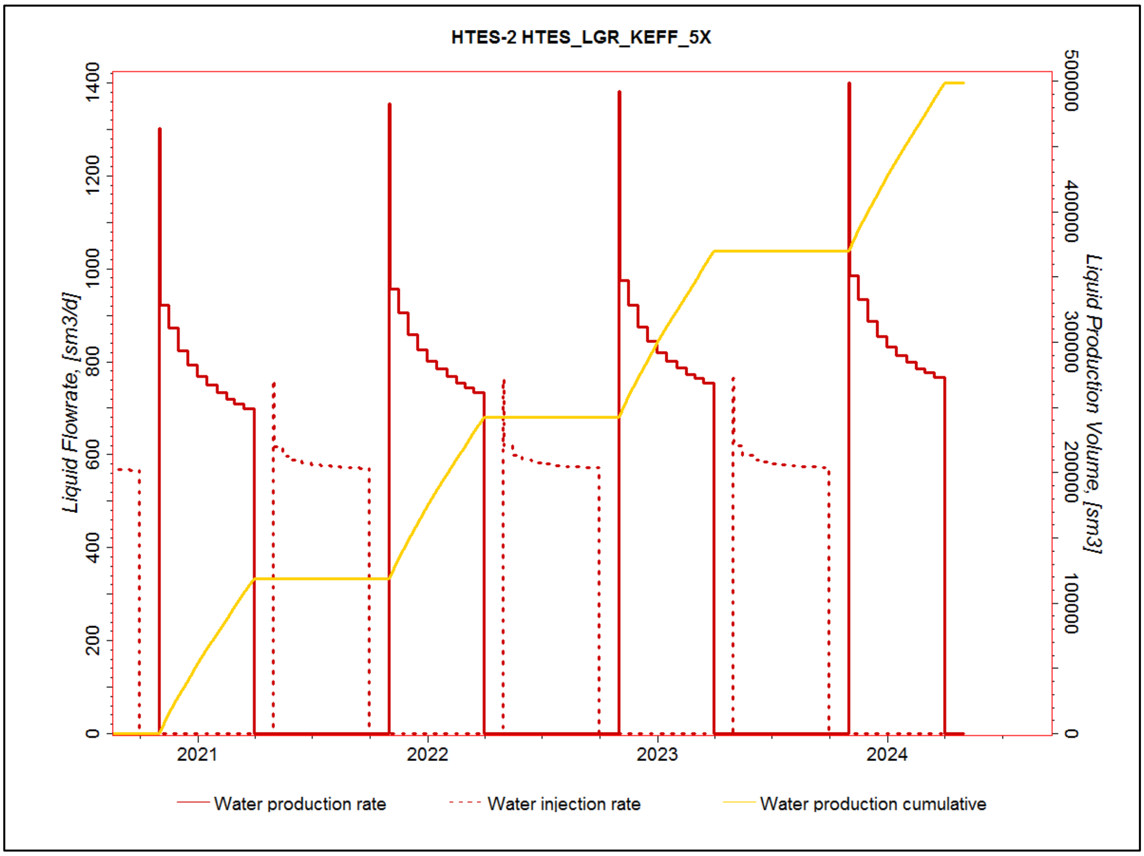


Figure 1.3: *Modelled production/injection cycles in the HTES-2 well ('Warm Well'), years 2021–2025. Observe that the simulated water production rate decreases during an extraction period, as the pre-heated water tends to loose less energy close to the well bore. During the 4 years period, there is a slight increase in both the production and injection rates, as the overall temperature in the storage zone slightly increases, leading to lower viscosity of the water.*

1.3 Conceptual model for presumed faulted/fractured sites ('prospects')

The 'prospects' are associated with areas affected by intensive faulting, creating fractures in the chalk. These areas correspond to the presumed faulted and fractured sites related to the prominent Amager, Carlsberg and Øresund fault systems. These fault systems consist of a series of faults and not just one major fault plane. Hydrogeological investigations of the chalk and limestones in the Copenhagen area have shown that especially the Carlsberg Fault zone is associated with a general increase in permeability and hydraulic conductivity.

One particular 'prospect' is considered in the following text, specifically the faulted site at line HGS-001; see **Figure 1.2** for location. The figure also points out pronounced fault zones and it provides an overview of the pre-Quaternary strata. The structural position of the formation tops related to this ‘prospect’ is someplace between the Vestforbrænding and Margretheholm tops. As an approximation, surface depths are calculated as averages of the formation tops at the two localities Vestforbrænding and Margretheholm. The storage interval encompasses the Hvidskud, Boesdal and Flagbanke Members, and the storage zone consists most likely of heterogeneous chalk characterised by many fractures that have different apertures (fracture width). Occasionally, intervals with crushed chalk will probably be present and presumably, the crushed chalk reflects intense faulting of the chalk section.

A general geological well prognosis accompanied by reservoir parameters is tabulated below (**Table** 1.4). The temperature data are based on an average temperature gradient of 22°C/km. The table lists a range with respect to effective permeabilities, as the prediction of permeability in this faulted area is associated with large uncertainty. In fact, no information about the reservoir permeability exists in the GEUS database, when dealing with the depth range 400–800 m (i.e. the planned storage depth). Occasionally, effective permeabilities up to 100 mD may occur in the aquifer, but GEUS cannot guarantee that such high permeabilities are generally applicable to the chalk reservoir at this site. The permeability estimate of 100 mD is in line with the average permeability of the fractured Bryozoan limestone in the greater Copenhagen area.

This conceptual HGS-001 model may be representative of almost all faulted and fractured sites related to the Amager, Carlsberg and Øresund fault systems. The Amager and Carlsberg Faults are identical when dealing with the Amager Island. The parameters listed in **Table** 1.4 (including tops) are to be adjusted, once considering a particular site within these faulted areas. GEUS finds that especially the Carlsberg Fault zone is relevant when considering thermal storage.

Not only the HGS-001 site (‘prospect’) described above, but in fact all sites related to highly faulted zones are considered high-risk ‘prospects’ as the degree of fracturing is difficult to address, meaning that the effective permeability estimates listed in the table are very uncertain. The effective permeability assessments are therefore only rough estimates as described above. Furthermore, the extension of the fractured areas cannot be mapped in detail due the limited resolution of the seismic 2D data. In addition, a fault plane may act as a pathway for transporting the water away from the storage site.

- A fault may provide a connection between the upper fresh water resources and deeper salt water, and injection and pumping at deeper levels most likely affects the present groundwater resources and the surface environment. Such a situation is particularly problematic in water protection areas and nature protection areas (Natura 2000). Blem (2002) modelled the effects of pumping from the upper part of the Carlsberg fault, and he found that lowering of the water table primarily propagates along the fault zone. In this shallow setup inflow of water from the harbour also appears to take place. In order to progress, GEUS recommends to carry out more detailed modelling of the hydrology of the Carlsberg fault zone – and faulted zones in general.

- GEUS recommends investigating the areas affected by intensive faulting in further detail, aiming at improving the geological model – and with the objective to reduce the geological uncertainty and the uncertainty connected to the assessment of reservoir properties (**Table** 1.4). Especially extra work that can help in decreasing the uncertainty related to the reservoir permeability is essential. The fluid flow pattern related to fractures and fault planes should also be investigated.

- The areas with presumed enhanced permeability are difficult to identify, as the exact locations of the faulted areas are difficult to identify. Each major fault system most likely consists of a series of minor faults. Prior to drilling, additional mapping and further examination on the location of the fault planes is recommended. Especially the fan shooting method appears to be an effective way to map the trace of fault zones in densely urbanized areas (Nielsen et al.

2005). GEUS also recommends to utilize these authors' work on mapping of the Carlsberg Fault in the present study.

- Despite further investigations, it may turn out that drilling and coring is the only practicable way to test and evaluate the 'prospect'.

Table 1.4: Well prognosis for the HGS-001 faulted zone site

For location, see Figure 1.2

Locality:	-at line HGS-001	Top	Base	Thick	Top	Base	Porosity	matrix	Effective
Fault zone	**PROGNOSIS**	(mMD)	mMD	(m)	b.MSL	b.MSL	(%)	Permeabiliy (mD)	
Quaternary	Quaternary undiff	0	16	16	-16	0	N/A	N/A	N/A
DANIAN	København lst.	16	36	20	0	20	N/A	N/A	N/A
DANIAN	Bryozoan lst.	36	84	48	20	68	38	30	100
MAASTR.	Sigerslev Mb	84	194	110	68	178	35	3	5 – 100
MAASTR.	Rørdal Mb	194	278	84	178	262	29	2	5 – 100
MAASTR.	Hvidskud Mb	278	565	287	262	549	26	2	5 – 100
MAASTR.	Boesdal/Hansa Mb	565	710	145	549	694	20	0.5	1 – 15
CAMP.	Flagbanke Mb	710	763	53	694	747	18	0.5	1 – 15
Cret.	Lower Chalk Unit	763	1400	637	747	1384			

Locality:	-at line HGS-001	Temperature	Thermal	vol.Heat	Rock
Fault zone	**PROGNOSIS,**	mid unit (*)	cond.	capacity	density
Copenhagen	**cont.**	deg.C	(W/m/K)	(MJ/m3/K)	(g/cc)
Quaternary	Quaternary undiff	8.2	2	unknown	2.5
DANIAN	København lst.	8.6	N/A	N/A	N/A
DANIAN	Bryozoan lst.	9.3	1.69	2.9	2.6
MAASTR.	Sigerslev Mb	11.1	1.78	2.8	2.7
MAASTR.	Rørdal Mb	13.2	1.98	2.7	2.7
MAASTR.	Hvidskud Mb	17.3	2.08	2.6	2.7
MAASTR.	Boesdal/Hansa Mb	22.0	2.31	2.5	2.7
CAMP.	Flagbanke Mb	24.2	2.39	2.4	2.7
Cret.	Lower Chalk Unit	31.8			

(*) The temperature data listed in the well prognosis are based on an average temperature gradient of 22°C/km, and the predicted formation temperatures are calculated as follows: Temperature (on avg.) = 8°C + 22°C/km x Depth[km].

1.4 Geochemical reactions / carbonate precipitation

Operating the heat storage involves cyclic heating and cooling of the chalk aquifer. Laboratory experiments on chalk samples suggest that the mechanical strength of the chalk reservoir rock decreases as consequence of repeated heating and cooling (Voake et al., in prep.). GEUS recommends conducting additional geotechnical testing of the reservoir chalk, both in-situ and in the laboratory.

Periodical heating of groundwater (formation brine), along with injection and storage in a chalk aquifer, may also lead to geochemical reactions in the rock-water system. Calcite is likely to precipitate due to heating of groundwater during the cycles of aquifer thermal energy storage. Therefore, water treatment is most likely needed, e.g. ion exchange or addition of acid, in order to prevent clogging of the heating facilities including the injection well (Sanner, 1999). The exact composition of the precipitate may differ from that of pure calcite due to the presence of cations such as iron, magnesium and manganese. Furthermore, the exact environment of precipitate formation is difficult to judge from thermodynamic consideration alone (Griffeoen & Appelo 1993). Therefore, investigations related to the specific location of the HTES plant, groundwater chemistry and aquifer type would be needed in order to prevent clogging, carbonate precipitation and mineral deposition (scaling) at the Copenhagen site.

The challenge is to design an optimal water treatment procedure that can handle the circulating water before it enters the heat exchanger, i.e. a pre-processing unit should be added to the system. The overall objective is removal of cations, but also particle removal is essential. GEUS recommends considering application of advanced filter technology, use of ion exchangers, addition of acids to lower pH, and addition of scaling inhibitors. Furthermore, the HTES system should be kept pressurized to prevent degassing. The final design of an appropriate water treatment programme is to be set up in a subsequent Phase 2; detailed information about the composition of the formation brine is needed prior to designing the water treatment programme.

1.5 General recommendations

In the view of GEUS and based on the presently available data, the potential storage sites identified so far are high-risk ‘prospects’. Moreover, it is not possible to identify well-defined target locations representing the best production zones (conventional sweet spots). Alternatively, potential drilling sites may be pinpointed from the location of existing infrastructure facilities or from the position of the structural elements. If the unconventional “sweet spots” described in paragraphs 1.2 and 1.3 still are positively assessed with respect to risks, volumes and economical aspects, **GEUS thus recommends a series of de-risking activities, including drilling a pilot well prior** to establishing a storage system in the chalk section. **GEUS recommends to core, log and flow test the well** with the objective to achieve additional information about chalk productivity, reservoir properties, geological and geotechnical parameters. It is recommended to focus on determining the effective permeability, fracture presence and reservoir parameters in general, but focus should also be on evaluating the elastic moduli, stiffness and strength of the reservoir chalk. A core from the storage zone is needed for more accurate assessments of the matrix permeability and the geotechnical properties of the chalk.

GEUS recommends to base the storage design on a chalk cylinder combined with an array of wells (multi-well system). GEUS recommends applying well stimulation for enhancing the natural permeability and thereby increase the effective permeability. Well stimulation may include activities such as acid stimulation, high energy stimulation and/or hydro-fracturing. The latter methodology is described in detail in Smith (1989) and in Comeskey & Smith (2016). The purpose of applying well stimulation is to ensure and maintain reasonably high production/injection rates in a low permeability chalk reservoir.

GEUS recommends using water treatment in order to handle clogging, scaling and corrosion processes in the chalk-water system. The challenge is to design an optimal water treatment procedure that can handle the circulating water before it enters the heat exchanger, i.e. a pre-processing unit should be added to the system. GEUS suggests to consider ion exchange, lowing of pH and to make use of filters (cation and particle filters).

GEUS has considered two types of prospects: (i) matrix types like Vestforbrænding and (ii) prospects located close to a fault zone. GEUS recommends placing a coming thermal storage outside fault zones, because there is a risk that the injected water gets into contact with large volumes of cold sediment, and withdrawal of hot water may, therefore, not be possible.

1.6 Conclusions

GEUS has assessed the storage potential of the chalk in the greater Copenhagen area. The evaluation of the existing data material led to the following conclusions on the target zone and the expected reservoir performance:

1. The porosity of the chalk at Copenhagen is well-known, e.g. from interpretation of well-logs.
2. For the time being, the database with reservoir-geological data is sparse and the existing geological model should therefore be updated as soon as new data become available. No direct permeability measurements are currently available from the chalk in the storage zone, but the GEUS evaluation of the existing data material points to a matrix permeability of 2 mD and an effective permeability that is 5 times higher than the matrix permeability.
3. The GEUS investigations signify that the chalk section can be used for heat storage, but potential water production rates are difficult to assess. To address rates, GEUS conducted reservoir simulation studies based on the current geological model and our present-day knowledge on reservoir parameters. The GEUS base case simulations point to an average injection rate of *c.* 600 m^3/day (~25 m^3/h) and an average flow rate of *c.* 800 m^3/day (~35 m^3/h) per well, when considering a 4 year production/injection period.
4. The water injection leads to increased pressure in the storage zone. The reservoir simulations carried by GEUS indicate that this pressure disturbance affects the formation pressure at the base of the groundwater zone, but only to a limited extent (i.e. <1 bar due to the full voidage replacement constraint). Conversely, the fluid flow in the storage zone does not interact with the groundwater zone. In the view of GEUS, a thermal storage can be established in the chalk section and a potential conflict between storage and groundwater interests is not foreseen.
5. No geotechnical tests/data are available from the storage zone, meaning that the elastic moduli, stiffness and strength of the chalk are not known. These parameters are critical for deciding on an appropriate production technology, e.g. well stimulation.
6. No production tests or well tests are presently available from the chalk section in the depth interval 400–800 m, meaning that the productivity (and effective permeability) of the chalk in the storage zone is not known. With respect to determining pertinent reservoir parameters, is will be essential to conduct a production test to assess chalk productivity.
7. GEUS considered two prospect types having storage potential: (i) a matrix type like Vestforbrænding and (ii) a prospect located close to a fault zone. Especially the latter prospect type is associated with high risks and problems related to withdrawal of hot water and loss of injection water. With respect to favored storage site, a location outside faulted zones is preferred to a fault zone location.
8. GEUS carried out a number of reservoir simulations, including sensitivity studies on potential production rates. These studies are based on various permeability assessments and the use of different well stimulation techniques.
9. In order to de-risk a preferred prospect and the concept of using chalk for thermal storage, GEUS suggests a series of de-risking activities, such as improved prospect evaluation, drilling a pilot well and comprehensive data acquisition prior to establishing a thermal storage plant. GEUS recommends to core, log and flow test the well with the objective to achieve additional information about chalk productivity, fracture presence, reservoir parameters and the geological aspects of the chalk in the storage zone.

1.7 Suggestions for Phase-2 work

The existing knowledge on the reservoir parameters of the chalk in the storage zone is limited. GEUS recommends, therefore, to acquire more accurate and thorough data during a Phase-2 working period. With respect to Phase-2 work, GEUS suggests to:

- Drill a pilot well into the storage zone. The well drilling process should be accompanied by data acquisition: testing, coring, and logging.
- Analyze and describe the cores cut in the pilot well: Measure porosity, permeability, fractures and geotechnical parameters, make core flooding experiments etc.
- Evaluate the well test data and the acquired logs from the pilot well to point out the best layers for thermal storage. The results of the core analyses, well test interpretation and the log interpretation will positively assist in the decision making on storage design etc.
- Test if the chalk is an appropriate storage media. Examine how the chalk reacts to water injection and withdrawal.
- GEUS suggests the use of water treatment in order to handle clogging, scaling and corrosion processes in the chalk-water system. This water treatment may include the use of ion exchange, acids and filters (for cations and particle removal).
- Collection of a water sample from the target zone for geochemical analysis.
- Examining the possibilities of applying well stimulation – and apply well stimulation, if appropriate.
- Set up of a full-scale (full-field) reservoir simulation model. The main purpose is to history match of the production test data. Furthermore, the effects of long-term production can be predicted.

2. Introduction and background

The project 'HTES' (High Temperature Energy Storage) aims at demonstrating a new seasonal storage technology. The HTES project examines the possibilities of establishing thermal storage in the subsurface limestones and chalks of the greater Copenhagen area in the depth range 400–800 metres, integration into a practical context in the district heating sector and gaining operational experiences with the technology for subsequent commercialisation. The project aims at establishing a wells system using modern water well drilling equipment, whereby costs can be lowered compared to the expenses of a standard rig drilling for hydrocarbons.

The planned project period is 4 years, divided into three phases:

The **first phase** (year 2017) reviews the existing knowledge on thermal energy storage, evaluates relevant geological and geophysical data from the study area and sets up a numerical groundwater and reservoir model. This phase also includes an evaluation of information from geotechnical wells. The aim of the data compilation is e.g. to provide a geological well prognosis accompanied by reservoir parameters for a pilot well, complying with standard water well drilling equipment. This phase also comprises work on searching for potential prospects (or sweet spots).

In the **second phase** (2018-2019) a pilot well will be drilled *if* sweet spots, representing the most productive areas of the reservoir, are identified in phase 1. It is planned to core the well and in addition, the well will be logged with a suite of petro-physical logs and the hydraulic capacity will also be tested.

If satisfying reservoir zones are proven, an additional well will be drilled in the **third phase** in order to test and demonstrate the reservoir properties in real-life production/injection conditions and possible long-time effects on the overlying groundwater system will be examined in an observatory groundwater well.

2.1 Heat storage concept at Copenhagen

Storage of energy in the subsurface will in the near future become an important part of the total Danish energy system as part of the necessary levelling out of large variations in energy production and consumption. The solution is to build buffers into the energy system, so that surplus energy can be stored seasonally. The present project 'HTES' (High Temperature Energy Storage) aims at demonstrating a new storage technology. The limestone deposits and chalks in the greater Copenhagen area are candidates for heat storage, because of a large storage potential (high volumes) and the shallow burial depth. However, the reservoir parameters of the chalk are not well-known and further analysis of the flow system is definitely needed prior to establishing a thermal heat storage in the chalk section.

The planned storage depth (400–800 m) implies that interaction between the storage and groundwater zones may occur. Two numerical groundwater and reservoir models are established, therefore, with the objective to simulate the storage potential, water flow rates, pressures and temperatures in the depth range 0–1000 m. Both the groundwater and storages zones are included in the model-simulation in order to uncover possible effects on the groundwater system.

2.2 Previous studies and the various storage techniques

The Danish HTES project utilizes information from a number of High-Temperature Aquifer Thermal Energy Storage systems located in Germany, France, Holland and England. Most commonly, these storage systems deal with sandstone aquifers, but the German plant in Dingofing involves storage of surplus energy in a Jurassic limestone aquifer at about 500 m depth (Bavarian Malm). The idea behind the German storage system is very similar to the concept of the planned Danish HTES system.

An ATES system, in which water flows from an injection point to a production well located some distance away (say 300–1000 m), is commonly preferred for heat storage. However, both in the German and Danish HTES case, hot water is to be injected into the aquifer via an injection well during the summer period, and the same well is used for producing the pre-stored water during the winter period (i.e. retrieval of thermal energy). Prior to injection, it is planned to heat up the water to 90°C in the Danish plant.

At **Dingofing**, the storage process takes place in a closed circuit that is located between the surface and the subsurface (**Fig. 2.1**). The figure illustrates the different operations during the summer and winter period, respectively. The water is recovered from a production well in the summer, and then heated to up to 130°C via heat exchanger. Next, the water is fed back into the Jurassic "Malm" aquifer via an injection well. The limestone aquifer thus stores heat energy during the summer period and provide heat energy during wintertime. As a result, the water balance is in equilibrium and water is not permanently removed from the limestone aquifer.

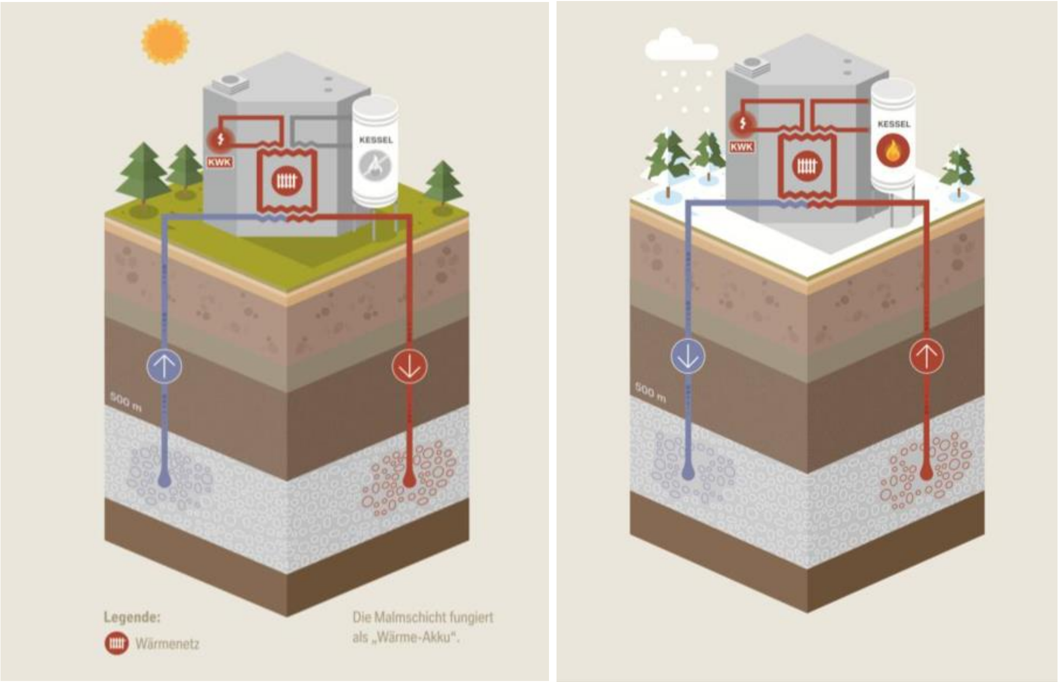


Figure 2.1: *Summer (left): Loading of the aquifer via combined heat and power plant (CHP). Winter (right): Withdrawal of thermal energy from the aquifer and application as heat source.* Reference: https://www.hydro.geo.tum.de/projects/aquifer-thermal-energy-storage/

Apart from the Dingofing plant, not that much information about thermal energy storage in limestones and chalks is available from the literature. An ATES system located in the Paris Basin,is outlined in details by Réveillère et al. (2013). In this basin, hot water is stored in carbonate deposits characterized by very high permeabilities, and these sediments are not comparable to chalks and limestones at Copenhagen. In the London area, chalk is used for thermal energy storage (ATES system). The London chalk is highly fractured and chiefly, the water flow takes place in the fractures and not in the matrix (Law et al., 2007). The London chalk is thus not comparable to the Copenhagen chalk, either.

The current HTES project utilizes results from an on-going EUDP-project **"Evaluation of the potential for geological heat storage in Denmark".** This project deals both with sandstone and limestone aquifers, but with respect to limestone aquifers, only Borehole Thermal Energy Storage (BTES) is considered. BTES does not involve injection of water into the limestone deposits. The following text provides a short and general summary of the above-mentioned EUDP project, including ATES, BTES and heat storage at shallow depths.

In Denmark both wind power and district heating are integrated parts of the energy supply and according to the politically adopted plans for a transition toward a fossil free energy supply by 2035 all electricity and heat production must come from renewable energy sources. However, extensive periods with surplus of both solar and wind power calls for innovative ways to store this energy and make it available when needed. By the concept of Geological Storage surplus electricity can be converted to heat and along with surplus heat from solar panels and as well as surplus of industrial heat stored in the ground for later use. Furthermore, implementation of heat storage can make it possible to expand district heating supply without building new production facilities and subsurface heat storage will often be the only possibility, especially in city areas, due to areal limitations. Though the potential is large, the experience with this concept is currently relatively limited. This project aims to explore the possibilities to store and retrieve heat from relevant geological formations in Denmark to be used at larger and smaller district heating plants as well as other relevant industries when needed.

Since technically and environmentally sound solutions for geological storage of heat to a large degree depends on the local geological settings and depths, it is essential to identify potentially favourable geological conditions and the related possible technical solutions. In this project, selected geological settings will be investigated and the potential, risks and investment costs of different types of storage facilities and geometries will be examined.

The aim of the project is to provide district heating companies and other relevant industries with maps and guidelines to facilitate planning and construction of storage facilities in connection with their current power plants.

One part of the work regarding shallow energy storage will be based on present experience and data from an existing test plant at Brædstrup District Heating. This work will focus on possible ways to upscale such a test plant using novel combinations of proven technologies.

The present project will draw on experience from previous projects investigating deep and shallow geothermal potentials in Denmark. Selected projects are listed under the description of each partner in annex 5. The project group consists of the following partners:

- The Geological Survey of Denmark and Greenland (GEUS)
- VIA University College, Horsens
- PlanEnergi, Skørping
- Brædstrup Fjernvarme, Amba
- Geoscience Aarhus University (AU)

In addition, three industry partners are associated to the project and have committed to provide data and relevant knowledge.

3. Geophysics

A number of seismic lines of various quality and vintage covers the greater Copenhagen area, but only the locations of the high-quality lines are plotted in the **Figure 3.1**. The greater Copenhagen area is not covered by a modern 3D survey suitable for seismic inversion and porosity evaluation, but the available 2D lines provide valuable information about chalk stratigraphy and the structural development.

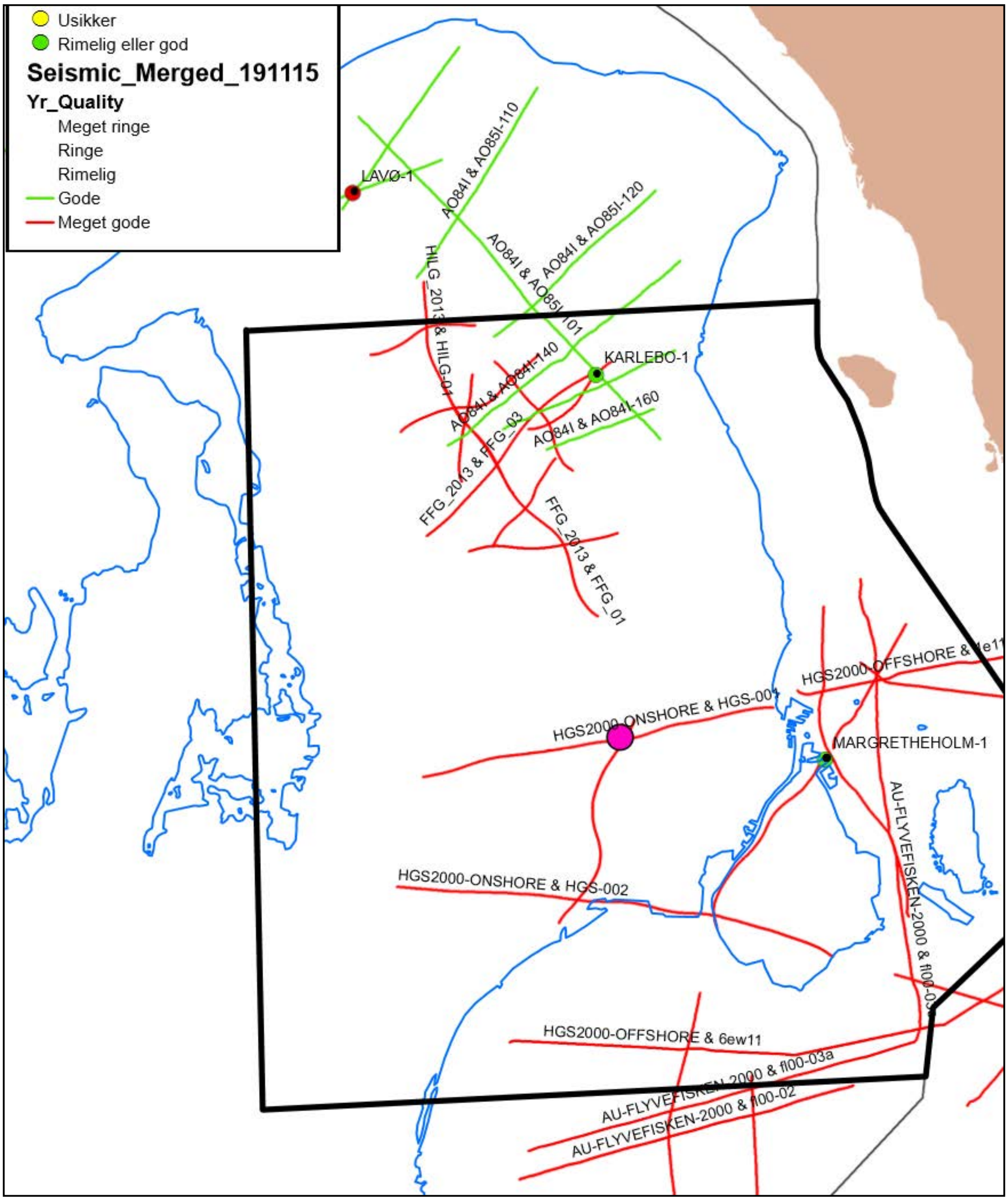


Figure 3.1: *Map showing the location of the seismic lines and the quality of the seismic data. The locations of the deep wells Margretheholm-1, Karlebo-1 and Lavø-1 are also shown. The pink circle indicates the location of the "Vestforbrænding" site.*

3.1 Seismic interpretation

Very recently, Connie Larsen (Larsen, 2016) interpreted the seismic data available from the Upper Cretaceous–Danian carbonates, leading to a number of intra chalk horizons along with the Top Chalk and Base Chalk surfaces (Fig. 3.2). Most of the seismically derived horizons correlate to the well-log picks identified from logs acquired in the deep wells, and thus the seismic data assist in subdividing the chalk and limestone sections into litho-stratigraphic units. After depth conversion, the seismic horizons also assisted in predicting the depth to the various chalk units at prognosis localities (e.g. the Vest-forbrænding site). Initially, the depth conversion was based on an average chalk velocity of 3300 m/s. This interval velocity originates from TWT and depth data from the Margretheholm-1 and Stenlille-1 wells. The velocity model was later refined according to data from Nielsen et al. (2011); the chalk velocity is only about 2200 m/s in the shallow parts and increases to c. 4300 m/s in the deeper parts of the chalk section.

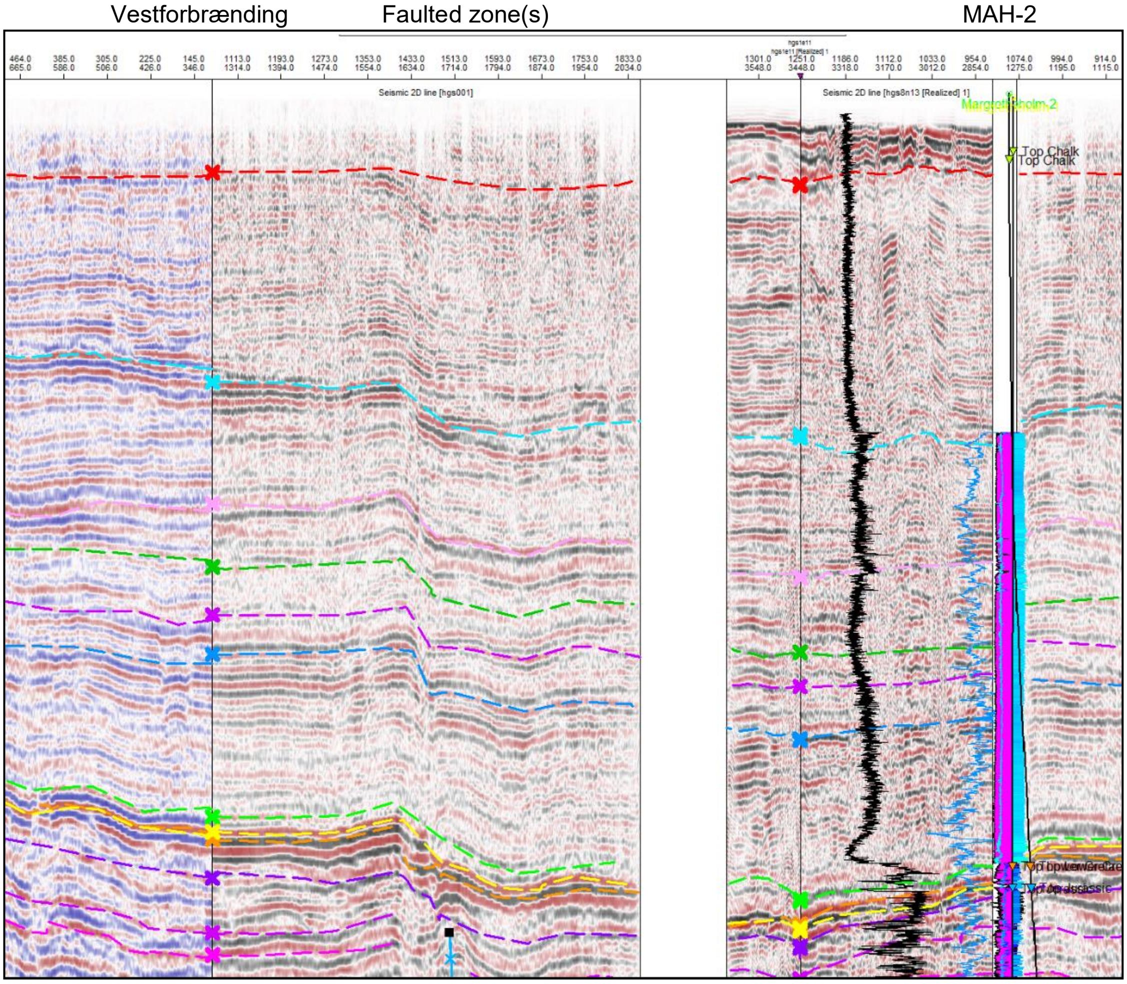


Figure 3.2: *Composite seismic section from the Margretheholm-2 well (MAH-2, right) to the Vestforbrænding location (left). The seismic section included the lines HGS-8N-13 (right), HGS-001 (mid) and HGS-005 (left), see Figure 3.1 for location. Larsen (2016) interpreted several horizons within the Chalk Group, and the figure illustrates that the intra-chalk horizons are found structurally higher at Vestforbrænding than at Margretheholm. The position of faulted zones corresponds to the Carlsberg and Øresund Fault systems. A blue line in the lower part of the figure signifies the fault system, but note that the line stops below base chalk. The black log curve at Margretheholm illustrates a gamma-ray log.*

3.2 Maps

GEUS mapped the Top Chalk and Base Chalk horizons in a previous study (Fig. 3.3). Neither GEUS nor Larsen (2016) have generated depth structure maps for the intra chalk horizons. However, Larsen (2016) mapped the reflection time to the seismic units defined in her study. These time structure maps are helpful in the HTES study, but provide only an overview, as the scale is approximately 1:1,500,000.

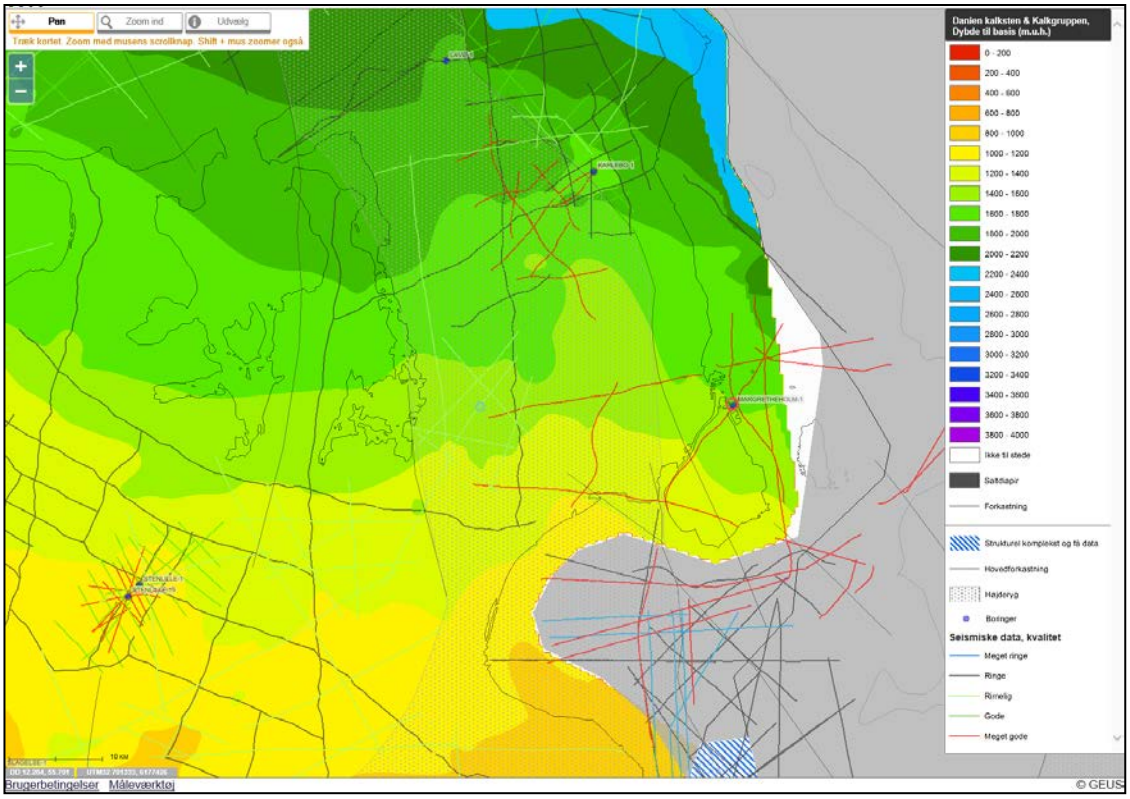


Figure 3.3: *Depth structure map showing the depth to base chalk (base Upper Cretaceous) in the greater Copenhagen area (in metres, TVDss). The map also shows the location of the seismic lines, deep wells, main fault systems and structural highs. A colour code illustrates the seismic data quality. The map is downloaded from the GEUS WebGIS portal.*

3.3 Carlsberg (Amager) Fault

The exact trace of the Carlsberg fault within the Copenhagen city area is not known, but Nielsen et al. (2005) attempted to locate and map the fault zone (Fig. 3.4). Their mapping is based on seismic refraction, reflection and fan profiling – and includes, as a minimum the depth range 0–500 m. Especially the fan shooting method appears to be an effective way to map the trace of fault zones in densely urbanized areas (Nielsen et al. 2005).

Similarly, the Carlsberg Fault (i.e. the 'Amager Fault' on Amager) can be identified from the seismic interpretation of lines HGS-003 and HGS-002 (consult Fig. 3.6). The seismic interpretation points to potential storage sites at the fault zones locations.

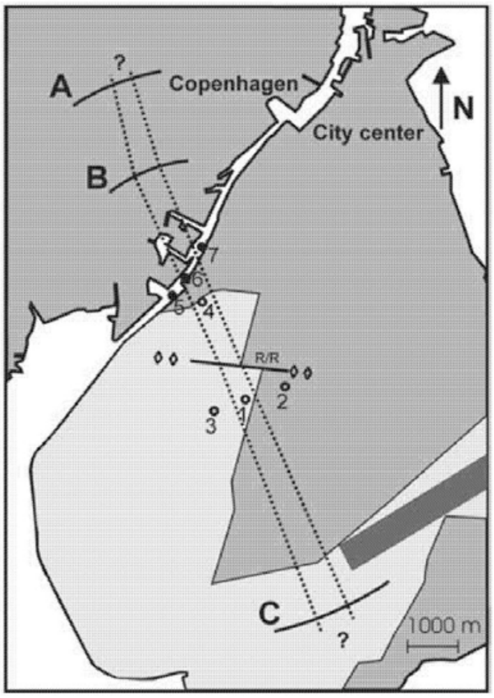


Figure 3.4: *Map showing the interpreted location of the Carlsberg Fault zone (shown by dotted lines). The fan shooting method is illustrated as follows: Points A, B and C are receiver arrays (forming part of a greater circle), open circles are shot point locations. R/R indicates an integrated refraction/reflection seismic line. After Nielsen et al. (2005).*

The complex faulting related to the Carlsberg Fault zone is exemplified in Fig. 3.5. The seismic profile represents approximately the uppermost 200 metres of the limestones and chalks, and the faulting produces relative displacement of the various limestone and chalk units. The København Limestone unit disappears towards the West as consequence of the faulting. Both the Carlsberg and Øresund Faults are major structural elements related to the Fennoscandian Border Zone, and these fault systems transects not only the carbonaceous deposits, but also older geological strata of Triassic and Jurassic age.

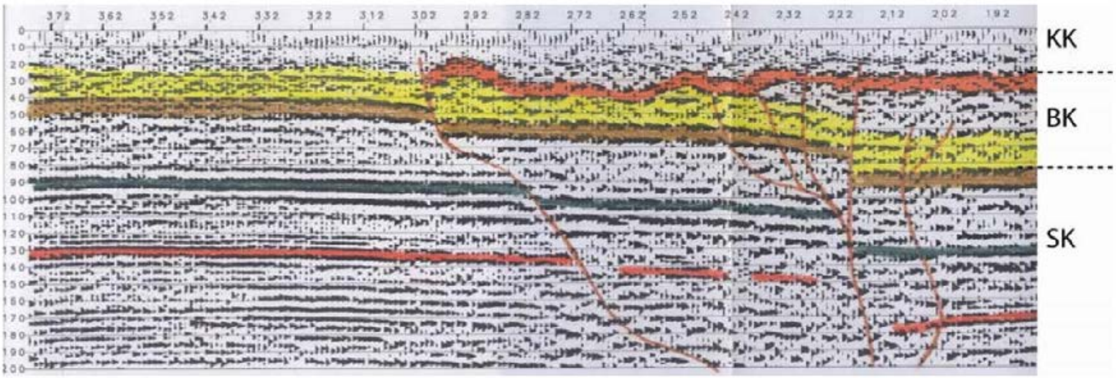


Figure 3.5: *Seismic profile across the Carlsberg Fault system on Amager (Location: Motorway E20, exit 19). The vertical scale represents two-way-time in milli-seconds. The faulting implies that the København Limestone (KK) disappears at approximately point '302'. KK: København Limestone, BK: Bryozoan Limestone, SK: Skrivekridt/Chalk. Figure from Fallesen, 1995.*

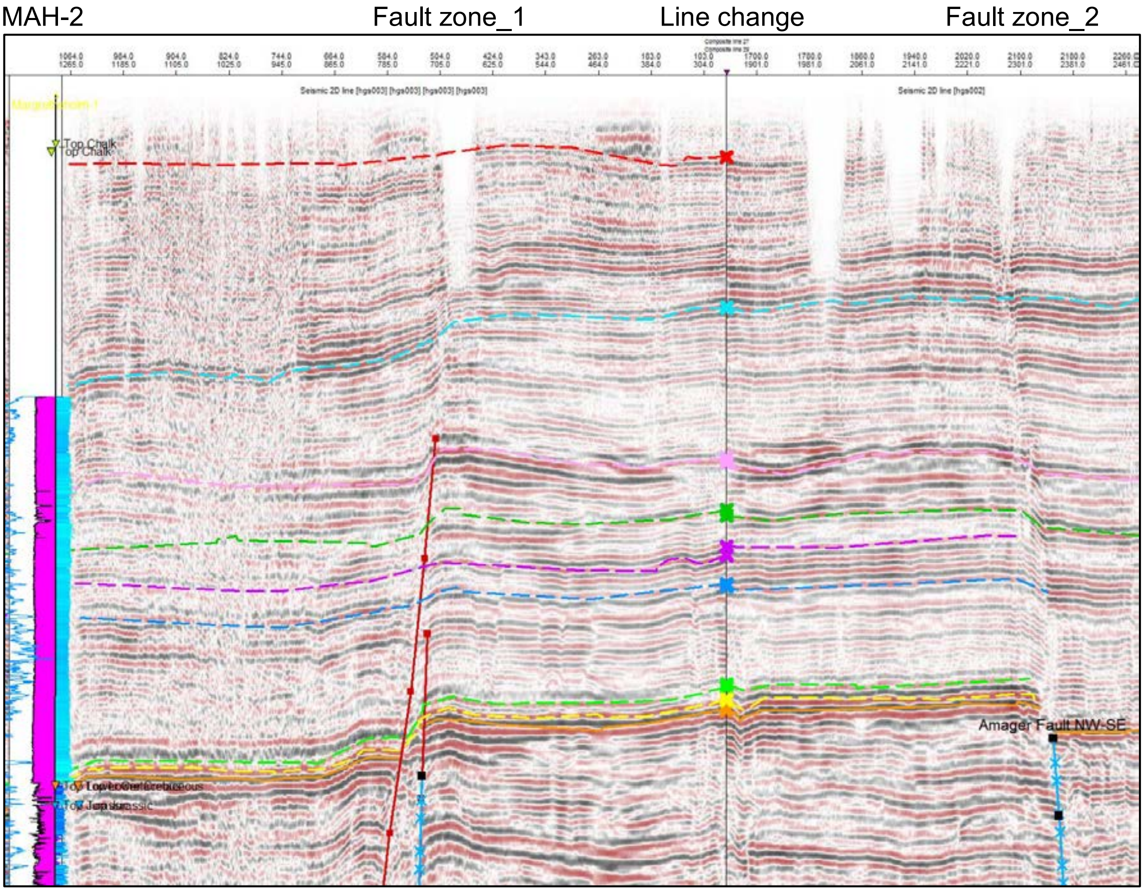
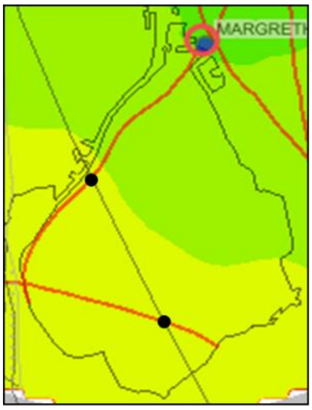


Figure 3.6: *Composite seismic section from Margretheholm-2 (left) to southern Amager (right). For location, see the loop marked by red lines in the figure below. The loop passes the Amager/Carlsberg Fault Zone two times (indicated by black dots in the figure below). Two seismic lines are included; HGS-003 (left) and HGS-002 (right). Interpreted by Larsen, 2016.*



Location map linked to the figure above. The figure shows the location of the Magretheholm-2 well and the positions of seismic lines (red). A black solid line indicates the approximate position of the Amager Fault.

4. Geology

In the greater Copenhagen area, a thick package of chalks and limestones, overlain by a relatively thin section of Quaternary sandy and clayey deposits, dominate the topmost part the geological section. However, an up to 100 m thick section of glacial deposits are found to the north, especially in buried valleys, while these deposits only constitutes a thin coved to the south. The entire section of chalks and limestones is considerably thick (up to c. 2 km). Table 4.1 below presents a stratigraphic subdivision relevant for this study.

4.1 Pre-Quaternary geology

Apart from Paleogene marls and glauconitic sandstones to the west, the rocks at the Pre-Quaternary surface consist of different types of Danian limestone (Fig. 1.1), reflecting a lateral variation in sediment distribution due to erosion and structural uplift, occasionally combined with faulting.

4.1.1 Danian limestones

The thickness of the Danian limestones is only in the order of 100 metres. The Danian limestone section consists of a variety of carbonate-rich deposits, occasionally with flint beds: calcarenites, limestones, calcilutites and conglomerates. The Danian constitutes two key units in the study area, the ‘København Limestone Formation’ and the ‘Bryozoan Limestone unit’. The København Limestone is composed predominantly of sand-size carbonate grains (probably 20–30%) and limestone. This carbonate rock is thus a calcarenite or a carbonate sand. The Bryozoan Limestone is dominated by bryozoan-rich limestone, occasionally with large amounts of clay-size and silt-size carbonate grains (i.e. a calcilutite). Especially the lower part of the Bryozoan Limestone is clayey in parts. The stratigraphy, lithology and the related hydrology of the Danian limestones are fairly well-known from a number of larger infrastructure and groundwater mapping projects. Reference is made to e.g. Frederiksen et al. (2002) and Klitten et al. (2006). Furthermore, cores are available from Stevns-1 and several TUBA-boreholes (railway tunnel investigations).

4.1.2 Maastrichtian and Campanian chalks

The planned storage zone is located in the Maastrichtian and Campanian chalks, i.e. in a zone located below the Danian limestone succession. The lithostratigraphic subdivision of Paleocene and Upper Cretaceous sediments is presented in Table 4.1 below. The nomenclature connected with the Units, Formations and Members is based on information from Surlyk et al. (2013) and Stenestad (1976); see later.

Overall, the chalk is a porous, white and soft carbonate rock composed primarily of the mineral calcite. It is formed at marine conditions, mostly from accumulation of calcite shells (coccoliths). Cuttings descriptions from the local Margretheholm wells indicate that the chalk consists white to light grey chalk, being soft to hard, and occasionally flint nodules occur. The chalk is partly argillaceous and has traces of grey laminations. Apart from the presence of flint nodules and small amounts of clay, the chalk is particularly homogenous, but the degree of cementation and the amount of natural fractures vary considerably with depth. The chalk expected to be present in the storage zone is presumably analogous to the chalk drilled in the Margretheholm wells, if dealing with an approximate depth of 400–800 m.

Table 4.1: Chronostratigraphy, lithostratigraphic subdivision and nomenclature

Chronostratigraphy (Geological age)		Unit/ Formation/ Member (**)	Local Member
Quaternary		Quaternary undiff.	
Paleocene	Selandian	Kerteminde Marl Fm Lellinge Greensand Fm	
Paleocene	Danian	København Limestone Fm	
		Bryozoan Limestone unit (Stevns Klint Fm)	
Late Cretaceous*	Maastrichtian	Sigerslev Mb	Højerup Mb
		Rørdal Mb	
		Hvidskud Mb	
	E. Maastrichtian–L. Campanian	Boesdal Mb	
	Late Campanian	Flagbanke Mb	
	L. Campanian–Cenomanian	Lower Chalk unit	High GR unit
	Santonian and older	-	

* In the Danish onshore area, the late Cretaceous chalks belong to the informal 'Chalk Group' (Nielsen & Japsen 1991). (**) The nomenclature is based partly on information from Surlyk et al. (2013) and Stenestad (1976).

The large number of Units, Formations and Members listed in Table 4.1 reflects that the stratigraphy, lithology and reservoir parameters vary considerably within the study area, both vertically and horizontally. This complex situation is a challenge for the geological assessment. The lithostratigraphic units are also considered flow units (reservoir units), and thus the unit subdivision is essential, both from a geological and reservoir technical point of view.

4.1.3 Well-to-well correlation and lithostratigraphic subdivision

The geological evaluation of the chalks and limestones is based on well-logs, cores and seismic data. Log data suitable for well-to-well correlation and lithostratigraphic subdivision are available from the Stevns-1, Karlslunde-1 Stenlille-1 and Margretheholm-1 wells (Fig. 4.2; well locations are plotted on a map, refer to Fig. 4.3). In addition, the Swedish Höllviksnäs-1 well is included in the analysis. The well-to-well correlation is based primarily on the gamma-ray log, but also the sonic log is included, if available. After depth conversion, the seismic reflection data - including interpreted seismic horizons - assisted in defining the well picks. Moreover, the fully cored boreholes of Stevns-1, Stevns-2 and Karlslunde-1 provide lithological, biostratigraphical and reservoir properties for the Maastrichtian – Upper Campanian interval.

In addition to the log data, cores were cut in Stevns-1, Karlslunde-1 and Tuba-13. The cores provide information about cementation, grain size and clay content. In the chalk section, the degree of cementation generally increases with depth. The Boesdal and Flangbanke Members are characterised by a higher clay content than the Hvidskud Member, meaning that the porosity level is somewhat lower in the Boesdal and Flangbanke Members as indicated by the trend lines in the figure below (Fig. 4.1). When dealing with Upper Cretaceous chalks, **the Sigerslev and Hvidskud Members are considered the best reservoir units** due to a general clean chalk composition and relatively shallow burial (c. 200–600 m). The Danian carbonates are also considered reasonable reservoir units; these units are commonly fractured and generally present within the depth interval 0–200 m.

4.1.4 Stratigraphic break down

The stratigraphic break down of the limestone and chalk sections relevant for this study aims at providing a framework of intra chalk units with different reservoir properties that can be correlated throughout the Copenhagen area, with focus on the depth interval 200–800 m. The stratigraphic break down, including unit thicknesses and the composition of the carbonate deposits, is described in detail in the following text. Comments on reservoir properties are also given.

The **Lower Chalk unit** comprises Cenomanian – Upper Campanian strata of chalk, marly chalk and marl. The unit is 800 m thick at Magretheholm-1A and 600 m thick in Stenlille-1. An unconformity occurs in the upper part and is associated with a permeable zone that caused a dynamic loss of drilling mud in the Margretheholm-1 well (30-50 m^3/hour at depth 956 m). This zone is probably stratigraphically equivalent to the sandstones of the Lunda Member in Skåne. The unconformity is interpreted as a seismic marker horizon, i.e. the intra-Campanian unconformity of Larsen (2016), and Esmerode et al. (2007). The lower chalk unit has generally poor reservoir properties apart from the high permeable zone in Margretheholm-1 as described above.

The subdivision of the Upper Campanian–Maastrichtian strata is based on the lithostratigraphy at Stevns as described by Surlyk et al. (2013). These authors include data from coastal outcrops and fully cored boreholes. The subdivision of the Danian strata is based partly on the lithostratigraphy of Surlyk et al. (2013, 2006), partly on the lithostratigraphy of Stenestad (1976).

The **Flagbanke Member** (Upper Campanian) is 44 m thick at Stevns-1 and consists of chalk, with thin marly beds and thin marls and few thin chalk intraclast conglomerates. It is correlated to an interval of about 55 m thick in Margretheholm-1. Chalk porosities are illustrated in Fig. 4.1.

The **Boesdal Member** (Upper Campanian–lowermost Maastrichtian) is 85 m thick in Stevns-1 and consists of chalk, marly chalk and up to centimetre thick marl beds and abundant chalk intraclast conglomerates. The equivalent interval in Stenlille-1 is 45 m thick and 170 m in MAH-1. An arenaceous limestone interval about 30 m thick is recorded in Margretheholm-1. The Boesdal Mb probably correlates to the sandy Hansa Member in Sweden. Sandy deposits in the interval is restricted to halfgraben in Skåne and correlative units in the distally positioned Copenhagen area shows slightly sandy and clayey carbonates. The reservoir properties of the Boesdal Mb are slightly better than observed in the Flagbanke Mb.

The **Hvidskud Member** (Lower–Upper Maastrichtian) is 204 m thick in Stevns-1 and consists of white and marly chalk, with common nodular flint bands. The unit shows prominent thickness variations: 126 in Stevns-2, 100 m in Stenlille-1 and 270 m in Margretheholm-1. The porosity of the chalk is very high in Stevns-1 and Karlslunde-1. See also Fig. 4.1 for additional information about chalk porosity. The matrix permeability is discussed in Chapter 6 (this Chapter also provides information about the porosity).

The **Rørdal Member** (Upper Maastrichtian) is 29 m thick in Stevns-1 and consists of marly chalk with thin marl beds. The equivalent interval shows similar characteristic high gamma ray peaks in Karlslunde-1 (50 m thick) and in Stenlille-1 (95 m thick), whereas in the interval is 120 m thick in Margretheholm-1. A pronounced marly layer, affecting reservoir properties, characterises the Rørdal Mb.

The **Sigerslev Member** (Upper Maastrichtian) is 61 m thick in Stevns-1 and consists of pure white chalk with flint nodules and only a few marly chalk units. The equivalent interval is 57 m in Margretheholm-1 and 120 m in Karlsunde-1, but only 35 m in Stenlille-1.

The **Danian** interval is up to about 100 m thick. The lower part comprises bryozoan limestone, which is assigned to the Stevns Klint Fm (Surlyk et al. 2006). In the Copenhagen area, cf. core material from the Tuba-13 well, the bryozoan limestone is intercalated with chalk (lime mudstone) units in the lowermost part and middle part. In the more central parts of the basin at Stenlille-1, the Danian consists of slightly clayey chalk mudstone.

The København Limestone Formation forms the upper part of the Danian succession and is subdivided into three units in the Copenhagen area (Stenestad 1976). The lower unit comprises marly and muddy fine sand-grade carbonates, about 5 m thick. The middle units consists of biomottled partly silicified sandy carbonates, c. 20 m thick. The upper unit comprise regular bedded muddy and sand-grade carbonates, c. 15 thick. Flint bands and nodules occur in all three units. The lower unit have porosities in the order of 30%; the middle and upper units show porosities alternating between 20% and 60% (cf. DGU no. 94.0.000 and DGU no. 93.0.007).

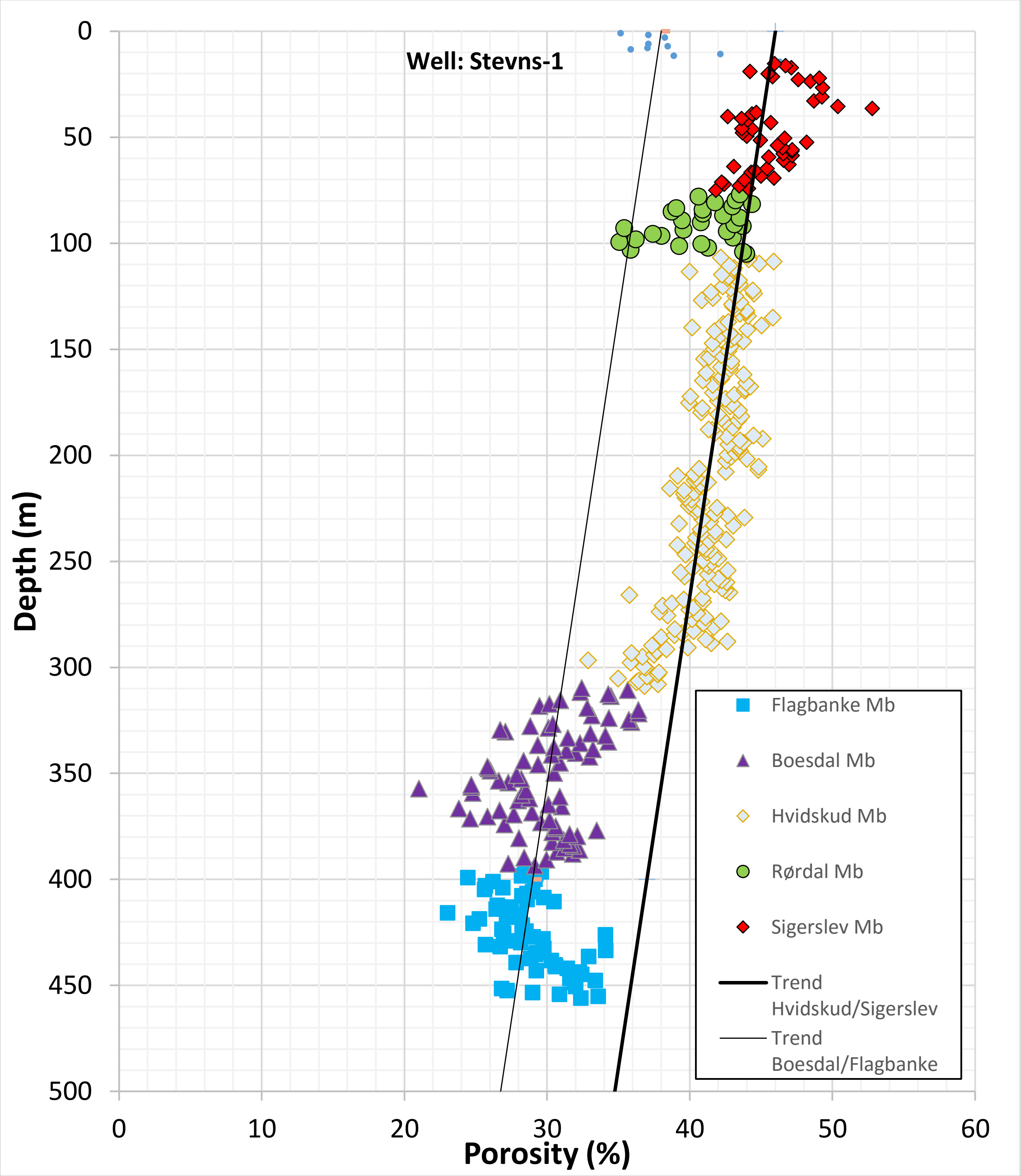


Figure 4.1: *Porosity-depth plot for Stevns-1. Based on core porosity data. The various Members are characterised by different porosity-depth trends, indicating different reservoir properties. The slope of the trend lines, but not necessarily the absolute porosity values, are generally applicable to the chalk section of the greater Copenhagen area. Actually, porosities are somewhat lower at Copenhagen compared to the Stevns area.*

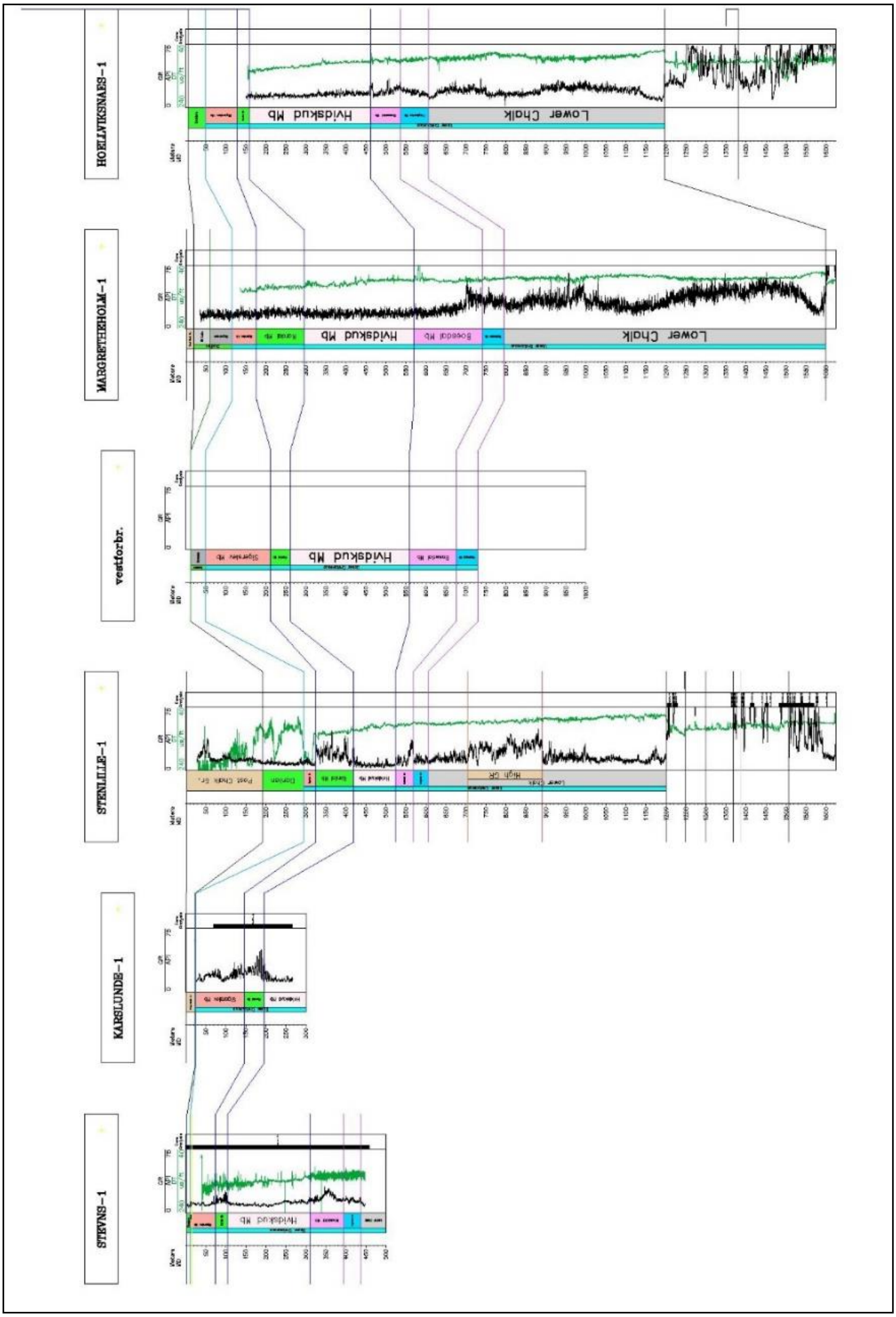


Figure 4.2: *Well-to-well correlation and lithostratigraphic subdivision. Based on log data (gamma-ray and sonic) from Stevns-1, Karlslunde-1 Stenlille-1, Margretheholm-1 and Hölviksnäs-1. The predicted positions of the correlation lines at the Vestforbrænding site are also shown.*

4.1.5 Faults in the area

The Carlsberg Fault and Øresund Fault trending NNW–SSE are only partly mapped due to poor seismic coverage. They show the main displacement in pre-Chalk strata, and locally in the chalk succession, the displacement is up to about 50 m. The Carlsberg Fault is synonymous with the Amager Fault. The Øresund Fault terminates, or joins the Carlsberg Fault, north of Kalveboderne. The position of the major fault systems are shown in Fig. 3.3.

A normal fault, the “Ishøj Fault” NE of Karlslunde-1, strikes NW–SE and forms an apparent flexure in the chalk succession. Its northern continuation is not known in detail; the fault probably terminates towards the north. Away from this fault system, especially the Danian part dips towards the west.

The Carlsberg and Øresund Faults influence the thickness of both the chalk and limestone units, and greater thicknesses are thus recorded east of the faults. Internally, the chalk section shows subtle variations in general dip and unit thicknesses.

Minor mounded reflectors are recorded internally in the chalk succession, notably above the intra Campanian reflector and above the base Maastrichtian reflector (Larsen 2016).

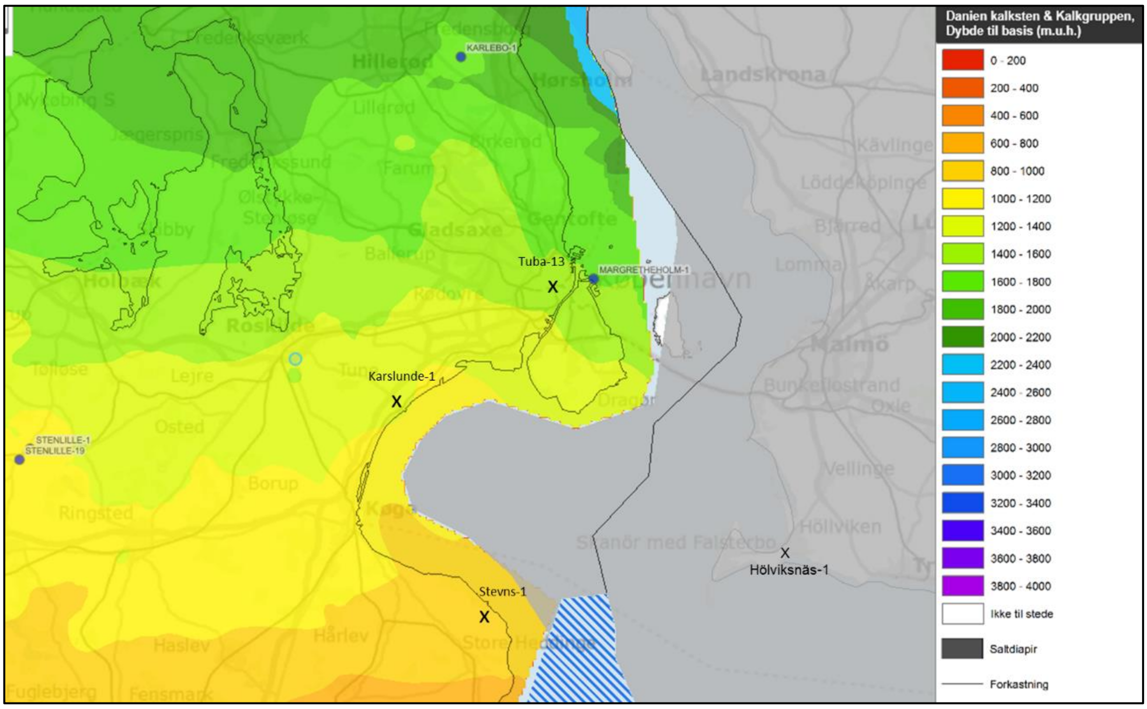


Figure 4.3: *Well locations; Stevns-1, Karlslunde-1 Stenlille-1, Stenlille-19, Margretheholm-1, Karlebo-1 and Hölviksnäs-1. The coloured base map corresponds to a base chalk depth structure map (metres below MSL; refer to the legend to the right). The depth structure map is available from the GEUS WebGIS portal* [*http://dybgeotermi.geus.dk/*](http://dybgeotermi.geus.dk/)

4.2 Biostratigraphy

GEUS screened cuttings samples from the limestone and chalk sections in the Margretheholm-1 well and carried out both nannofossil and foraminfera analyses to support the stratigraphic subdivision. Initially, GEUS focused on determining the usefulness of the nannofossil biostratigraphy on this well and secondly, GEUS focused on the nannofossil biostratigraphic resolution.

With respect to nannofossil samples, 47 nannofossil samples were prepared from washed, dried ditch cuttings samples from the chalk of the Margretheholm-1 well from 30 m to 1635 m. Next, a screening of the samples was carried out.

The highest sample at 30 m was characterised by nannofossils from the Maastrichtian to Campanian. Due to the content of the underlying samples, the nannofossils in the sample at 30 m were probably reworked and this sample requires further screening for Danian nannofossils. The sample at 45 m contains *Prinsius martinii* indicating a 'middle to upper' Danian (NNTp4C or younger age, Varol *et al.* 1998.).

Danian chalk (NNTp3 and older) represents the section down to and including 130 m as evidenced by the nannofossils *Chiasmolithus danicus*, *Prinsius tenuiculus*, *Prinsius dimorphosus*, *Zeugrhabdotus sigmoides*, *Coccolithus pelagicus* and *Cruciplacolithus tenuis*.
Samples from and including 150 m – 400 m include *Arkhangelskiella maastrichtiana* and *Nephrolithus frequens*, which together indicate upper Maastrichtian subzones UC20c–b (Burnett 1998). The marker for uppermost Maastrichtian subzone UC20d was not found during the screening of this interval.

A general Maastrichtian – Campanian age is given for the 425 m – 580 m interval.
The first downhole occurrence (FDO) of *Reinhardtites levis* at 595 m indicates the presence of lower Maastrichtian zone UC18, probably down to 745 m. Interestingly within this interval, two samples (620 m and 670 m) contain *Cribrosphaerella daniae*, the marker for uppermost Maastrichtian subzone UC20d.
At 780 m the FDOs of *Broinsonia parca constricta, Broinsonia parca parca* and *Monomarginatus quaternarius* mark the top of the Campanian and subzones UC16d – c. The FDOs of *Orastrum campanensis, Heteromarginatus bugensis* and *Reinhardtites anthophorus* at 825 m indicate the top of subzone UC15d and the lower part of the Upper Campanian. The Campanian continues down to at least 1010 m where *Arkhangelskiella cymbiformis*, *Prediscosphaera stoveri* and *Reinhardtites levis* are still present. These fossils have their last downhole occurrence in the Campanian, but as the samples are ditch cuttings samples, the risk of caving still has to be taken into consideration.

From 1030 m to 1550 m, nannofossil assemblages comprise predominantly long ranging species which make it difficult to date the samples. A single occurrence of *Quadrum eptabrachium* at 1030 m suggests the possibility of a Santonian – Turonian age, and common *Eiffelithus eximius* at 1350 m suggests a broad Campanian to Turonian age. However a specimen of *Helenea chiastia* (Cenomanian – Tithonian) at 1350 m and of *Broinsonia galloisii* (Albian – Aptian) at 1420 m, in the presence of nannofossils with a younger range, indicates the possibility of reworking. The sample at 1635 m (lowest sample) was not calcareous.

A higher nannofossil biostratigraphic resolution can be attained with further, more detailed work. It is planned to use the results of the biostratigraphic analyses in a Phase-2 study on adjusting the current subdivision of the chalk section.

5. Screening of groundwater aspects

The Copenhagen area is exclusively supplied from local and regional groundwater reservoirs. The yearly abstraction within The Capital Region of Denmark (Region Hovedstaden) amounts to around 78 mio. m^3 (Danmarks Statistik 2015). Around 50 mio. m^3 is produced by HOFOR Greater Copenhagen Utility while other minor waterworks accounts for the rest. The catchment areas and the location of the main waterworks of HOFOR are shown in figure 5.1.

Figure 5.1: *Catchment areas and main water work of HOFOR -Greater Copenhagen Utility*

Since Copenhagen is totally dependent on local water resources and the present abstraction rate is around 80% of the recharge (Henriksen et al. 2014), it is of paramount importance that these resources are protected. In this chapter an account of the groundwater resources and the related hydrogeology within the study area is presented.

5.1 Introduction to the hydro-geology of the greater Copenhagen Area

Aquifers used for abstraction of groundwater are found both in glacial deposits and in the underlying carbonate formations. Primarily glacial meltwater sand and Danian limestone formations are used for abstraction.

The thickness of Quaternary deposits varies through the project area. In general, larger thicknesses (up to around 100 m) are found to the north especially in buried valleys (the Søndersø Valley and The Alnarp Valley, cf. Klitten et al. 2006), while the Quaternary deposits to the south constitutes a thin cover mainly of clay till (Fig. 5.2). A more detailed account of the Quaternary deposits and stratigraphy is published in Frederiksen et al. (2002) where further references also can be found.

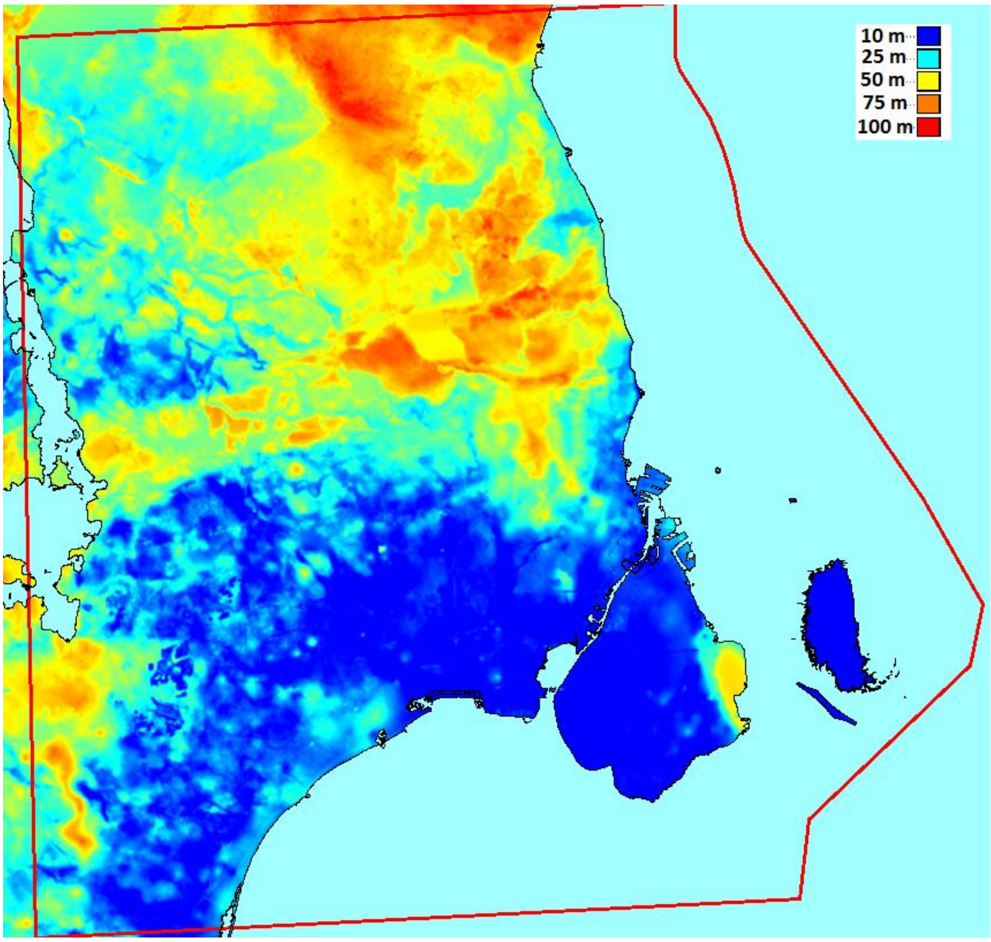


Figure 5.2: *Thickness of Quaternary deposits (m).*

The maximum thickness of Danian limestone is about 100 m in the study area (Thomsen 1995). The Danian deposits consist primarily of Bryozoan Limestone and København Limestone (carbonate sand), cf. Fig. 5.3 and Chapter 4 of this report. The stratigraphy, lithology and related hydrology of the Danian limestones are fairly well-known from a number of larger infrastructure and groundwater mapping projects. For an overview, reference is made to Markussen (2002) and Klitten et al. (2006). From these investigations it has been possible to establish a log stratigraphy subdividing especially the Copenhagen Limestones in permeable and less permeable zones (Klitten and Wittrup 2006). The areal distribution of different limestone formations at the base of the Quaternary is shown in Fig. 1.1.

Below the Danian limestones, Upper Cretaceous chalks are deposited with thicknesses of 1500 to 2000 m. The geology and stratigraphy of the chalk section is described in Chapter 4.

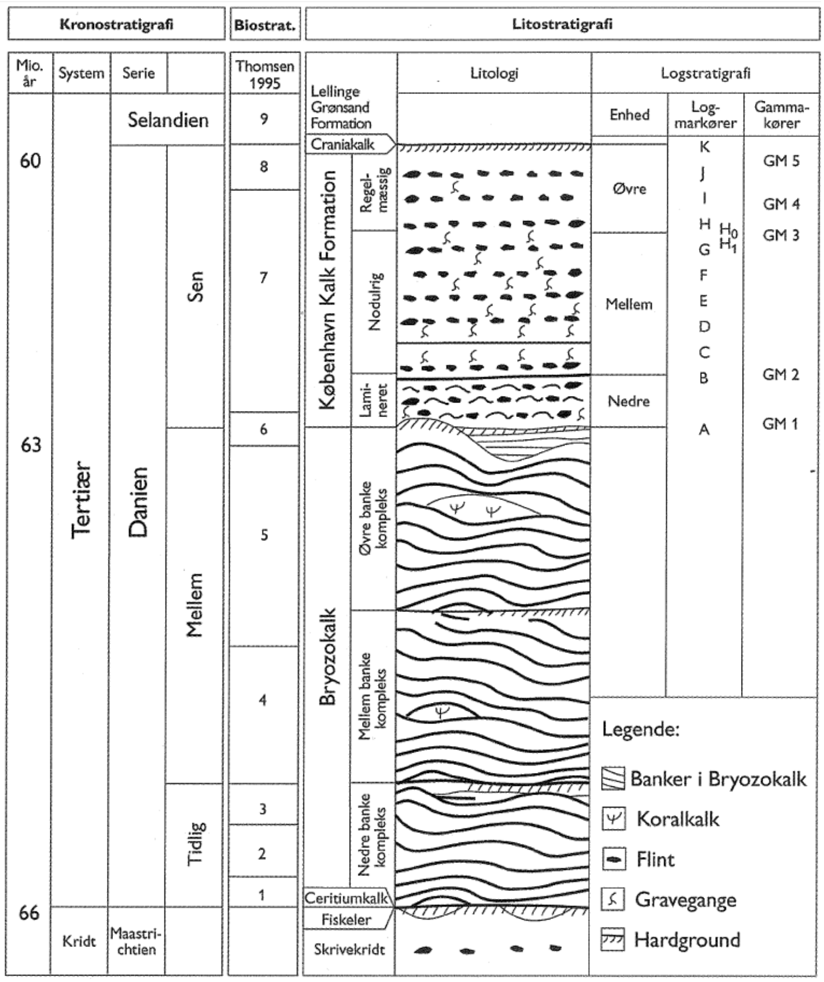


Figure 5.3 *Chrono- and lithostratigraphy of the Danian Limestones at Copenhagen (from Knudsen et al. 1995).*

5.2 Origin and structure of the freshwater zone

From analysis of 124 flowlogs, covering both the chalk section and Danian limestones, it is found that the major part of the influx of fresh water to the boreholes takes place in the upper 5-10 m of chalk or limestone, i.e. just below the base of the Quaternary.

Throughout Danian limestone units, several levels with influx can be encountered. In the underlying chalk, however, the number of influx levels and the amount of influx decreases. Especially at depths exceeding 70 m below the base of the Danian succession, only very limited influx occurs (Larsen et al. 2006).

The density of fractures in the chalk has been studied in outcrops at Stevns and from logging of boreholes in the area (Larsen et al. 2006). The field investigations showed that the chalk at Stevns is divided into an almost orthogonal network of un-fractured matrix with low permeability surrounded by fractures. Comparing the distance between water bearing zone / fractures observed at the outcrop with the distance between water bearing zone at increasing depth inferred from borehole logs, a preliminary model of the size of un-fractured blocks in the chalk vs depth was developed (Larsen et al. 2006).

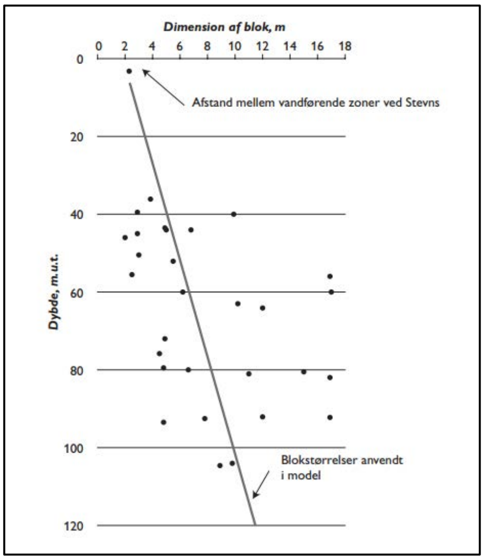


Figure 5.4: *Size of un-fractured blocks (m) in a network of orthogonal fractured Chalk as function of depth (m). Larsen et al. (2006).*

In this model (Fig. 5.4), the size of un-fractured blocks of chalk increases with depth, partly because the sub-horizontal fractures are closed with depth due to the elevated hydrostatic pressure. At a depth of 120 m, the dimensions of the un-fractured blocks are estimated to be around 10 m.

These findings support the major conclusion of Larsen et al. (2006) that in large parts of North Zealand the transition between fresh and salt groundwater corresponds the base of the Danian limestone or at an internal marl layer a few meters down into the chalk (Fig. 5.5). Exceptionally salt groundwater has entered higher stratigraphic level in coastal areas and fault zones (Klitten et al. 2006).

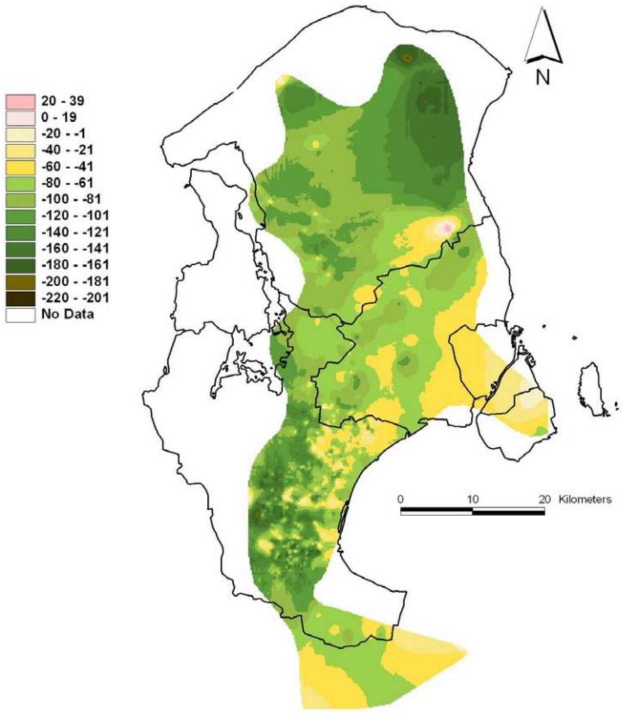


Figure 5.5: *Map of the fresh / salter water boundery (m a.s.) from boreholes and TEM soundings (Klitten et al. 2006).*

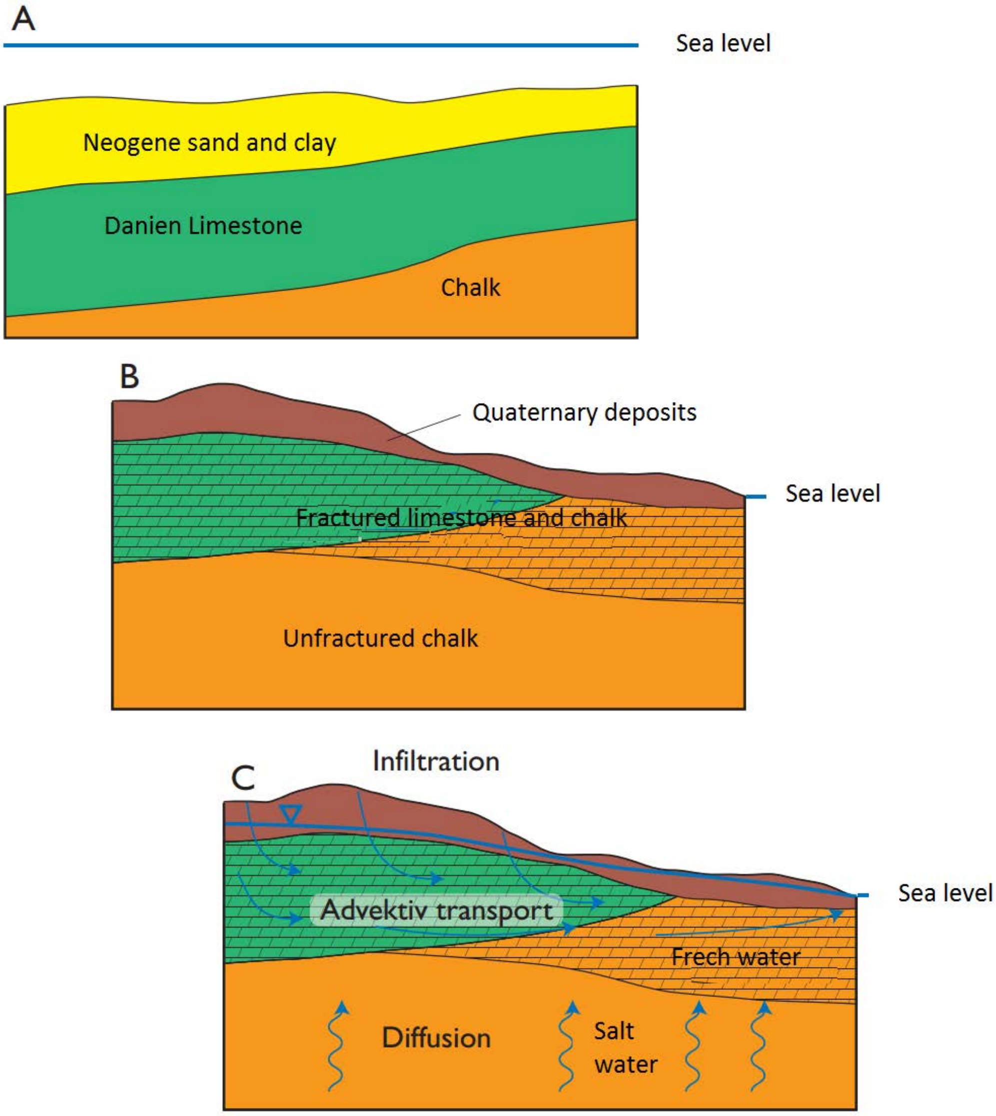


Figure 5.6 *Conceptual hydrogeological model for leaching of salt water from the un-fractured chalk to the freshwater zone (Larsen et al. 2006).*

Larsen et al. (2006) developed a conceptual model for the origin and structure of the fresh to salt water transition in the greater Copenhagen area (Fig. 5.6). In this model, limestone and chalk were initially covered by Neogene sediments (Fig. 5.6A). These sediments were eroded in glacial times and fractures in the carbonate rocks were formed by tectonic compression and isostatic uplift (Fig. 5.6B). In postglacial times, fresh water infiltrates from the surface and is transported to the coast by advective flow through the Quaternary deposits and fractured levels in the Danian limestones. Salt rises from below by diffusion through the un-fractured chalk and is washed out by groundwater flow in the fractures (Fig. 5.6C). This results in a transition zone between the salt and the fresh water zones containing a decreasing density of fractures and an increasing concentration of salt with depth. This zone is typically found in the upper part of the chalk section. Thus, the chalk in general holds limited groundwater resources in the Copenhagen area.

5.3 Existing groundwater models

Within the last 20 years, a number of geological models and related numerical groundwater models for the greater Copenhagen area have been produced. The models have different focuses, and applications and were set up in different software. Many of the models have been produced as part of the national groundwater mapping and are generally publicly available. Private companies also compiled a few regional models, and these models are not in public domain, however.

Starting as a research project in 1996, a national water resources model (DK-model) was developed by GEUS to advance the assessment of groundwater quantitative status accounting for interactions with surface water and anthropogenic changes, such as groundwater extraction strategies and land use, as well as climate change. Through continuous development, the model is gradually improved and increasingly applied by research projects and for decision support.

Within the study area the model consists of four Quaternary sandy aquifers of varying thickness intercalated with glacial clay below which a layer, representing carbonate aquifers (of Limestone and Chalk), is found. The limestone and at places also the upper part of the chalk are attributed with varying hydraulic conductivities derived and interpolated logarithmically from specific yields in boreholes registered in the national borehole database (cf. Fig. 5.7). At the base, the model contains an impermeable layer representing un-fractured Chalk.

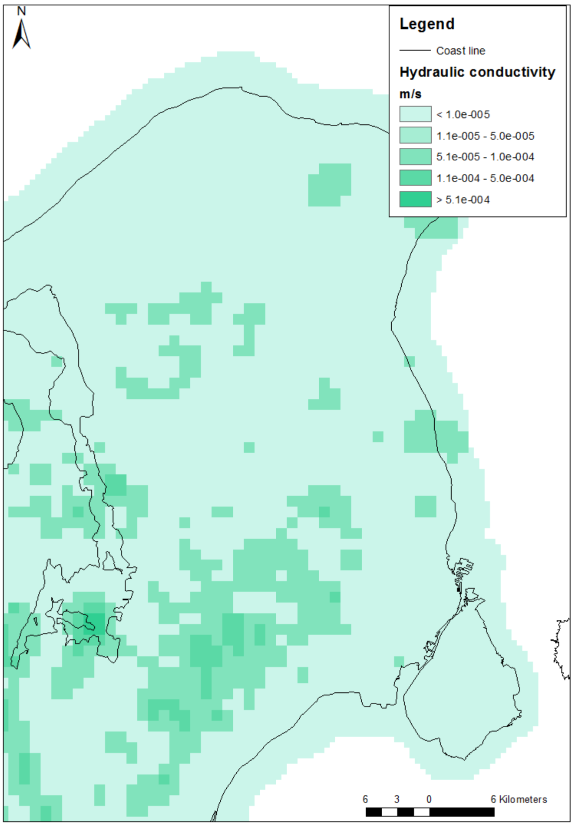


Figure 5.7: *Map of distributed hydraulic conductivity for the permeable limestone applied in the DK model. A hydraulic conductivity of* $1 \cdot 10^{-5}$ *m/s corresponds to approx. to a permeability of 1.4 Darcy (at 8 ℃).*

As part of the national groundwater mapping, the DK model has been updated with input from a number of more detailed local models. This is especially the case on Zealand and in the present screening of groundwater aspects, it has been found that relevant data from practically all available models, to the extent possible, have been integrated into the national model.

Thus the model offers an overall 3D representation of the hydrological circle in the study area down to about 100 m b. MSL and can therefore contribute with input regarding flow in the fresh water zone to the modelling carried out in the present HTES project.

However, the scale and the scope the DK model also results in some limitations e.g. in the representation of the very local hydrology at specific fault zones etc.

5.4 Existing groundwater maps

A number of thematic maps illustrating different local and regional groundwater issues within the project area has been compiled for different purposes. In the present context, the following maps are of special interest.

5.4.1 Maps of the hydraulic head (potentialekort)

Maps of the hydraulic head in specific aquifers (e.g. Fig. 5.8) have been compiled partly from synchronous soundings as a basis for different infrastructure and groundwater mapping projects in the greater Copenhagen area, (Rambøll 1995, Rambøll 1999, Dansk Geofysik 2000 and Region Hovedstanden 2009).

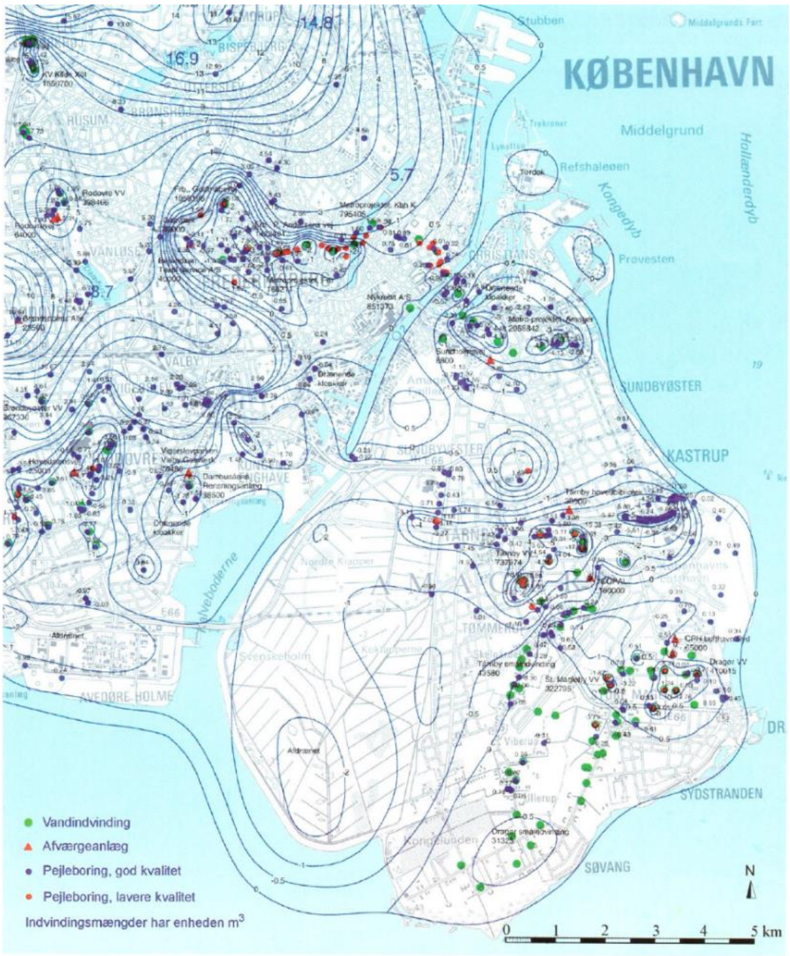


Figure 5.8: *Hydraulic heads in the limestone aquifer October 1999. (Rambøll 1999).*

The map presented in Fig. 5.8 clearly illustrates the effect of water abstraction for both consumption and constructional lowering of the groundwater table at the time of the sounding. The map gives a general indication of the direction of the groundwater flow in the limestone aquifer, but to evaluate groundwater flow in greater detail, local knowledge of the present water abstraction is needed.

5.4.2 Maps of the catchment areas

Maps of catchment areas have been compiled based on results from numeric flow models by the Environmental Protection Agency (former Nature Agency). They represent catchment areas for water works and larger well sites both inside and outside areas with specific groundwater interests.

5.4.3 Wells for water abstraction

Location, depth and geology of abstraction wells and the related purpose of the abstraction can be retrieved from the national borehole database (Jupiter) at GEUS. This information is important when evaluating local groundwater interests more specifically close to a potential storage site.

5.4.4 Maps of the transmissivity in the limestone aquifer

Beside the maps of distributed transmissivity and hydraulic conductivity applied in the DK model a more local map of the transmissivity in the limestone in Copenhagen has been compiled from a large number of well tests (Fig. 5.9); see also Markussen (2002). Considerable variations in the transmissivity are observed, and zones with enhanced transmissivity appear to be related to the NW-SE trending geological structural elements in the area.

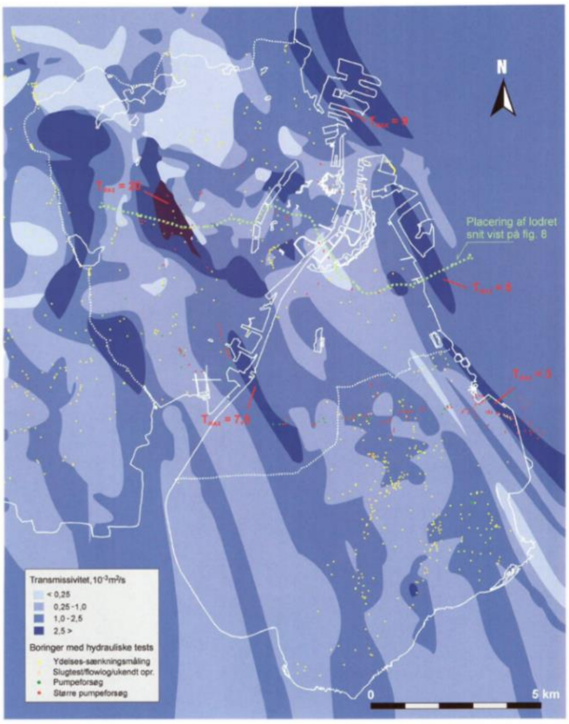


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Figure 5.9 *Detailed mapping of the transmissivity in the limestone in central Copenhagen (from Markussen 2002)*

Very high transmissivities characterize the carbonate deposits close to the Carlsberg Fault zone (Fig. 5.10). A depth scale is plotted to the left and right in the figure: Only the Quaternary and the uppermost c. 100 metres of the carbonate deposits are shown in the figure.

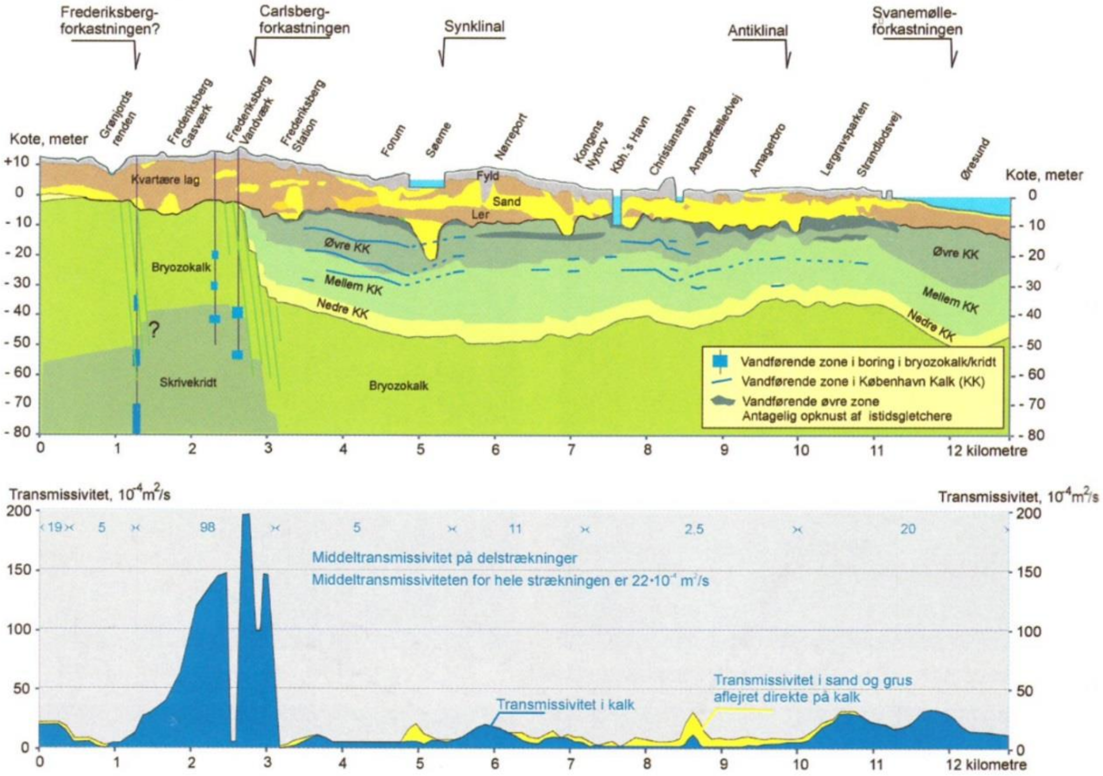

Figure 5.10: *Transmissivity in limestone (blue) and meltwater sand (yellow) in an east–west trajectory passing the Frederiksberg and Carlsberg Fault zones (from Markussen 2002).*

5.4.5 Water protection areas (OSD and OD)

As a basis for the national groundwater mapping program (cf. Thomsen et al. 2004), areas with specific groundwater interests (OSD) and areas with general groundwater interests (OD) have been designated. Based on the mapping results, specific and general protection measures are described in individual protection plans prepared by the municipalities. Commonly, the authorities approve plans for abstraction of groundwater on application. In general, it must be documented that the groundwater resources will not be affected, before the authorities can approve other activities in the subsurface.

As shown in Fig. 5.11, the major part of the HTES project area is assigned with special groundwater interest. West of the central Copenhagen and on the southeast of Amager, areas with general groundwater interests are designated. Only in the central harbour area and on western Amager a zone with limited groundwater interests is found.

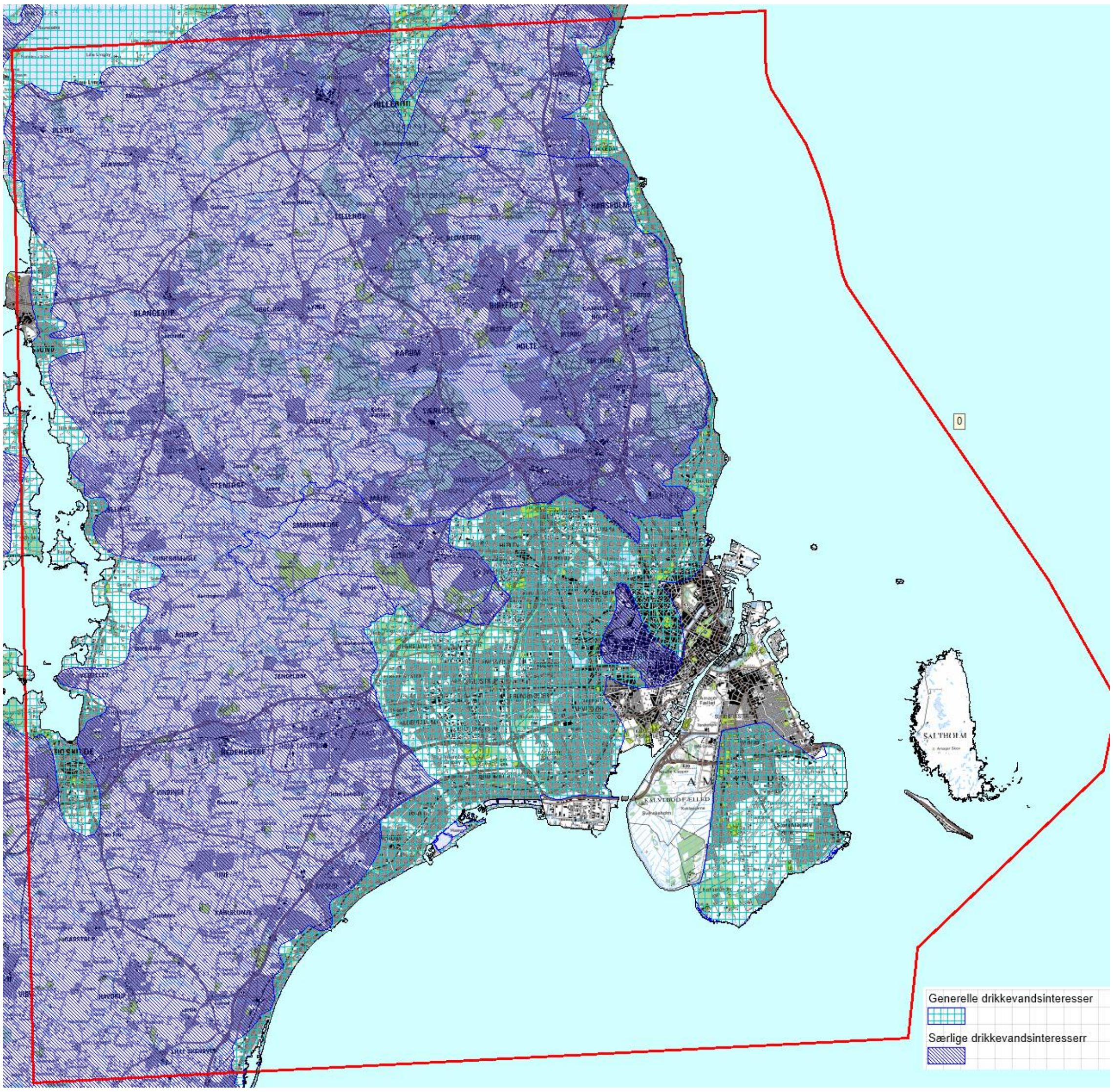

Figure 5.11: *Designated groundwater interests. Dark blue areas are with special groundwater interests. Light blue are with general groundwater interests.*

6. Reservoir parameters

The chalks and limestones are characterised by a number of reservoir parameters such as temperature, thermal properties, porosity and permeability. The variation in reservoir parameters depends e.g. on depth and the composition of the chalks and limestones. The degree of cementation also affects reservoir properties.

6.1 Formation temperature

The Formation temperatures in the depth range of 400-800 m are available from temperature measurements in two wells, Grøndalseng, Frederiksberg (DGU nr. 201.12) and Stenlille-1. Furthermore, at shallower depth temperature measurements have been carried out in two wells on Stevns, Stevns-1 (DGU nr. 218.1938) and Stevns-2 (DGU nr. 218.1945) with well depth of 456 m and 350 m, respectively, as well as one at Faxe (DGU nr. 217.724) with a well depth of 200 m. While drilling the well at Grøndalseng between the years 1894 and 1907, accurate temperature measurements were carried out as equilibrium bottom hole temperature at each 50 m in the interval 100 m – 850 m depth (Bonnesen et al. 1913). In the Stenlille-1 well, continuous high precision temperature logging using a quartz temperature measuring principle was acquired in 1986 (Balling et al. 1992).

In relation to groundwater investigations in the greater Copenhagen area, c. 60 shallow wells are temperature logged as part of the conventional geophysical wireline logging package. The majority of the wells are open holes within limestone and chalk sections, and internal water flow in the well between fractured zones at different level is expected to disturb the equilibrium temperature; thus, only the bottom temperature and selected temperatures at major inflow intervals are used (Møller et al. 2014).

The temperatures in the Grøndalseng well (DGU nr. 201.12) and the Stenlille-1 well are shown in Fig. 6.1 and Table 6.1. At 400 m the temperature is 17.0 °C in Grøndalseng and 16.1 °C in Stenlille-1, respectively and at 800 m 25.5 °C in Grøndalseng and 25.4 °C in Stenlille-1, respectively. The temperature gradient in the Chalk at the interval 100–800 m in the Grøndalseng well is 21.4 °C/km and at the interval 300–800 m in the Stenlille-1 well 23.0 °C/km.

Table 6.1
Temperatures at selected depths at the Grøndalseng and Stenlille-1 wells. The average temperature of the measurements from the two wells is used for the variation estimate.

Depth [metres below surface]	Temperature [°C]		
	Grøndalseng (DGU no. 201.12)	Stenlille-1	Average
100	10.5	9.8	10.2
200	12.8	11.9	12.4
300	14.8	13.9	14.4
400	17	16.1	16.6
500	19.1	18.4	18.8
600	21.1	20.7	20.9
700	23.5	23	23.3
800	25.5	25.4	25.5

Variations both in the bounding temperature at the ground surface and the temperature gradient can be expected. Variations related to the bounding temperature at ground surface and the quaternary overburden are examined using the temperature measurements in the shallow groundwater wells. The shallow temperature measurements, plotted in Fig. 6.1, show a variation of +/- 1.0 °C at about 80-120 m depth.

Temperature gradients of 20-25 °C/km are observed for the Chalk in several wells in Jutland and in the Stevns-2 well, whereas higher temperature gradients of 30-40 °C/km are observed in the Stevns-1 and the Faxe wells. There has not been found any reasons to believe that the measurements are corrupted in the Stevns-1 and Faxe wells. The anomalously high temperature gradients can be explained by either an extremely high porosity (>> 50 %) in the chalk (Fig. 6.2; Balling et al. 1981) and/or high content of clay influencing in the thermal conductivity or a local granite in the basement causing a locally higher heat flux.

Since the temperature gradients observed for the Chalk in the Grøndalseng and Stenlille-1 wells lies within the range of 20-25 °C/km; this temperature gradient expectedly also apply to the greater Copenhagen area.

Based on the temperature variation in 100 m depth (+/- 1.0 °C) and the temperature gradient variation in the interval of 20-25 °C/km, the temperature variation bars in Fig. 6.1 are constructed. The lower temperature range is given as the average temperature of Grøndalseng and the Stenlille-1 wells at 100 m depth - 1 °C. The temperatures in the depth interval 200–800 m are calculated using the low gradient of 20 °C/km. The upper temperature range is given as the average temperature of Grøndalseng and the Stenlille-1 wells at 100 m depth + 1 °C. The deeper temperatures are calculated using the high gradient of 25 °C/km.

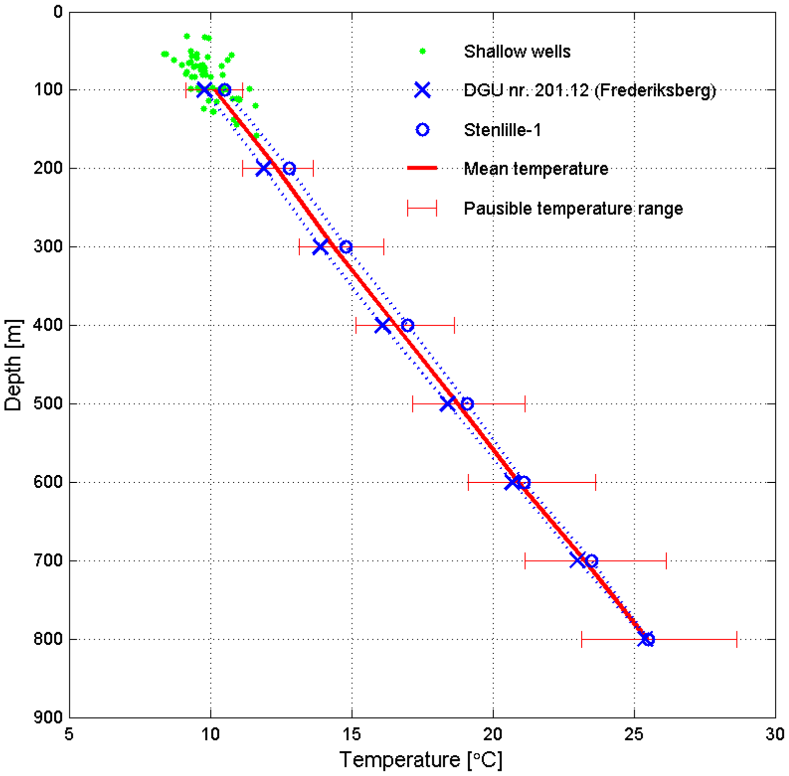

Figure 6.1: *Temperature versus depth based on data from Stenlille-1 and the Grøndalseng (Frederiksberg) wells. Data from these wells along with bottom temperatures form c. 60 shallow groundwater wells are used for temperature variation estimates.*

A linear temperature relation based on the least squares fit of the average temperatures of Grøndalseng and Stenlille-1 wells within 300–800 m depth interval is:

Temperature = 7.65°C + 22.2°C/km x Depth [km] and as a rough estimate with rounded values:

Temperature (on avg.) = 8°C + 22°C/km x Depth [km].

6.2 Thermal conductivity and heat capacity

Heat transport in the subsurface rocks is related primarily to three mechanisms: conduction, advection and hydrodynamic dispersion. The following paragraph on thermal conductivity in chalk has been prepared by Søren Erbs Poulsen (VIA-University Colleges) as part of the EUDP project: Mapping the Potential for Geological Heat Storage in Denmark (1887-0017).

6.2.1 Chalk and Limestone

The bulk thermal conductivity depends on the volumetric fractions of the individual constituents such as the mineral matrix, pore fluids and gasses. In the present case, it is assumed that the chalk is fully saturated with water such that the bulk sediment is a mix of two components: the mineral matrix and the pore fluid. The fractions of each are determined by the porosity of which the variation, for the studied depths and BHE lengths, must be taken into account. In this study, the geometric mean mixing law is applied (Woodside and Messmer, 1961):

$$\lambda(\varphi) = \lambda_f^{\varphi} \cdot \lambda_m^{(1-\varphi)}$$

λ, λ_f and λ_m are the bulk, fluid and matrix thermal conductivity, respectively [W m-1 K-1]; φ is the porosity. Bulk volumetric heat capacity (ρc) is calculated using an arithmetic average:

$$\rho c = \varphi(\rho c)_f + (1 - \varphi)(\rho c)_m$$

Balling et al. (1981) investigated the relation between the bulk thermal conductivity of the chalk and the porosity in the Danish area (Fig. 6.2).

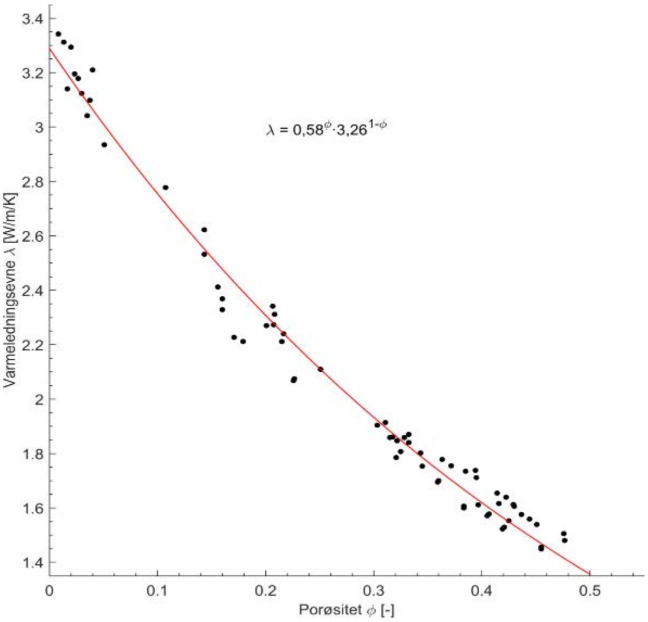

Figure 6.2: *Thermal conductivity vs. porosity in chalks and limestones. Balling et al. (1981) suggested this relationship between porosity and thermal conductivity.*

Lastly, in order to parameterize thermal conductivity and heat capacity, the relation between porosity ϕ and burial depth z must be specified. The relationship between ϕ and z is modelled by an exponential function (Athy, 1930):

$$\phi = \phi_0 e^{-kz}$$

ϕ_0 is the surface porosity and k is a formation specific parameter.

6.2.2 Thermal conductivity of Quaternary sediments

When modelling the progression of heat and possible effect on the shallow fresh water resources knowledge about the thermal properties of the upper, quaternary deposits is also relevant.

A general sensitivity study by Ditlefsen et al. (2016) has shown that the amount of heat transported by conduction is very sensitive to variation in the thermal conductivity within the range found in glacial sediments while variation in the specific heat capacity of theses sediments was shown to have limited effect on the heat transport.

Ditlefsen et al. (2014) investigated the thermal conductivity of common shallow Danish sediments through laboratory measurements. The thermal conductivity of different groups of sediments from this investigation is shown in Fig. 6.3

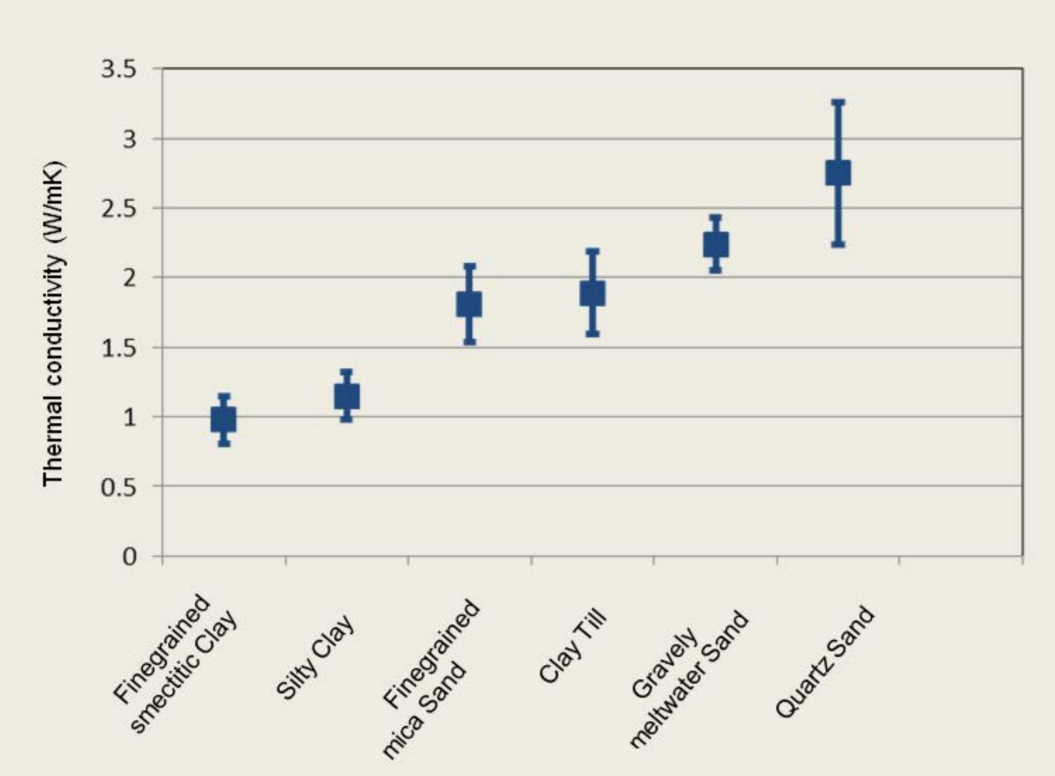

Figure 6.3: *Thermal conductivity of different groups of sediments. Ditlefsen et al. (2014)*

6.2.3 Heat capacity

Information about the heat capacity is needed for the reservoir simulation work. So far, a linear relationship between heat capacity and porosity is suggested, as illustrated below (Fig. 6.4). This relationship is expected to be valid for the storage zone (chalk/limestone aquifer).

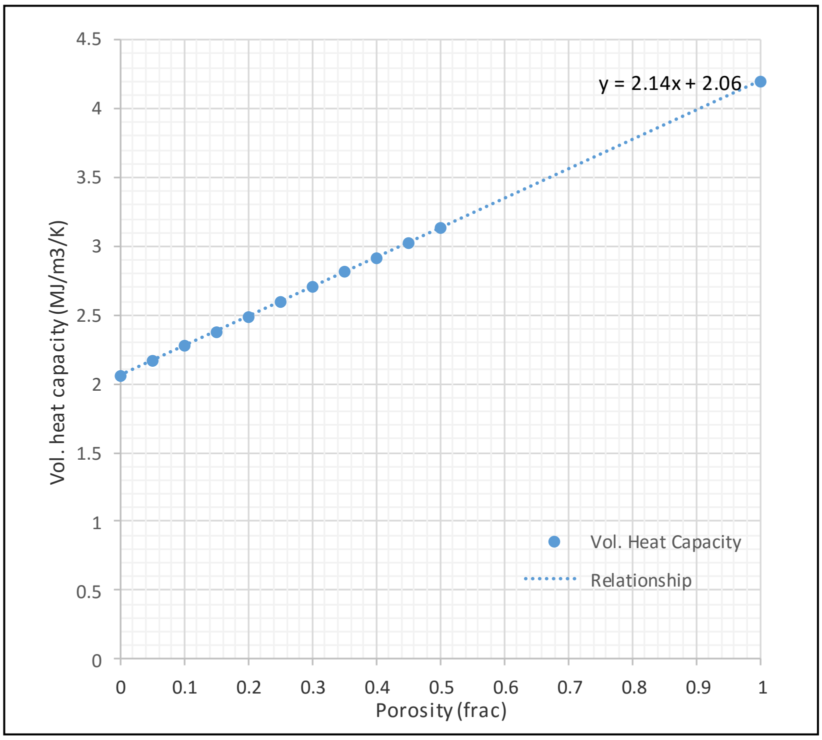

Figure 6.4: *Plot of Vol. heat capacity vs. porosity. This relationship is based a heat capacity for water of 4.20 MJ/m^3/K and for limestone: 2.06 MJ/m^3/K. The equation is listed in the figure*.

6.3 Publication on thermal properties onshore Denmark

In 2018, it is planned to submit a paper on temperature, thermal conductivity and heat flow properties onshore Denmark in the depth range 0–300 m. The results presented in the article are based on a compilation of thermal property data available from the Danish onshore area, and the article deals with:

- **Temperatures**. A number of temperature maps, showing interval temperatures, have been generated. The assigned depths are 50, 75, 100, 150, 200and 250 metres.
- **Thermal conductivity data**. The data compilation is referred to lithostratigraphic units.
- **Temperature gradients** and the distribution of temperature gradients throughout the Danish on-shore area. The work is based on data from *c.* 50 temperature logs. The chalk/ limestone section is treated separately.
- **Heat flow.** Regional estimates are prepared.

An article entitled ***'Shallow subsurface thermal structure onshore Denmark: temperature, thermal conductivity and heat flow'*** *by Ingelise Møller, Niels Balling and Claus Ditlefsen is intended for submission to Bulletin of The geological Society of Denmark. The abstract is presented below.*

Abstract

Information of shallow subsurface geothermal conditions is important for a number of applications including exploitation of shallow geothermal energy, heat storage and cooling as well as of general geoscience interest. Available measured temperatures and thermal conductivities covering Danish onshore areas to a depth of about 300 m have been compiled and analysed. Temperature data from about 50 boreholes, 100-300 m deep and thermal conductivities measured on samples collected at 31 well-characterized outcrops and on core material from 20 boreholes are included (Figure 6.5). Temperature gradients and thermal conductivities were grouped according to details of lithology over which they were measured.

Significant thermal variations are observed. At a depth of 100 m, temperatures vary between 7.5 and 12 °C and at 200 m, between 9 and 15 °C (Figure 6.6). Characteristic temperature gradients are in a range of 1 - 4 °C/100 m. Following Fourier's law of heat conduction (heat flow = thermal conductivity x temperature gradient) a correlation is observed between temperature gradients and thermal conductivities of different lithologies, and a regional estimate of characteristic shallow heat flow in Denmark is obtained. Quartz-rich sand deposits (high thermal conductivity) show low temperature gradients, chalk and limestone intermediate gradients (Figure 6.7) and almost pure clay (low thermal conductivity) high gradients. Mean thermal conductivities range between 0.6 and 6 W/mK. An estimated regional heat flow of about 37 mW/m^2 is in good agreement with local, classically determined heat-flow values from shallow borehole data. Due to long-term palaeoclimatic effect, this value is significantly below deep background heat flow.

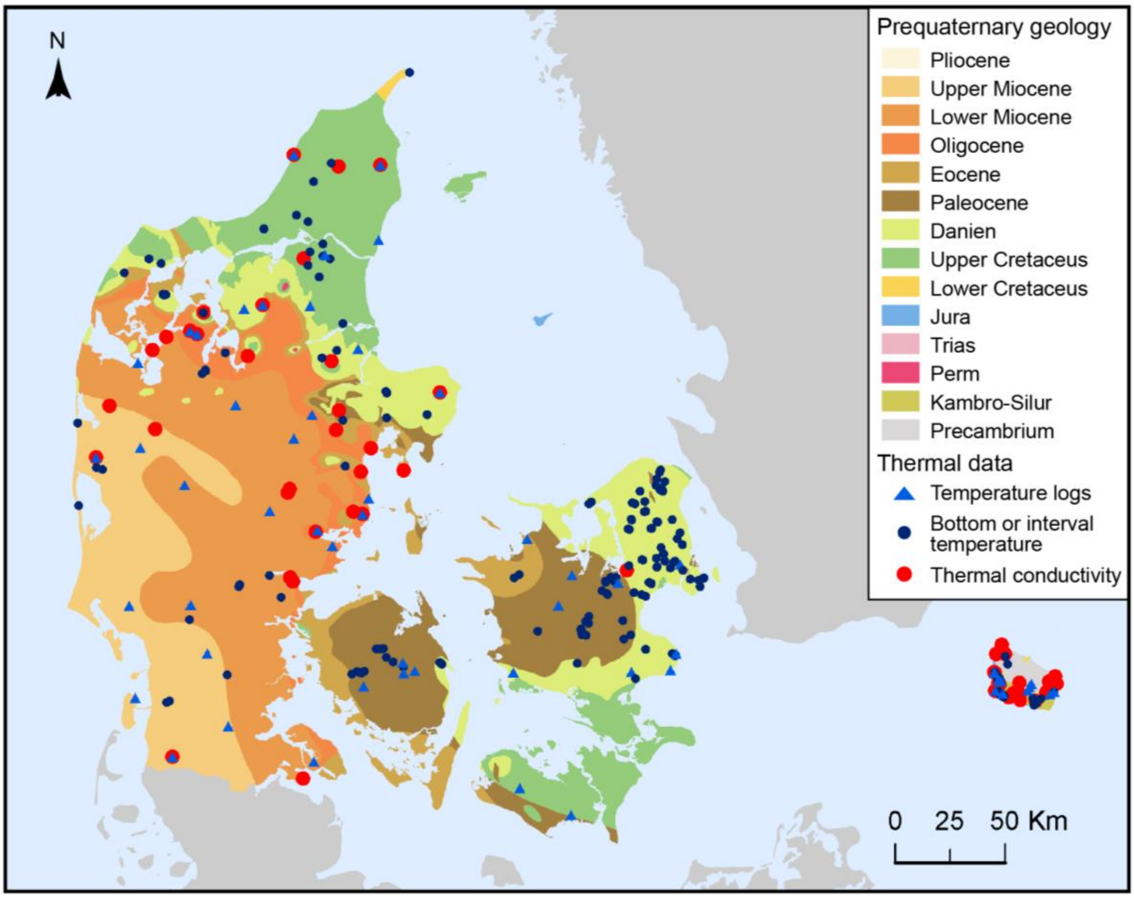

Figure 6.5: Location of boreholes with temperature logs, bottom and interval temperatures and sample locations for thermal conductivity measurements.

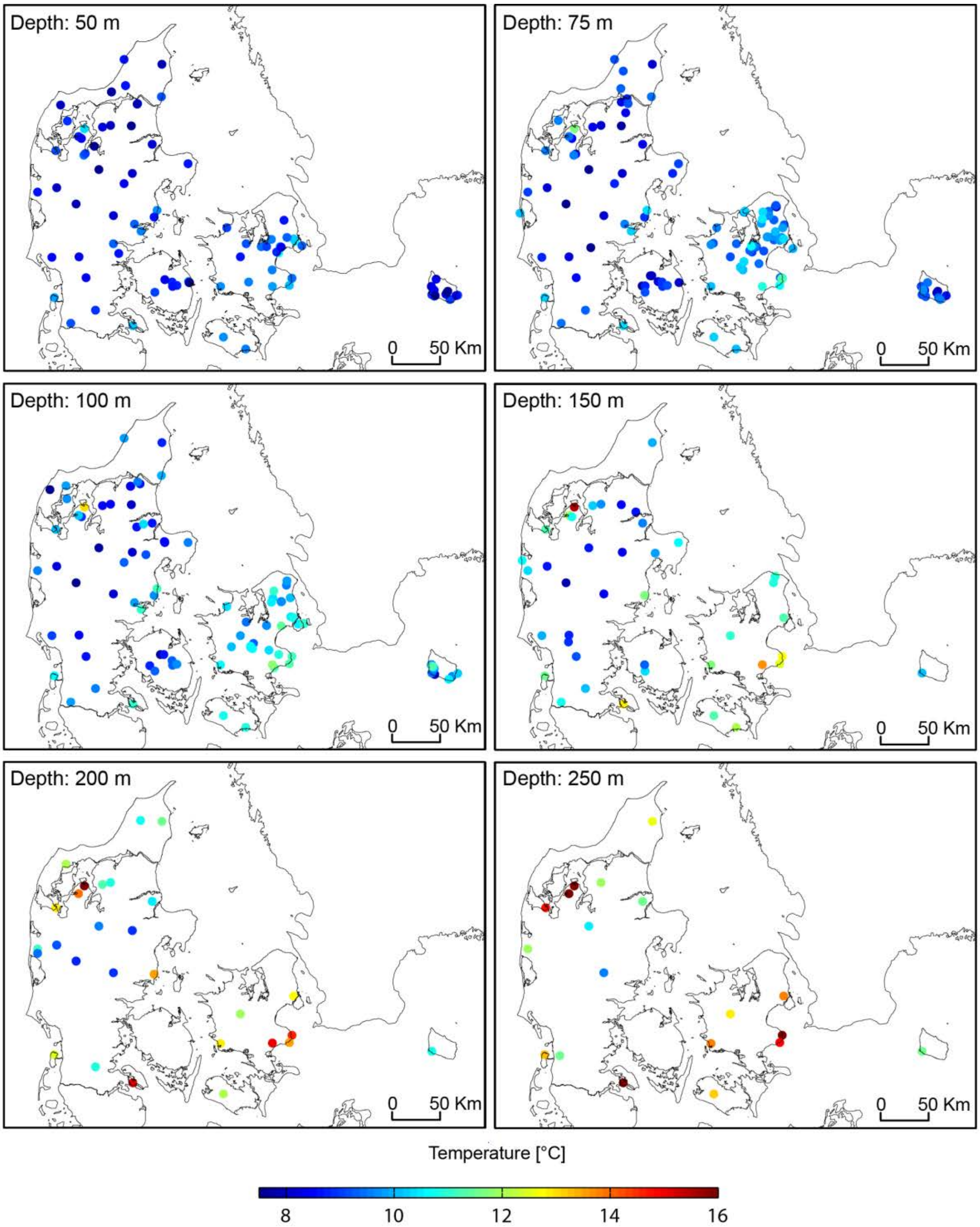

Figure 6.6: Temperature distribution in 6 depth intervals. The interval width of 25 m is centered around the depth displayed on the map.

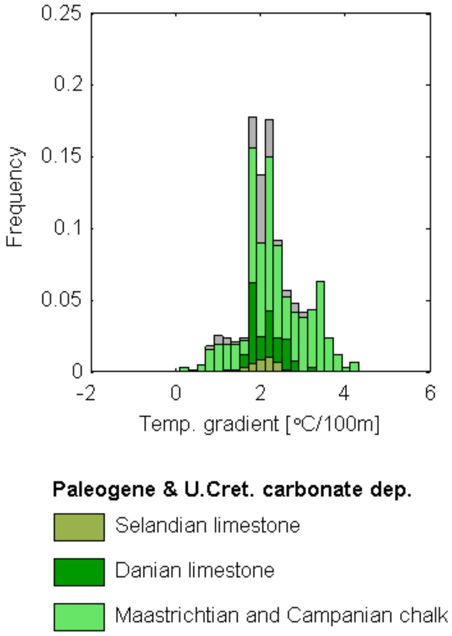

Figure 6.7:Temperature gradients for limestone and chalk deposits estimated over 20 m interval on continuous temperature logs and related to the lithostratigraphical unit over which measured.

6.4 Porosity

The porosity is an important reservoir parameter when addressing the storage potential. Information about the porosity of the chalks and limestones is available from logs and conventional core analysis data from several wells within the greater Copenhagen area. Core porosity data from the chalk section are available from **Stevns-1** (Sigerslev, Rørdal, Hvidskud, Boesdal and Flagbanke Mbs), **Karslunde-1** (Sigerslev, Rørdal and Hvidskud Mbs) and **Tuba-13** (Sigerslev Mb). The conventional core analysis data from the Stevns-1 and Karlslunde-1 wells are published in Bonnesen et al. (2009). The Tuba-13 data form part of the present HTES study and are analysed by the GEUS Core Analysis Laboratory in 2017.

Outside the cored intervals, well-log data provide information about the porosity distribution. Sonic log data are acquired in Stenlille-1, Margretheholm-1, Stevns-1 and the Swedish Höllviksnäs-1 well. In Margretheholm-1, the interval 700–1600 m also includes a density log suitable for calibrating the sonic log porosities, since the density log readings can fairly easily be transformed into porosities. Similarly, the core porosity data have been used for calibrating the sonic log porosities. The sonic porosities are estimated using the Wyllie Equation. The calibration data point to a ‘transit time compaction factor’ of 1.5 – this factor is in line with the rather shallow depth of the chalk section.

The well-log and core data indicate that chalk porosities are generally high or even very high (20-45%). As previously described, GEUS performed a well-to-well correlation of the borehole logs, and the log correlation provides information about the lateral porosity distribution. When combining the log and seismic interpretations, it may be possible to map units with high porosity.

6.5 Permeability

No permeability logs are acquired in the wells, but information about the matrix permeability is available from conventional core analysis data from Stevns-1, Karlslunde-1 and Tuba-13. The chalk matrix permeability is generally low or even very low, i.e. in the order of 1-10 mD.

The access to core analysis data makes it possible to establish a porosity-permeability relationship, as illustrated in the poro-perm plot below (Fig. 6.8). This plot is based on an analysis of small plug samples, but a good indication of the matrix permeability for a given porosity value is, nevertheless, obtained. When using this plot, it is possible to relate a log-derived porosity to a matrix permeability estimate as illustrated by the trend line. Such a permeability estimate is associated with uncertainty, because the correlation between porosity and permeability is not perfect, cf. the rather scattered datasets seen in the figure.

However, a permeability derived from a poro-perm plot does not equal the reservoir permeability (or the effective permeability), as the presence of fractures is not taken into account. Primarily the permeability determines the flow in the chalk, and well stimulation is recommended with the objective to increase the effective permeability considerably.

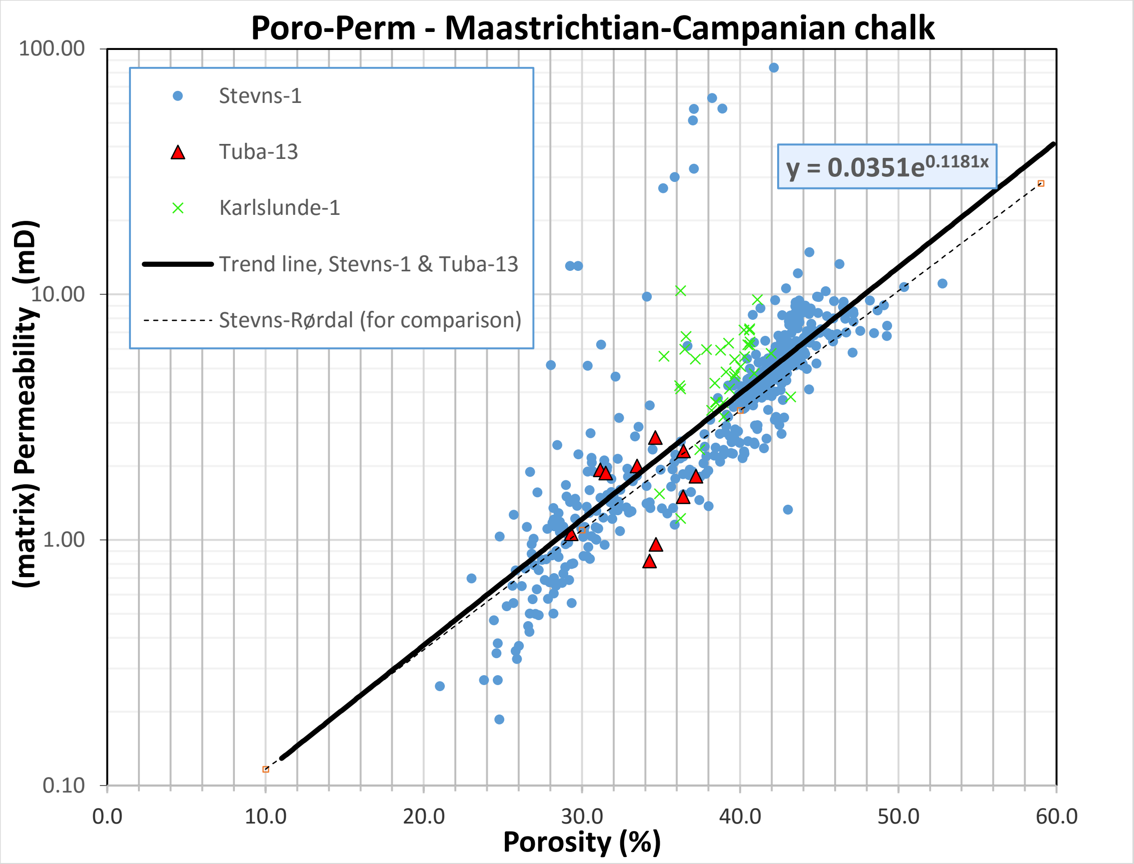

Figure 6.8: *Porosity-Permeability plot for the Maastrichtian-Campanian chalk in Stevns-1, Tuba-13 and Karlslunde-1. Based on conventional core analysis data (CCAL), i.e. core porosity data and matrix permeabilities measured on plug samples.*

6.6 Well plots and list of reservoir parameters

The well plots include lithostatigraphic subdivision, lithology (carbonate and shale), cored intervals, raw logs and the effective porosity as interpreted from the sonic and gamma-ray logs (Fig. 6.9 – 6.15). The reservoir parameters are averaged with respect to each lithostatigraphic unit, and the reservoir parameters are listed in tables (Tables 6.1 – 6.6). The tables list formation tops, unit thicknesses, porosity, matrix permeability, effective permeability estimates, formation temperature, thermal conductivity, heat capacity and rock density.

6.7 Geochemical reactions and carbonate precipitation

Periodical heating of groundwater (formation water), along with injection and storage in a chalk aquifer, may lead to geochemical reactions in the rock-water system. The planned use of the chalk aquifer for thermal energy storage in the Copenhagen area may lead to changes of the carbonate equilibrium, possibly initiating precipitation and dissolution processes (Griffeoen & Appelo 1993). Such processes may have a negative effect on operating the heat storage system. Thus, the challenge is to mitigate the effects by controlling carbonate equilibrium, e.g. by implementing a water treatment system that can remove mainly Calcium (Ca^{++}) from the injection water. During summertime, rather cold formation water is produced from the chalk aquifer and most likely, the produced water is saturated with respect to calcite ($CaCO_3$). Upon heating the water in the heat exchanger, the water will become supersaturated with calcite when the temperature is elevated (calcite is more soluble in cold water). Throughout the subsequent injection process, there is a potential risk of clogging the perforations and a risk of carbonate precipitation within the pore space, because the warm and supersaturated water replaces the initial water in the chalk aquifer. Repeated charging and withdrawal of water from the storage aquifer intensifies the problem of carbonate precipitation, as the concentration of Ca^{++} increases during these repeated processes.

Calcite is thus likely to precipitate due to heating of groundwater during the cycles of aquifer thermal energy storage. Therefore, water treatment is most likely needed, e.g. ion exchange or addition of acid, in order to prevent clogging of the heating facilities including the injection well (Sanner, 1999). The exact composition of the precipitate may differ from that of pure calcite due to the presence of cations such as iron, magnesium and manganese. Furthermore, the exact environment of precipitate formation is difficult to judge from thermodynamic consideration alone (Griffeoen & Appelo 1993). Therefore, investigations related to the specific location of the HTES plant, groundwater chemistry and aquifer type would be needed in order to prevent clogging, carbonate precipitation and mineral deposition (scaling) at the Copenhagen site.

The challenge is to design an optimal water treatment procedure that can handle the circulating water before it enters the heat exchanger, i.e. a pre-processing unit should be added to the system. The overall objective is removal of cations, but also particle removal is essential. GEUS recommends considering application of advanced filter technology, use of ion exchangers, addition of acids to lower pH, and addition of scaling inhibitors. Furthermore, the HTES system should be kept pressurized to prevent degassing. The final design of an appropriate water treatment programme is to be set up in Phase 2; detailed information about the composition of the formation brine is needed prior to designing the water treatment programme.

Operating the heat storage involves cyclic heating and cooling of the chalk aquifer. Laboratory experiments on chalk samples suggest that the mechanical strength of the chalk reservoir rock decreases as consequence of repeated heating and cooling (Voake et al., in prep.). GEUS recommends conducting additional geotechnical testing of the reservoir chalk, both in-situ and in the laboratory.

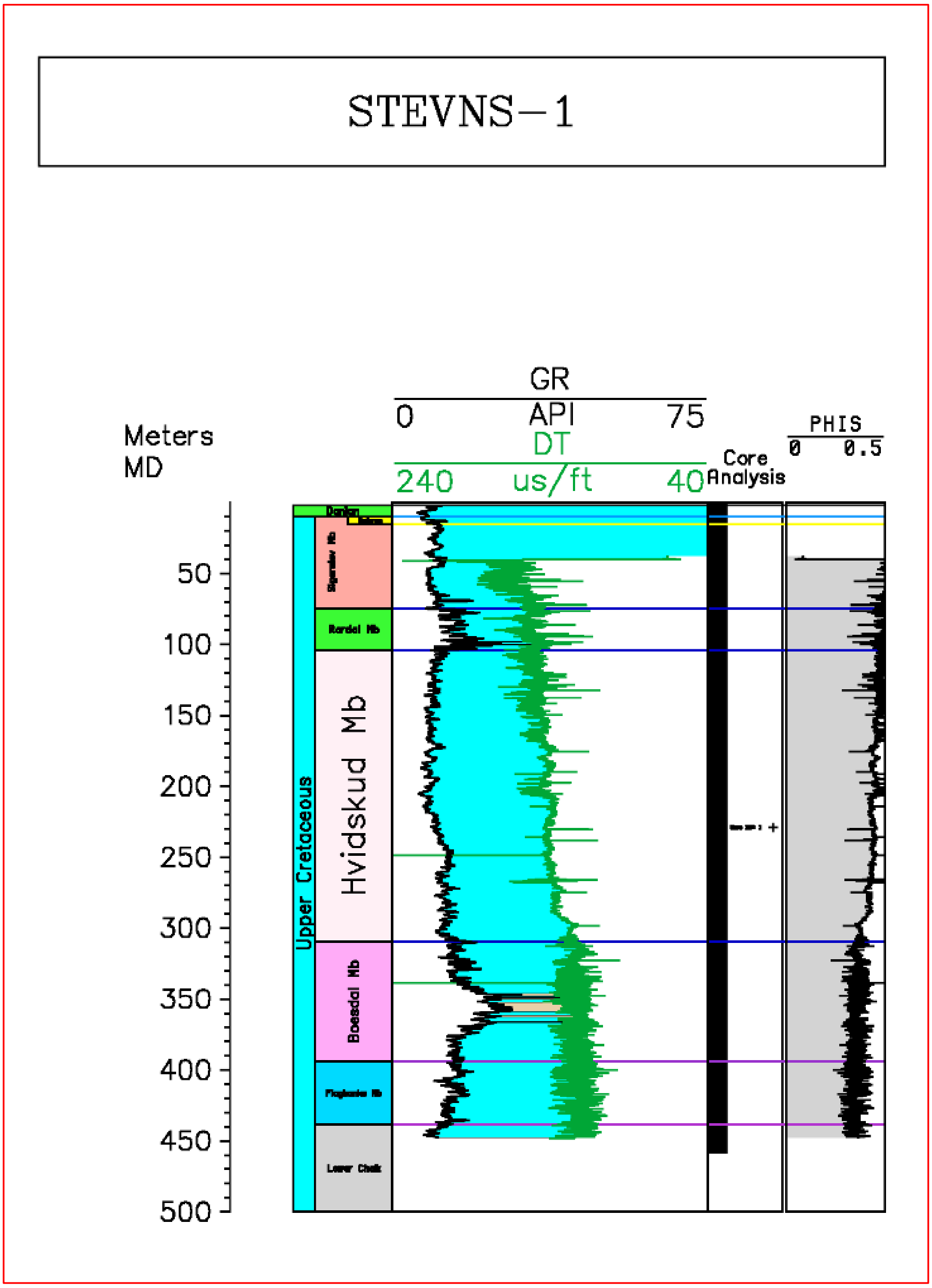

Figure 6.9: *Lithostratigraphic subdivision and petrophysical interpretation of the Stevns-1 well. GR: Gamma-ray log. DT: Sonic log. Cores and core analysis data are available (the black bar indicates the cored interval). PHIS: Interpreted porosity, the porosity interpretation is based on a combined use of sonic log data and core porosity data. The DT log quality is rather poor. The base chalk surface has not been penetrated in the well.*

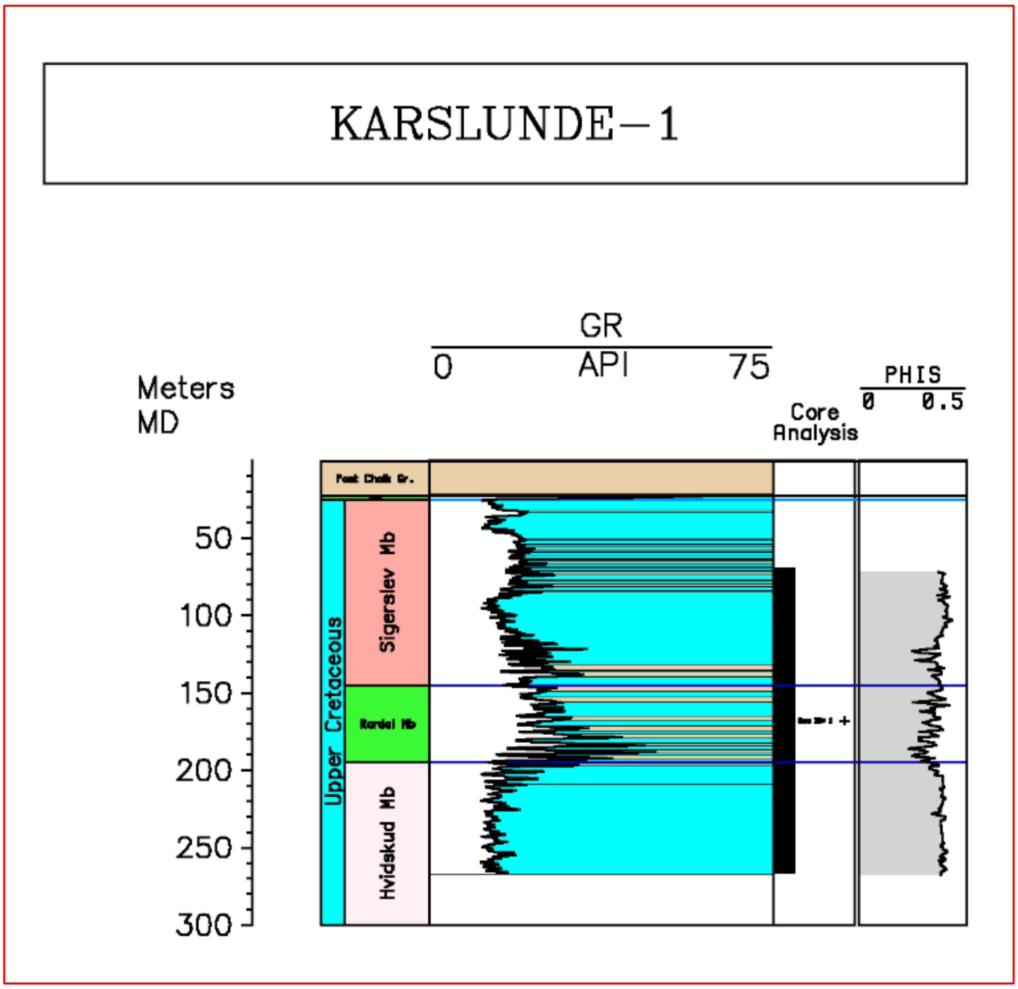

Figure 6.10: *Lithostratigraphic subdivision and petrophysical interpretation of the Karlslunde-1 well. GR: Gamma-ray log. Cores and core analysis data are available (the black bar indicates the cores interval). PHIS: Interpreted porosity, the porosity interpretation is based on information from core porosity data. A sonic (DT) log is not available from this well. The Hvidskud Member is only partly drilled; the base chalk surface has thus not been penetrated in the well.*

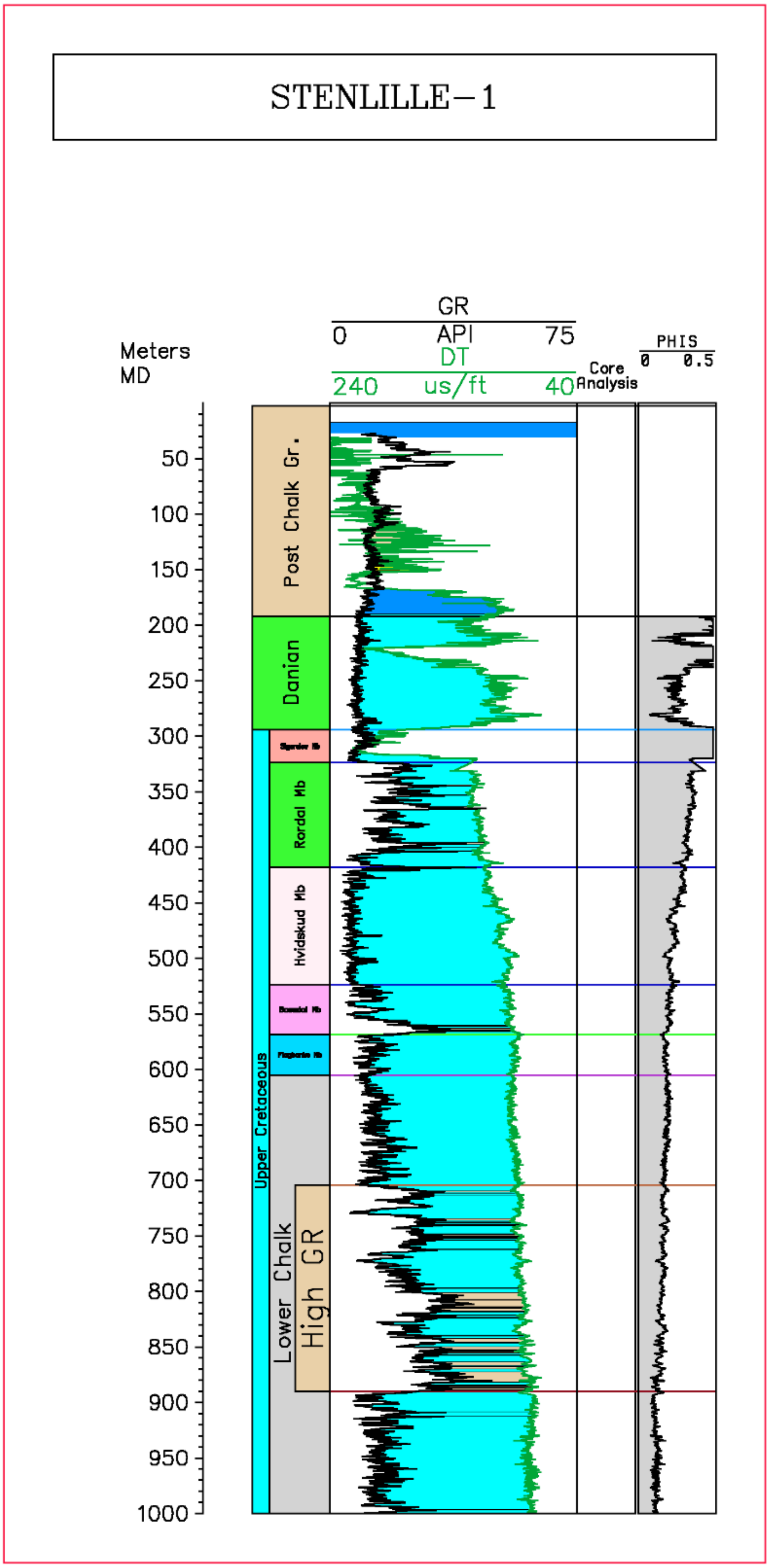

Figure 6.11: *Lithostratigraphic subdivision and petrophysical interpretation of the Stenlille-1 well. PHIS: Sonic log porosity. GR: Gamma-ray log. DT: Sonic log. The thickness of the chalk and limestone sections is 1008 m, base chalk at 1200 mMD (not shown).*

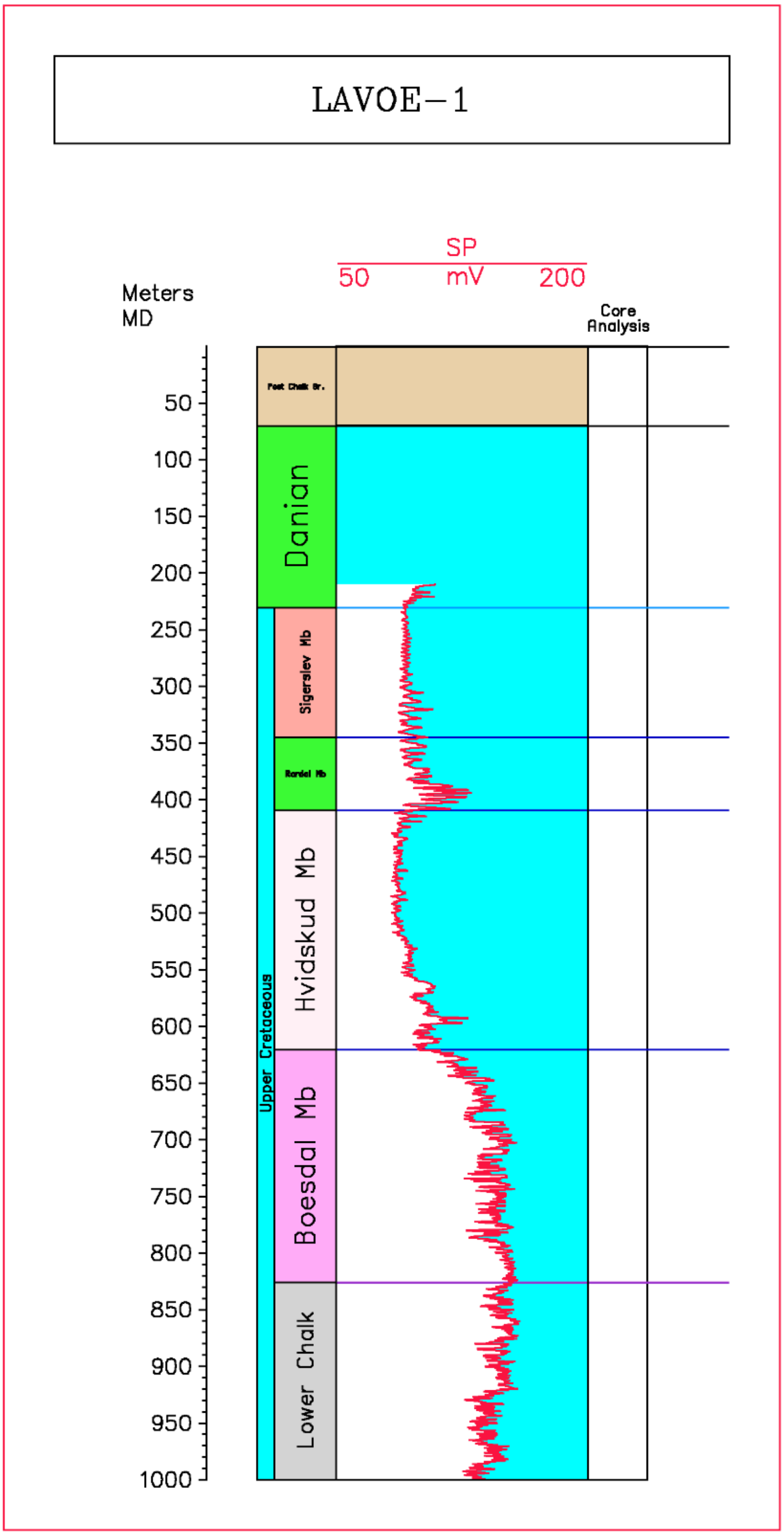

Figure 6.12: *Lithostratigraphic subdivision of the Lavø-1 well. SP: spontaneous Potential. A porosity interpretation of the chalk and limestone sections is not possible in this well due to incomplete log suite. The thickness of the chalk and limestone sections is 1873 m, base chalk at 1943 mMD (not shown).*

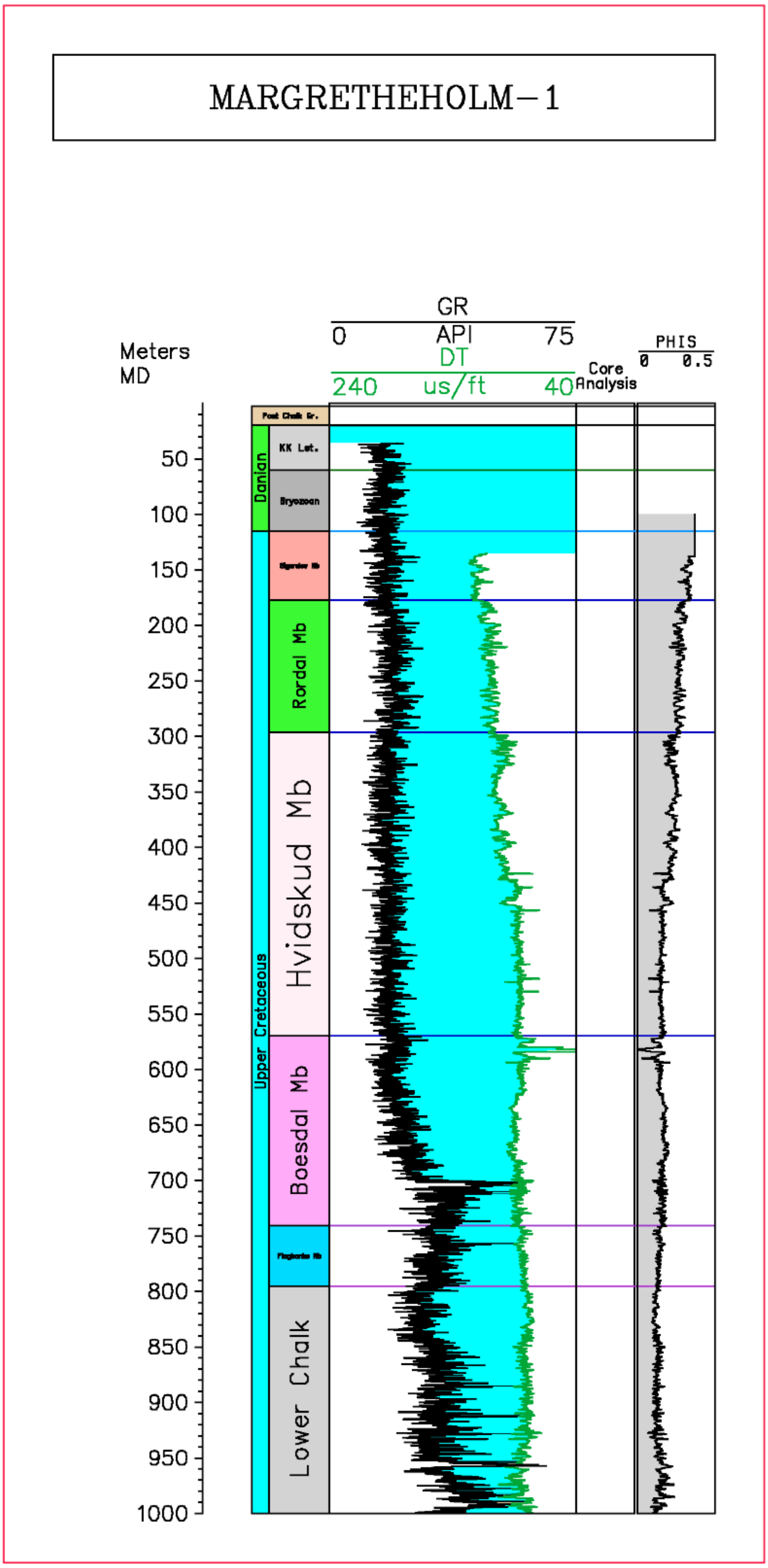

Figure 6.13: *Lithostratigraphic subdivision and petrophysical interpretation of the Margretheholm-1 well. PHIS: Sonic log porosity. GR: Gamma-ray log. DT: Sonic log. The thickness of the chalk and limestone sections is 1580 m, base chalk at 1600 mMD (not shown).*

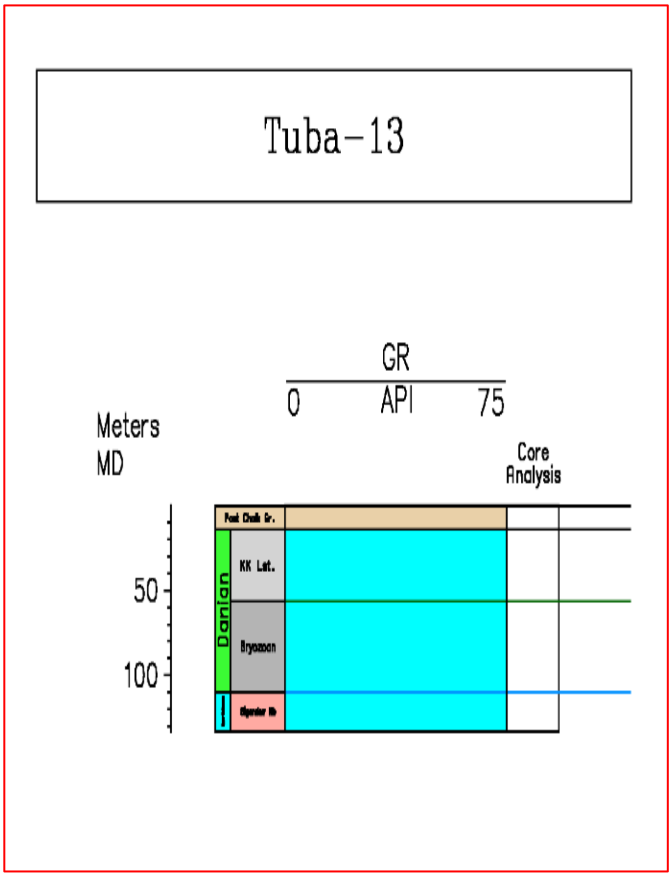

Figure 6.14: *Lithostratigraphic subdivision of the Tuba-13 well located close to the Copenhagen central station. The well was cored, but not logged. The Danian limestone is subdivided into København Limestone (upper) and Bryozoan Limestone (lower). With respect to the Maastrichtian chalk, only the upper part of the Sigerslev Member has been drilled. The subdivision of the chalk and limestone sections into into København Limestone, Bryozoan Limestone and Maastrichtian chalk is based on data from Stenestand (1976). The base chalk surface has not been penetrated.*

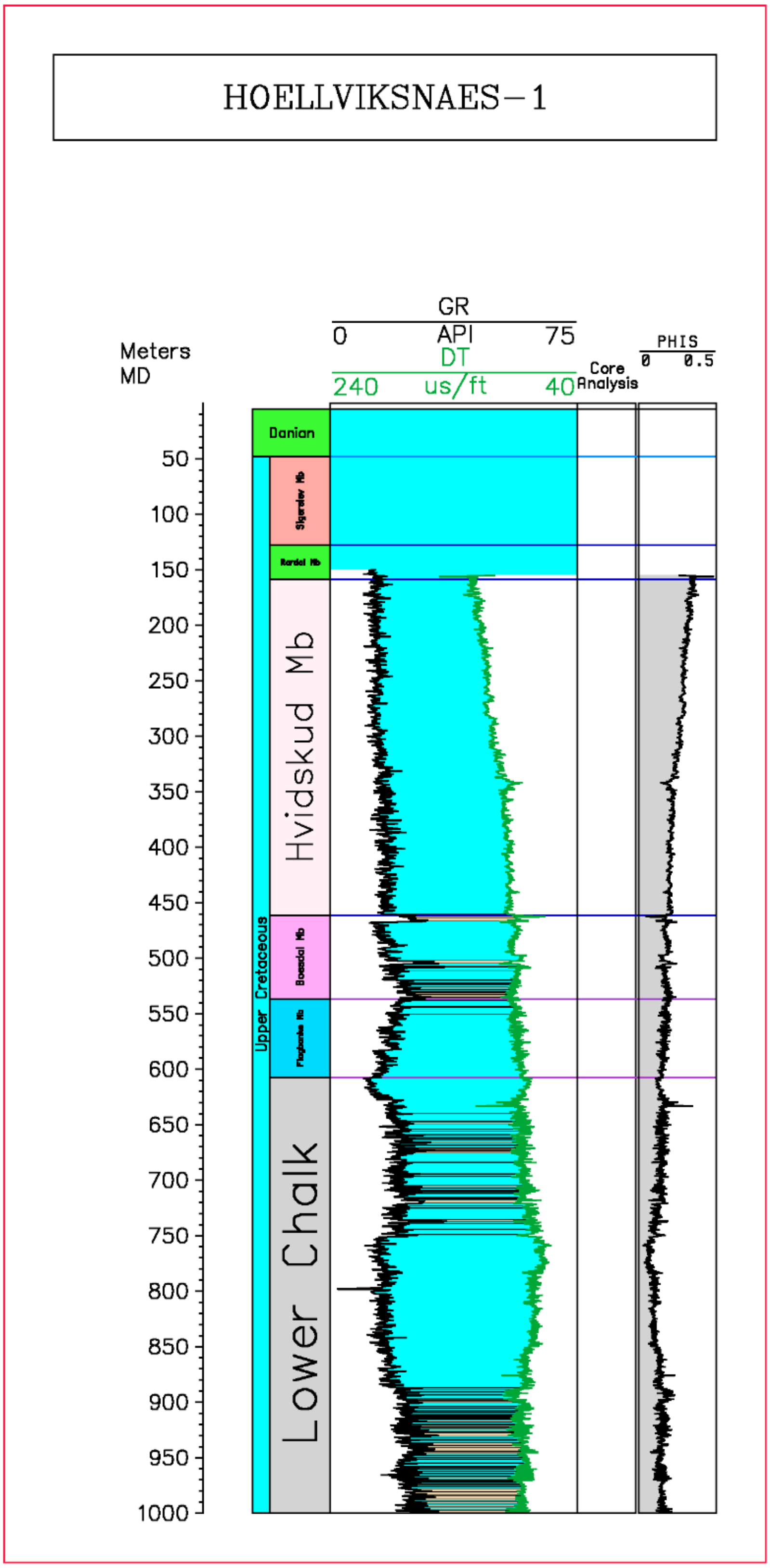

Figure 6.15: *Lithostratigraphic subdivision and petrophysical interpretation of the Höllviksnäs-1 well, Sweden. PHIS: Sonic log porosity. GR: Gamma-ray log. DT: Sonic log. The thickness of the chalk and limestone sections is 1197 m, base chalk at 1198 mMD (not shown).*

Table 6.1 Well: Stevns-1

	Units	Top	Base	Thick-ness	Top	Base	Po-rosity	Perm (mD)	
Stevns-1		mMD	mMD	(m)	b.MSL	b.MSL	(%)	Matrix	Eff.
Quaternary	Quaternary undiff.	0	1	1	-38	-37	N/A	N/A	N/A
DANIAN	Danian limestone	1	10	9	-37	-28	N/A	N/A	N/A
DANIAN									
MAASTR.	Højerup Mb	10	15	5	-28	-23	N/A	N/A	N/A
MAASTR.	Sigerslev Mb	15	76	61	-23	38	48	10	70
MAASTR.	Rørdal Mb	76	105	29	38	67	45	5	25
MAASTR.	Hvidskud Mb	105	309	204	67	271	43	5	20
MAASTR.	Boesdal Mb	309	394	85	271	356	35	2	6
CAMP.	Flagbanke Mb	394	438	44	356	400	30	1	3
L.Chalk	Lower Chalk unit	438	500	62	400	462			

Stevns-1		Temperature*	Thermal	vol.Heat	Rock
		mid unit	cond.	capacity	density
	Units	deg.C	(W/m/K)	(MJ/m3/K)	g/cc
Quaternary	Quaternary undiff		2	unknown	2.5
DANIAN	Danian limestone		unknown	unknown	2.6
MAASTR.	Højerup Mb		unknown	unknown	2.7
MAASTR.	Sigerslev Mb	9.4	1.42	3.1	2.7
MAASTR.	Rørdal Mb	10.9	1.50	3.0	2.7
MAASTR.	Hvidskud Mb	14.8	1.55	3.0	2.7
MAASTR.	Boesdal Mb	19.7	1.78	2.8	2.7
CAMP.	Flagbanke Mb	21.6	1.94	2.7	2.7
L.Chalk	Lower Chalk unit	22.9			

*Temperatures based on measured values (i.e. a temperature log): The formation temperature corresponds approximately to: Temperature (on avg.) = 8°C + 32°C/km x Depth[km].

Table 6.2 Well: Karslunde-1

									Estimated
Karslunde-1		Top	Base	Thick-ness	Top	Base	Po-rosity	matrix	Effective
	Units	m MD	m MD	(m)	below MSL	below MSL	(%)	Perm (mD)	Perm (mD)
Quaternary	Quaternary undiff	0	23	23	-3	20	N/A	unknown	unknown
DANIAN	Danian limestone	23	26	3	20	23	N/A	unknown	unknown
MAASTR.	Sigerslev Mb	26	145	119	23	142	38	3	25
MAASTR.	Rørdal Mb	145	197	52	142	194	33	2	10
MAASTR.	Hvidskud Mb	197	500	303	194	497	38	3	8
MAASTR.	Hansa Mb	Not drilled							
CAMP.	Flagbanke Mb	Not drilled							

		Temp.*	Thermal	vol.Heat	Rock
	Units	mid unit	cond.	capacity	density
Karslunde-1		deg.C	(W/m/K)	(MJ/m3/K)	g/cc
Quaternary	Quaternary undiff	8.3	2	unknown	2.5
DANIAN	Danian limestone	8.5	unknown	unknown	2.6
MAASTR.	Sigerslev Mb	9.9	1.69	2.9	2.7
MAASTR.	Rørdal Mb	11.8	1.84	2.8	2.7
MAASTR.	Hvidskud Mb	15.7	1.69	2.9	2.7
MAASTR.	Hansa Mb				
CAMP.	Flagbanke Mb				

*Temperatures based on: Temperature (on avg.) = 8°C + 22°C/km x Depth[km].

Table 6.3 Well: Stenlille-1

									Estimated
	Units	Top	Base	Thick- ness	Top	Base	Po- rosity	Matrix	Effective
Stenlille-1		mMD	mMD	(m)	below MSL	below MSL	(%)	Perm (mD)	Perm (mD)
Quaternary	Quaternary undiff	0	192	192	-41	151			
DANIAN	Danian lime- stone	192	294	102	151	253	33	4	unknown
DANIAN									
MAASTR.	Sigerslev Mb	294	323	29	253	282	45	9.1	70
MAASTR.	Rørdal Mb	323	417	94	282	376	30	1.7	10
MAASTR.	Hvidskud Mb	417	523	106	376	482	24	0.6	3
MAASTR.	Boesdal Mb	523	568	45	482	527	20	0.4	2
CAMP.	Flagbanke Mb	568	605	37	527	564	18	0.3	1
L. Chalk	Lower Chalk unit	605	1200	595	564	1159			
L. CRET	Lower Creta- ceous unit	1200	1247	47	1159	1206			
Fjerritslev Fm	Upper Jurassic Unit	1247	1368	121	1206	1327			
Fjerritslev Fm	Lower Jurassic Unit	1368	1507	139	1327	1466			
TRIASSIC	Gassum Fm	1507	1651	144	1466	1610			
TRIASSIC	Bunter Sst. Fm	not drilled							
L. Chalk	*High GR unit*	*704*	*890*	*186*	*663*	*849*			

		Temp.*	Thermal	vol.Heat	Rock
Stenlille-1		mid unit	cond.	capacity	density
	Units	deg.C.	(W/m/K)	(MJ/m3/K)	g/cc
Quaternary	Quaternary undiff	9.7	2	unknown	2.5
DANIAN	Danian limestone	12.8	1.84	2.8	2.6
MAASTR.	Sigerslev Mb	14.1	1.50	3.0	2.7
MAASTR.	Rørdal Mb	15.5	1.94	2.7	2.7
MAASTR.	Hvidskud Mb	17.7	2.15	2.6	2.7
MAASTR.	Boesdal Mb	19.5	2.31	2.5	2.7
CAMP.	Flagbanke Mb	20.4	2.39	2.4	2.7
L. Chalk	Lower Chalk unit	27.9			
L. CRET	Lower Cretaceous unit	36.7			
Fjerritslev Fm	Upper Jurassic Unit	41.0			
Fjerritslev Fm	Lower Jurassic Unit				
TRIASSIC	Gassum Fm				
TRIASSIC	Bunter Sst. Fm				

*Temperatures based on interpolation of measured values; a temperature log with a discrete measurement for each 100 m is available in depth range 100–1300 m: The formation temperature corresponds approximately to: Temperature (on avg.) = 8°C + 23°C/km x Depth[km].

Table 6.4 Well: Margretheholm-1

									Estimated
	Units	Top	Base	Thickness	Top	Base	Porosity	matrix	Effective
Margretheholm-1		mMD	mMD	(m)	below MSL	below MSL	(%)	Perm (mD)	Perm (mD)
Quaternary	Quaternary undiff	0	20	20	-10	10			
DANIAN	København lst.	20	60	40	10	50	40	35	100
DANIAN	Bryozoan lst.	60	120	60	50	110	38	30	100
MAASTR.	Sigerslev Mb	120	177	57	110	167	34	1.8	10
MAASTR.	Rørdal Mb	177	296	119	167	286	27	1.0	5
MAASTR.	Hvidskud Mb	296	570	274	286	560	20	0.5	2
MAASTR.	Boesdal Mb (+Hansa Mb)	570	740	170	560	730	16	0.3	1
CAMP.	Flagbanke Mb	740	795	55	730	785	14	0.2	1
L. Chalk	Lower Chalk unit	795	1600	805	785	1590			
	Lunda Sandstone Eqv.	*900*	*910*	*10*	*890*	*900*			
	Sandy chalk	*950*	*1000*	*50*	*940*	*990*			
L. CRET.	Lower Cretaceous unit	1600	1644	44	1590	1634			
Fjerritslev Fm	Upper Jurassic Unit	1644	1713	69	1634	1703			
Fjerritslev Fm	Lower Jurassic Unit	1713	1842	129	1703	1832			
TRIASSIC	Gassum Fm	1842	2025	183	1832	2015			
TRIASSIC	Bunter Sst. Fm	2368	2659	291	2358	2649			

	Units	Temp.	Thermal	vol.Heat	Rock
		mid unit	cond.	capacity	density
Margretheholm-1		deg.C	(W/m/K)	(MJ/m3/K)	g/cc
Quaternary	Quaternary undiff	8.2	2	unknown	2.5
DANIAN	København limestone	8.9	1.63	2.9	2.6
DANIAN	Bryozoan limestone	10.0	1.69	2.9	2.6
MAASTR.	Sigerslev Mb	11.3	1.81	2.8	2.7
MAASTR.	Rørdal Mb	13.2	2.05	2.6	2.7
MAASTR.	Hvidskud Mb	17.5	2.31	2.5	2.7
MAASTR.	Boesdal Mb (+Hansa Mb)	22.4	2.47	2.4	2.7
CAMP.	Flagbanke Mb	24.9	2.56	2.4	2.7
L. Chalk	Lower Chalk unit	(37)			
	Lunda Sandstone Eqv.				
	Sandy chalk				
L. CRET	Lower Cretaceous unit				
Fjerritslev Fm	Upper Jurassic Unit				
Fjerritslev Fm	Lower Jurassic Unit				
TRIASSIC	Gassum Fm				
TRIASSIC	Bunter Sst. Fm	73.4			

*Temperatures in the chalk section are based on: Temperature (on avg.) = 8°C + 22°C/km x Depth[km].

Table 6.5 Well: Tuba-13

									Estimated
	Units	Top	Base	Thick-ness	Top	Base	Po-rosity	matrix	Effective
Tuba-13		mMD	mMD	(m)	below MSL	below MSL	(%)	Perm (mD)	Perm (mD)
Quaternary	Quaternary undiff	0	14.4	14.4	-6.2	8.2	N/A	N/A	N/A
DANIAN	København limestone	14.4	56.5	42.1	8.2	50.3	N/A	N/A	N/A
DANIAN	Bryozoan Limestone	56.5	109.7	53.2	50.3	103.5	N/A	N/A	N/A
MAASTR.	Sigerslev Mb	109.7	150	40.3	103.5	143.8	34	2	10
MAASTR.	Rørdal Mb	Not drilled							
MAASTR.	Hvidskud Mb	Not drilled							
MAASTR.	Hansa Mb	Not drilled							
CAMP.	Flagbanke Mb	Not drilled							

		Temp.*	Thermal	vol.Heat	Rock
	Units	mid unit	cond.	capacity	density
Tuba-13		deg.C.	(W/m/K)	(MJ/m3/K)	g/cc
Quaternary	Quaternary undiff	8.2	2	unknown	2.5
DANIAN	København limestone	8.8	unknown	unknown	unknown
DANIAN	Bryozoan Limestone	9.8	unknown	unknown	unknown
MAASTR.	Sigerslev Mb	10.9	1.81	2.8	2.7
MAASTR.	Rørdal Mb				
MAASTR.	Hvidskud Mb				
MAASTR.	Hansa Mb				
CAMP.	Flagbanke Mb				

*Temperatures based on: Temperature (on avg.) = 8°C + 22°C/km x Depth[km].

Table 6.6 Well: Höllviksnäs-1

	Units	Top	Base	Thick ness	Top	Base	Po-rosity	matrix	Effec-tive
Höllviksnäs-1		mMD	mMD	(m)	b. MSL	b. MSL	(%)	Perm (mD)	Perm (mD)
Quaternary	Quaternary undiff	0	1	1	-8	-7	N/A	N/A	N/A
DANIAN	Danian limestone	1	50	49	-7	42	N/A	N/A	N/A
MAASTR.	Sigerslev Mb	50	130	80	42	122	N/A	N/A	
MAASTR.	Rørdal Mb	130	158	28	122	150	N/A	N/A	
MAASTR.	Hvidskud Mb	158	461	303	150	453	26	0.9	
MAASTR.	Hansa/ Boesdal Mb	461	536	75	453	528	17	0.3	
CAMP.	Flagbanke Mb	536	607	71	528	599	16	0.3	
L. Chalk	Lower Chalk unit	607	1198	591	597	1190			
L. CRET	Lower Cretaceous unit	1198							
Fjerritslev Fm	Upper Jurassic Unit								
Fjerritslev Fm	Lower Jurassic Unit								
TRIASSIC	Gassum Fm								
TRIASSIC	Bunter Sst. Fm								

7. Comparison of reservoir simulation software

As described in Paragraph 1.2.1, reservoir simulation techniques can be used to assess the productivity, injectivity, heat extraction and optimal well configurations for geothermal operations as well as use of the subsurface for energy storage.

Several reservoir simulation software packages exist in the market, which in general fall into two categories; software for groundwater modelling and software for modelling oil and gas production. Modelling of geothermal operations and subsurface energy storage can be handled by both groups of software, as it is basically the same type of governing equations that are solved.

The governing differential equations for fluid – and heat flow in a complex domain (geology) are solved numerically in space and time. Several numerical methods can be used for solving the equations; final difference -, final element - and final volume methods. In reservoir simulations the two first methods are predominantly used.

The objective for the present study is to compare simulation results from both types of software. **FEFLOW** (Diersch, 2009, 2014), a software often used in groundwater modelling, using the finite element method, and **Eclipse 100** (ECLIPSE, 2015), a finite difference modelling tool widely used by the oil & Gas industry, **are compared** using a conceptual model for an energy storage operation.

Simulations with both FEFLOW and Eclipse 100 were run at GEUS. At GEUS, FEFLOW is used by the groundwater modelling group in the Dept. of Hydrology and Eclipse 100 is used by the reservoir modelling group at the dept. of Reservoir geology.

The concept for the study was to solve a predefined heat storage problem using a conceptual model relevant to the HTES project. For an impartial comparison of the two software packages, two study groups solved the problem independently using standard work flows. The performance and results of the simulations were subsequently compared and evaluated.

The benchmark study is described in detail below.

7.1 Conceptual model

A simple box model with two wells was selected and constructed for the study. Two wells, HTES-1 and HTES-2, are placed in the middle of the box with an inter-well distance of 1000 m. Both wells act as injection/production wells throughout each year, see paragraph 7.2 for further details. Major et al. (2018) presented conceptual models for heat extraction in deep geothermal reservoirs. A number of findings from this research have been utilized in the present study.

7.1.1 Model domain and discretization

The model domain is a 10,000 m x 10,000 m x 1000 m large box. The top of the box is at ground level (z = 0), so the planned storage depth of 400 – 800 m is imbedded in the box.

Layering of the box is set to 110 layers. Layer thickness varies in the box in order to get high resolution in the storage zone; layers 1 – 20 are 20 m thick, layers 21 – 100 (storage zone) are 5 m and layers 101 – 110 are 20 m.

Lateral grid size (node distance) is 200 m x 200 m for the initial coarse model. FEFLOW uses a triangular mesh and Eclipse 100 uses a corner point grid.

To minimize effects from numerical dispersion in the dynamic calculations, the individual grids are refined around the wells (sources/sinks). The two types of grids are difficult to make fully equivalent for the two software. Individual work flows for the two modelling programs (i.e. Eclipse 100 and FEFLOW) were applied. No refinement in the vertical (z) direction was applied, as the chosen model layering secured a relative high vertical resolution for the storage zone.

In FEFLOW a triangular mesh is used to create the finite element grid. Elements are refined around the wells using supporting nodes to ensure ideal element size. Target element size is set to 20 m (see Fig. 7.1). Well diameter is 0.25 m and ideal element size around the wells is calculated to be 0.6 m based on information from Diersch (2009).

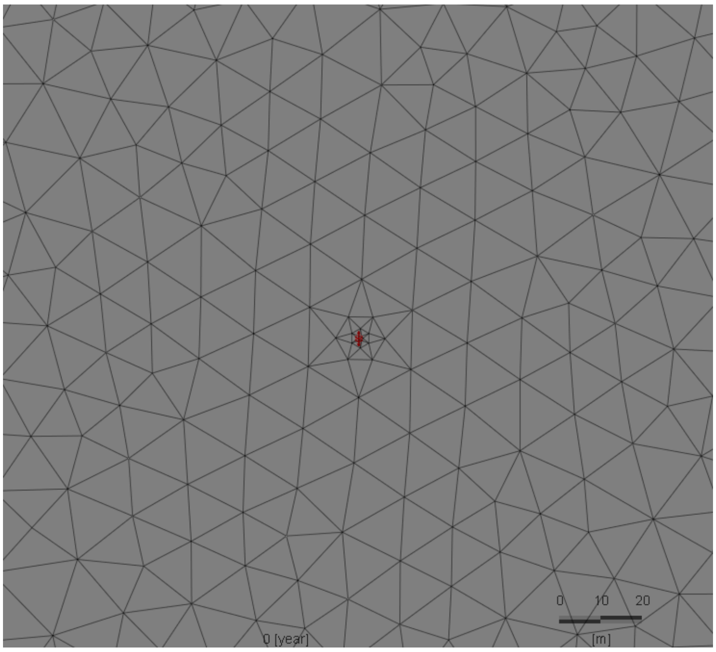

Figure 7.1: *Refinement of triangular elements around the well in FEFLOW. Only the injection well is shown, but same methodology was applied to both wells. See also figure 7.2 for well locations.*

In Eclipse 100 the corner point grid is refined around the wells by assigning a value for how many times the host cell is divided in the x, y (and z) directions, respectively. This can be done in several steps, making the grid cell sizes successive smaller towards the wells. Figure 7.2 displays the grid used in Eclipse 100 simulations.

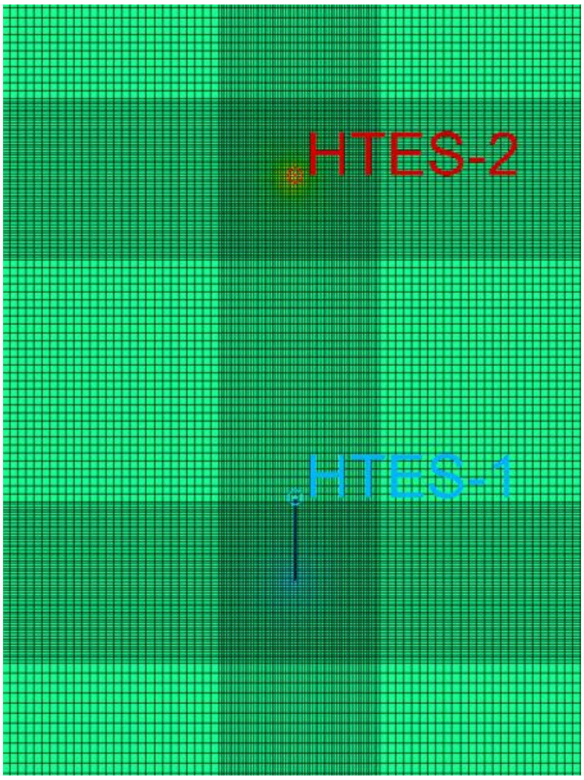

Figure 7.2: *Lateral profile showing the grid refinement around the two wells. The grid cell nearest the wells are 5 m in lateral length.*

For both FEFLOW and Eclipse 100, the refinement of the grid/mesh must be optimized by checking the simulation result for subsequent smaller grid sizes until the simulation results are independent on the grid size.

7.1.2 Model parameterization

For the conceptual model porosity and permeability values were constant in the entire model domain. A value of 30% for the porosity and a value of 2 mD for the permeability was chosen to reflect realistic reservoir values for the HTES project.

The density and viscosity are 1050 kg/m^3 and 1.2 cp, both at 20^{o}C. The viscosity variation with temperature is based on information from CREWES (2007) and is entered into Eclipse 100 as a table with linear interpolation between each table values.

Table 7.1: ***Viscosity as function of temperature (CREWES, 2007).***

Temp	Visc.
8	1.5
15	1.32
20	1.17
30	0.94
40	0.77
50	0.65
60	0.56
70	0.48
80	0.42
85	0.40

In FEFLOW the viscosity is entered as a second order polynomial of the temperature (T):

$\text{Viscosity} = 0.0002T^2 - 0.0305T + 1.7211$

The compressibility of the rock is set to 6.1×10^{-5} bar^{-1} and the compressibility of water to 4.5×10^{-5} bar^{-1}.

Heat conduction is entered as a porosity weighted average of the formation water - and the rock conductivities and is set equal to 1.94 W/m/K for both software, cf. Figure 6.2.

For both software the specific heat capacity is entered as 4.0 kj/kg/K for the formation water and 2060 kj/m^3/K for the rock. Values were determined using the 'heat capacity versus porosity' plot shown in Figure 6.4. In both FEFLOW and Eclipse 100, the bulk heat capacity is calculated on the basis of a porosity average value.

7.1.3 Model boundary conditions and initialization

The outer model boundary conditions are identically setup in the FEFLOW and Eclipse 100 software models. No-flow boundaries are used. The 400 m overburden and 200 m underburden secures the vertical boundary, and the 10,000 m x 10,000 m lateral model secures the horizontal no flow boundary.

The constraints on the wells, which also act as boundary conditions, are solved differently in the two software's. The Eclipse 100 well option is used to secure the inflow performance from the reservoir to the wellbore. The well option uses an analytical solution for the pressure drawdown in the near wellbore area (grid cells) (ECLIPSE, 2015). For the FEFLOW software, the individual nodes in the mesh defining the two wells are controlled by the applied drawdown pressure.

The initial temperature (T) is given as a function of model depth by the relation:

$T = 8^\circ C + 22^\circ C/km \times depth[km]$

The simulation in both software are initialized from hydrostatic conditions and with the above temperature gradient. It is assumed that the model is in hydraulic and thermal equilibrium. The initial datum pressure is set to 1 bar at the top of the model ($z = 0$).

7.1.4 Well configuration

The wells are setup as vertical wells with a well diameter of 0.25 m. Both wells are completed in each of the 80 layers comprising the storage zone. A skin factor (flow resistance in the near well area) of 0 is used; *i.e.* no extra resistance for flow from/to the reservoir to the wellbore.

A doublet well configuration is used with a well distance of 1000 m between the "hot" well – and the "cold" well.

When a well is in production mode, it is controlled by the bottom hole pressure, i.e. the draw down pressure in the top most grid cells in the storage zone. The bottom hole pressure is set to 3 bar. The 3 bar is defined in order to allow approximately 30 m of water above the production pumps.

The corresponding injection well is controlled by a full voidage replacement, i.e. an equal volume produced must also be injected. Volumes are given as reservoir volumes.

7.2 Simulation scenario

The simulation scenario is setup to simulate a heat storage operation. The scenario is defined as a scheme comprising a 5.5 month long period of charging the hot well by injection of 80°C hot water followed by a 0.5 month long pause. After the pause the hot well is put on production for 5.5 month period and again followed by a 0.5 month long pause. The charging and producing periods including the pauses comprises a full year, this is repeated in the simulations for a total of 25 years.

The volumes circulated in the system is determined by the producing well. When the system is being charged with hot water the "cold" well is the producing well. The amount of produced water from the cold well is constrained by the 3 bar drawdown and the viscosity of the cold water. As the viscosity strongly depends on temperature, cf. table 7.1, the circulated volume is constrained.

The 25 years heat storage operation is simulated by FEFLOW and Eclipse 100 for comparing and judging the simulation performance. Output from the simulations are production temperature profiles and development in pressure.

7.3 Results and discussion

Results of the reservoir simulations are presented in figures 7.3 and 7.4. Figure 7.3 displays the temperature profiles from the FEFLOW and Eclipse 100 simulations for a 25 years period. The temperature profiles are almost identical – only small discrepancies are identified (see below).

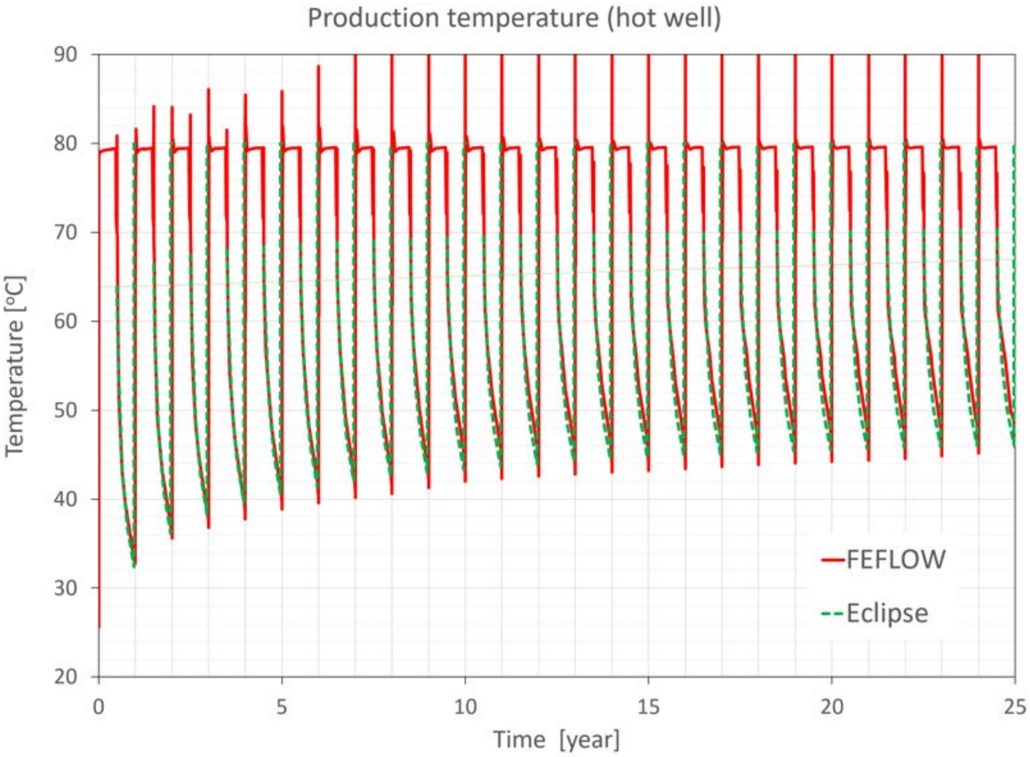

Figure 7.3: *Simulated production temperature for the 25 years injection-production scenario. The red line illustrates the FEFLOW results and the green dotted line shows the Eclipse results. Red "spikes" above 80°C for the FEFLOW simulation are an artefact from the setup of the well.*

The end-temperature, when producing the hot well tends to be a little lower for the FEFLOW simulation. This is illustrated by the cross plot of the end-temperatures for the two software types (Figure 7.4).

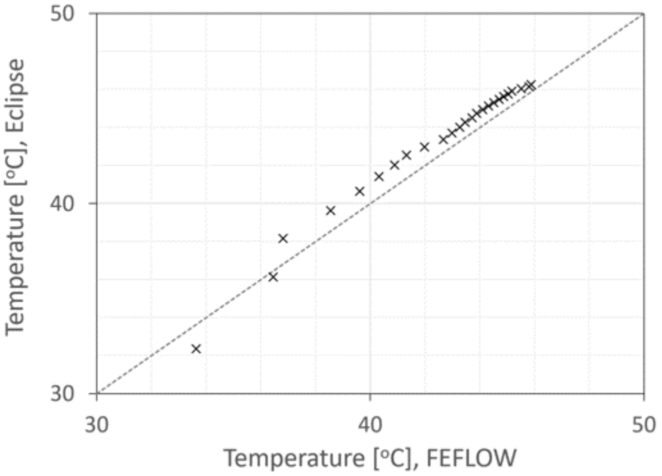

Figure 7.4: *Cross plot of simulated production temperature for the 25 years injection-production scenario. The displayed temperatures are the end-temperature after the individual production periods. Eclipse tends to simulate a higher end-temperature. The simulated temperatures from FEFLOW and Eclipse only deviate 1-2% (less than 1°C).*

The difference between the end-temperature from the two software are less than 1°C or a deviation of 1-2%. This is assess to be a relative minor difference and may be explained to originate from various sources.

- The numerical solution methodologies for the two software are different; FEFLOW uses the finite element method and Eclipse 100 uses the finite difference method. The two solution methods should in general be alike, but as presented above, the discretization of the model domain, especially in the spatial domain is quite different. It can be difficult to make the discretization almost identically for a direct comparison.

- Inherent uncertainty in performance for the two software may also result in small discrepancy in modelling results between FEFLOW and Eclipse 100. This effect was not quantified in the present study.

- The modelling procedures and work flows could also be a source for small discrepancies, especially the setup and control of the wells have a direct impact on the boundary conditions for the solution.

- The differences in production temperature may also be an effect of mechanical dispersion. FEFLOW take mechanical dispersion in to account in the heat transport, whereas Eclipse 100 only have options for anisotropy in the hydraulic parameters.

Overall it is concluded that the present results show large consistency in the simulation results. It must also be emphasized, that the simulations with the two software were run independently, i.e. the setup of the problem and subsequent optimization of the discretization in the spatial and time domains, the setup of boundary conditions, initialization and running the simulation are assessed to be feasible.

Furthermore, it is assessed that both software are well-suited for simulating heat storage operations, of cause with the reservation of the representativeness of the present model study.

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