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High Temperature Energy Storage – HTES project

GEOTECHNICS AND GEOLEGY SECTION

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High Temperature Energy Storage - HTES project

Geotechnics and Geology Section

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Preface

This report describes the geotechnical outputs elaborated by the DTU-Byg research group under the EUDP founded project HTES - High Temperature Energy Storage. The study is subdivided in four chapters, respectively *Introduction*, *Presentation of data*, *Discussion* and *Conclusion*. In Chapter 1 Introduction, the project aim, objectives and expected geotechnical outputs are listed. Chapters 2 Presentation of data and Chapter 3 Discussion show the available geotechnical and petrophysical dataset and the major findings. Finally, the conclusions are summarized in Chapter 4.

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Abstract

This research is part of the EUDP funded project HTES that aims at demonstrating the successful employment of Underground Thermal Energy Storage (UTES) in the subsurface of Copenhagen with a focus on the Chalk Group. The study investigates the geotechnical and petrophysical properties (i.e. stiffness and porosity) of the medium depth (800mbgl) Chalk Group. The majority of the geotechnical data available covers shallow depth, while deep well log data are fewer and of variable quality. In order to overcome the lack of information, this work evaluates the possibility to use Dan field in the central North Sea as an analogue for the chalk in Zealand comparing the effective stress and elastic moduli at the two locations. The maximum experienced effective stress for the formation is the same at the two geographical locations, which currently have different effective stress due to uplift and erosion of Zealand during the Neogene. The results shown were obtained calculating the maximum effective stress based on the burial anomaly as studied by Japsen (1998). In addition, the elastic moduli were calculated using the bulk density and the elastic P-wave velocity log data by means of the iso-frame model proposed by Fabricius (2003). The model allows us to estimate the elastic moduli by comparing the elastic modulus obtained by elastic P-wave measurements with the theoretical one obtained under the assumptions of either particles in suspension or cemented particles constituting a frame.

Acknowledgements

This research used data provided by Geological Survey of Denmark and Greenland (GEUS), an independent research institute under the Ministry of Climate and Energy and GEO, an engineering consultancy within the fields of soil and water.

1. Introduction

This report summarizes the geotechnical results obtained by the research group at DTU-Byg Section of Geotechnics and Geology during the one year project HTES (High Temperature Energy Storage), an EUDP funded project (EUDP Jno 64016-0014) in collaboration with Ross Offshore DK (project leader), Ingeniør Huse, Awell, GEUS, OE3i and Geo. The aim of the project is to demonstrate the successful employment of geothermal energy and thermal energy storage in the subsurface of the greater Copenhagen area with a focus on the Chalk Group (target depth 800mbgl), and to identify the best locations where such technologies could be applied. The work programme of the HTES project is divided in four Work Packages (WPs) and requires collaboration and interconnection between the partners. WP1 focus on the review of existing knowledge of HTES and local subsurface data, WP2 use the information collected by WP1 to model the thermal storage potential and possible effects on the groundwater system. Based on results achieved by WP1 and WP2, WP3 evaluate the optimal borehole design. Finally, WP4 coordinates the other work packages and manages the project.

The DTU-Byg research group is involved in WP1 and WP2 providing information regarding the mechanical properties of the limestones to support WP3 to reduce the well drilling risks and maximize the well productivity. The DTU-Byg research group consists of three members:

- Ida Lykke Fabricius: professor of technical geology.
- Irene Rocchi: assistant professor of geotechnics.
- Laura Paci: geologist (M.Sc. University of Pisa), PhD student.

The objectives of this work group are:

1. Reviewing the existing knowledge of HTES and local subsurface data
   i.e. Geotechnical and Petrophysical properties.
2. Evaluate the Elastic moduli, Stiffness and Strength of the limestones (Zealand).
3. Evaluate the correlation of these properties with Porosity and Permeability.

4. Associate Geothecnical and Petrophysical properties to different facies in the limestones (Zealand).

We expected that the different degree of induration of the limestone formations in the Chalk Group influence their mechanical properties. The degree of induration (H) of a rock describes how easily it breaks apart on a scale from one to five (H1 poorly indurated rocks and H5 well indurated rocks) [1]. This property reflects the diagenetic history of a rock (Table 1).

Table 1 Scale defining the degree of induration of a rock formation [2]

Degree of Induration	Description
H1: unlithified	The material can without difficulty be remoulded by fingers. Coarse material falls apart in dry condition.
H2: slightly indurated	The material can easily be cut by a knife and scratched by a nail. In coarse material single grains can be detached by using a fingernail.
H3: indurated	The material can be shaped by a knife but cannot be scratched by a nail. From coarse material grains can be detached with a knife.
H4: strongly indurated	The material can be scratched by a knife, but single grains cannot be detached with a knife. Fractures follow the grain contacts.
H5: strongly indurated	The material cannot be scratched by a knife. Fractures pass through the grains.

H4 and H5 indistinguishable in limestone. In practice, H4 relates to the stiffest limestone, whereas H5 refers to chert. The expected outcome at the beginning of the project was to build a geographical distribution of the Elastic moduli, Stiffness and Strength, associated to the limestone facies. The assessment of the mechanical properties of the limestones (reservoir hosting the thermal storage) is crucial to minimizomg the risks connected with the drilling phase (borehole and perforation stability) [3] and guarantee an optimal well and reservoir productivity (prediction of formation strength and well stimulation) [4] [5]. Evaluating the formation strength (reservoir pressure and stress conditions) is essential to avoid rock failure during well production, while estimating fracture pressure and height are a basis for well stimulation [6] [7]. Moreover, thermal fatigue in the limestones, due to the cyclic injection at extraction of formation water in connection with the thermal storage operations, could affects the formation strength. Gasc-Barbier et al (2014) demonstrate that cyclic temperature variation increase the risk of intergranular and intragranular cracking, inducing pore collapse [8]. In the North Sea, pore collapse has been observed during well production as a consequence of increasing effective stress and related decrease of pore pressure [9].

2. Presentation of data

Underground thermal energy storage (UTES) is an energy storage technology where natural underground sites are used for storing thermal energy. UTES technologies incorporate:

- Aquifer thermal energy storage (ATES): an aquifer (saturated and permeable underground layer) is used as storage medium. Thermal energy is transferred by extracting and re-injecting groundwater from the aquifer using wells.
- Borehole thermal energy storage (BTES): closed loop vertical heat exchangers installed underground (30-300 m depth, spacing range from 3 m to 8 m), which ensures the transfer of thermal energy into and from the ground (clay, sand, chalk, etc.).
- Pit thermal energy storage (PTES): lined, shallow pits filled with gravel and water as the storage medium.

In Denmark, the existing heat storage technologies applied include ATES, BTES and PTES, combing both heating and cooling as well as heat and power. The applications are both for single buildings (e.g. airports, industry, hotels, etc.) and for district heating or cooling. In particular, the preferred heat storage technologies are currently ATES and BTES in Zealand, concentrating in the Copenhagen area, and PTES in Jutland. This is because PTES, which are usually combined with solar plants, requires a large area for installation and land is more easily available and cheaper in Jutland compared to Zealand. Conversely, land requirements dominate the UTES in the Copenhagen area, making ATES a more attractive alternative. In addition, waste production is higher in Zealand, because of the population concentration and this makes energy production from waste incineration the green energy available in the greatest amounts. More than 30 heat storage systems were installed in the last 20 years in Zealand, 50% of which working as ATES. Typically 1 to 5 well dipoles are installed and the average capacity is 1900kW [10]

Based on the existing UTES plants that have been operating for some decades, experience is growing and following a similar move as hydraulic power, where a shift was observed towards mini-hydro starting a decade ago [11], UTES systems are also starting to concentrate on more widespread but limited production. In those countries where UTES systems are very widespread, such as the Netherlands, this has led to interference between neighbouring UTES and deep UTES may represent a necessary alternative.

In Denmark, most ATES are installed in shallow gravelly and/or sandy aquifer units below 50m from the ground level or limestone. Figure 1 shows that the top of Chalk Group (Upper Cretaceous limestones and Danian limestones) is between 0 and 200m in Zealand and in the northern part of Jutland, while it is between 200 and 600m in the west and south of Denmark. Therefore, two geological scenarios are encountered in Denmark with respect to the use of limestones in ATES systems, according to the geographical location. In Zealand and northern Jutland, the limestones are encountered from relatively shallow depth (0-30m) to 1-2km depth and typically are capped with stiff sediments such as Paleogene clays and glacial tills in Zealand or soft sediments in the north of Jutland.

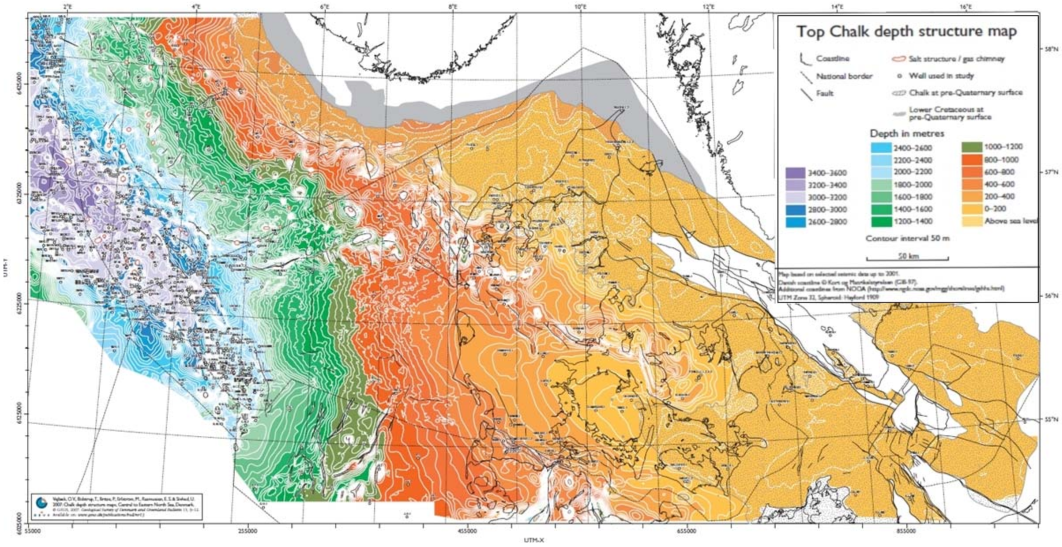

Figure 1 Top Chalk Group structure map [12].

For the purpose of UTES design, information regarding limestones must include hydrogeological, thermal and geotechnical properties. The few deep wells completed in Denmark are related to scientific investigation, gas storage, and petroleum exploration, and provide little geotechnical information (Figure 2). Sporadic geophysical logging of variable quality has been carried out, so that porosity and elastic P-wave velocity are available together with a lithological description. A wider, but shallow (maximum depth 100mbgl) number of geotechnical data (Triaxial shear test, Unconfined Compressive Strength – UCS test and Tensile test) was acquired in connection with the major public engineering infrastructures such as the Copenhagen Cityringen Metro and the Øresund Bridge projects. In the first case, a new circular metro line is under construction in the centre of the city with 17.4km tunnels and 17 new stations at 30mbgl. The Øresund Bridge is a combined railway and motorway bridge across the Øresund strait between Sweden and Denmark.

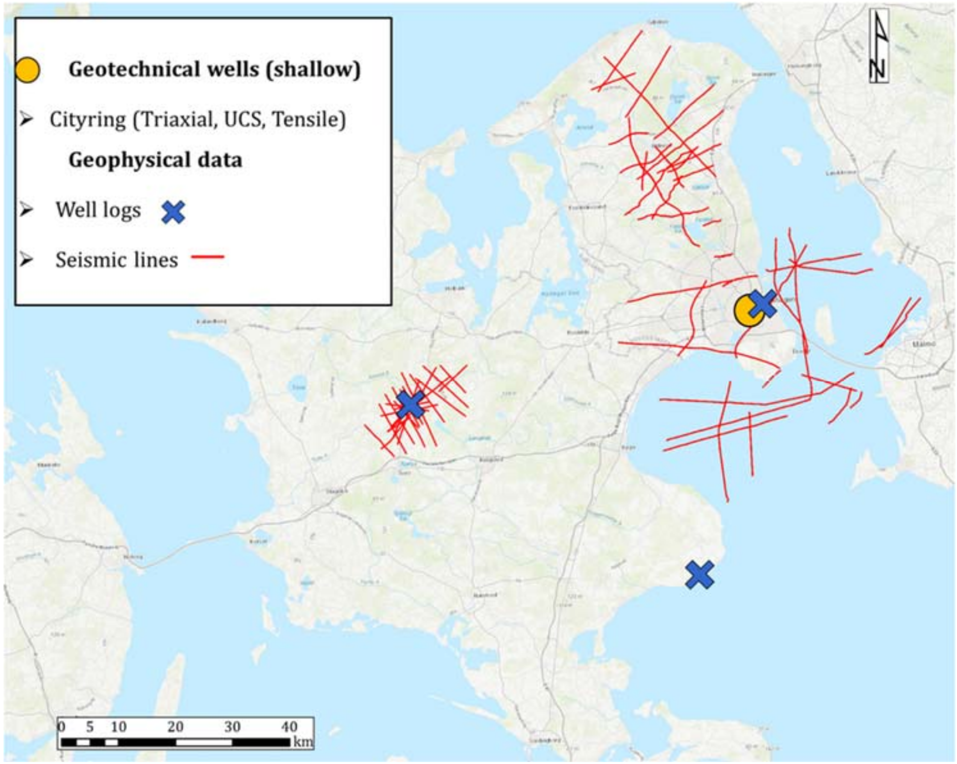

Figure 2 Map of the available data.

In order to overcome the lack of geotechnical information at depth, this study considers Dan field (North Sea), where both geotechnical and geophysical data are available, as a possible analogue for the Chalk Group in Zealand. Well log analysis and the estimation of the maximum effective stress (σ´) are used to assess this possibility. The effective stress links the magnitude of the mechanical response of a rock to variations in total stress (σ) and pore pressure (U), (Equation 1).

Equation 1 Effective stress calculation. The Bulk modulus defines the resistance to isotropic compression of a rock.

$$\sigma' = \sigma - \alpha U$$

$\sigma' =$ Effective stress

$\sigma =$ Load from overburden

$\alpha =$ Biot´s coefficient

$U =$ Pore pressure

$$\sigma = \rho_b * g * z$$

$\rho_b =$ bulk density

$g = gravitational\ acceleration$

$z = depth$

$$\alpha = 1 - \frac{K_{dry}}{K_{min}}$$

$K_{dry} =$ Bulk modulus

$K_{min} =$ Bulk modulus mineral

The Dan field is a hydrocarbon field located in the south-western corner of the Danish North Sea sector. The field has a dome structure and the main lithology is chalk. It is well known from the study of well cores and seismic lines that the Chalk Group is distributed across the northwest Europe, from the United Kingdom throughout the North Sea toward Denmark (Figure 1 and Figure 3). The Chalk Group contains an Upper Cretaceous-Danian limestone succession of chalk consisting mainly of the remains of planktonic algae and other pelagic organisms. The thickness of the limestones is greater in the Copenhagen area, between 900m and 1800m, as compared to in the Dan field (450-600m) [12]; while the burial depth ranges from over 3500m in the Central Graben to less than 100mbgl in the Danish Basin. Along the margins of the North Sea Basin, the thickness of the overburden deposits has been reduced due to the uplift and erosion during the Neogene. Therefore, the Chalk Group is overcompacted along the western and eastern margins due to the original greater burial depth. The magnitude of this event is approximately 1km and 750m respectively South of Bridlington, United Kingdom and in the North of Denmark (Aalborg, Copenhagen and Helsingør). In connection with the exhumation of the margins, the central North Sea area has experienced rapid burial of a maximum magnitude around 1.5km during the Late Cenozoic. Consequently, the chalk in the central North Sea is overpressured up to 20MPa at 2600m depth and underconpacted (Figure 4) [13]. Overpressure (ΔU) is the difference between the current pore pressure and the calculated hydrostatic pressure at the depth (Equation 2).

Equation 2 Overpressure (ΔU) and calculated hydrostatic pressure (U_H).

$$\Delta U = U - U_H \Rightarrow U = \Delta U + U_H$$

$$U_H = \rho_f * \mathrm{g} * \mathrm{z}$$

$U = measured\ pore\ pressure$

$U_H\ = calculated\ hydrostatic\ pressure$

$g = gravitational\ acceleration$

$z = depth$

$\rho_f = density\ of\ pore\ fluid$

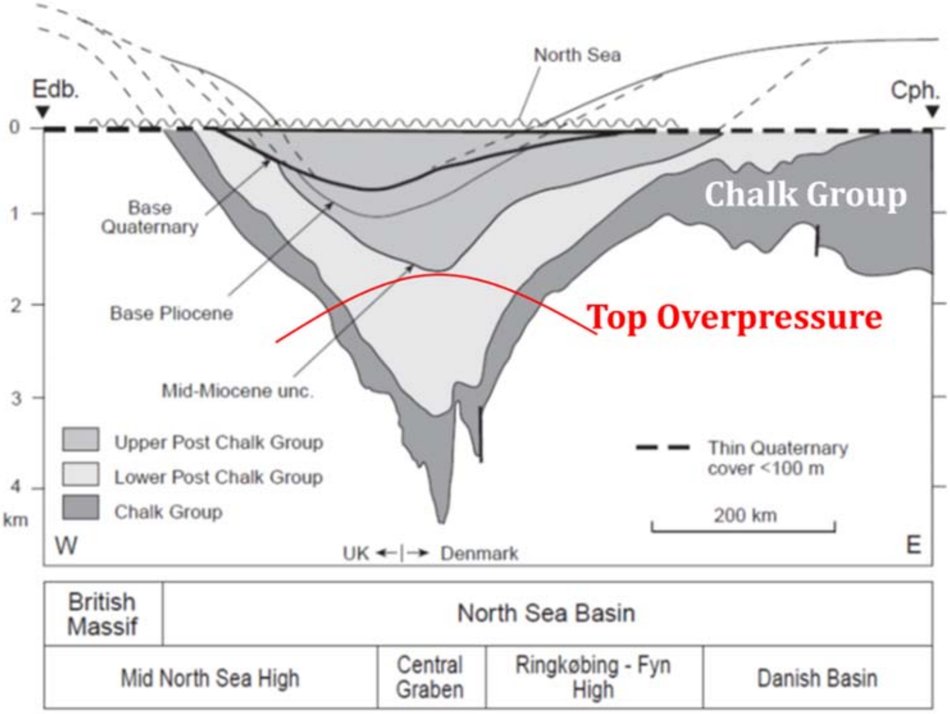

Figure 3 Burial profile of the Chalk Group across the North Sea from Edinburgh (Edb.) UK, to Copenhagen (Chp.) DK with indication of structural elements (bottom of the figure) [13].

Figure 4 shows the extension of the overpressured chalk in the central North Sea with a range between 5MPa and 20MPa. The area strikes North-Northwest covering a surface of around 425x125km^2. Japsen (1998) suggests that the chalk formation overpressure is proportional to the thickness of the late Cenozoic deposits (Upper

Post Chalk Group, Figure 3) and the region of overpressured chalk is limited by the Mid-Miocene unconformity at a depth greater than 1km (Figure 3).

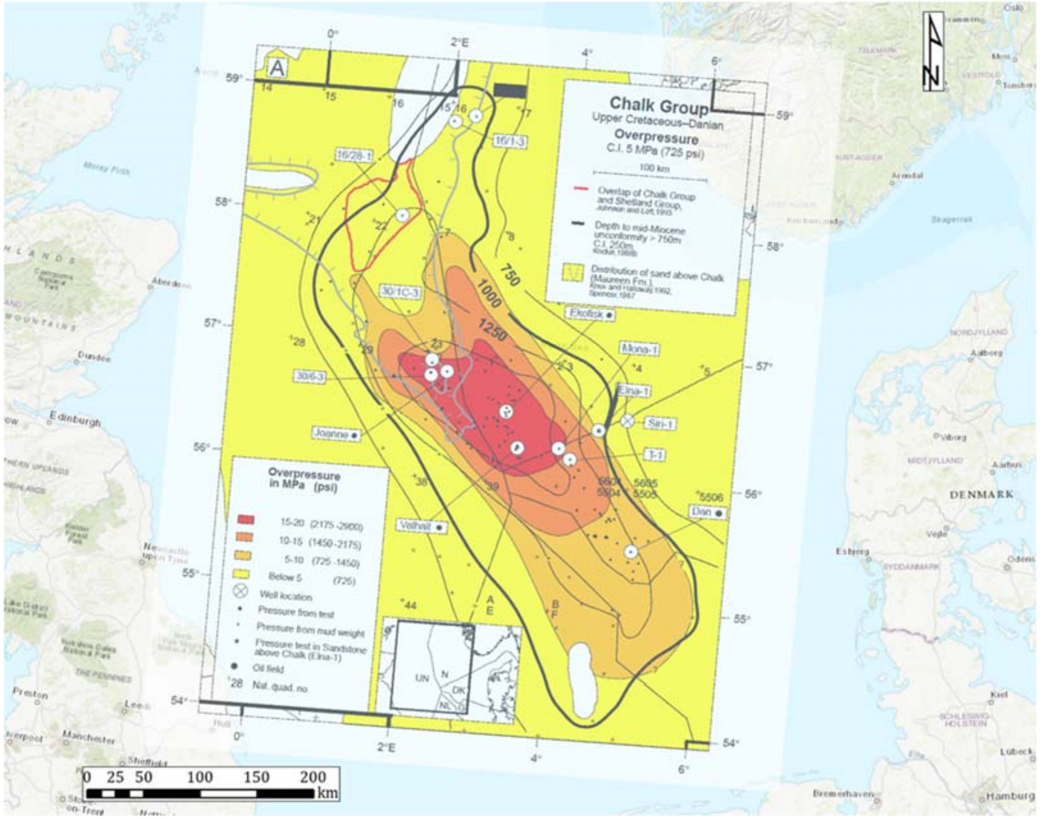

Figure 4 Map of the areas affected by overpressure in the North Sea Basin based on pressure measurements and Chalk burial anomalies [13].

3. Results

Based on the burial anomaly as studied by Japsen (1998), the effective stress of Dan field and the greater Copenhagen area is compared (Figure 5 and Figure 6). The maximum effective stress (σ´) for the formations are the same at the two geographical locations (5-15MPa), which currently have different effective stress due to uplift and erosion of Zealand during the Neogene. In Zealand, the present effective stress is below 5MPa, while it reaches a maximum of 15MPa in the Dan field. The Upper Cretaceous formation is found at much greater depth in the Dan field, resulting in a greater overburden stress. However, the effective stress is comparable to the maximum value encountered in Zealand (i.e. before uplift and erosion), due to overpressure in the Dan field. Overpressure has allowed a higher porosity to be retained in the Dan field, resulting in undercompaction of the chalk. Increase in maximum effective stress results in lower porosity. Therefore, any difference between stiffness and maximum effective stress relations results from cementation processes, which are not always porosity-reducing.

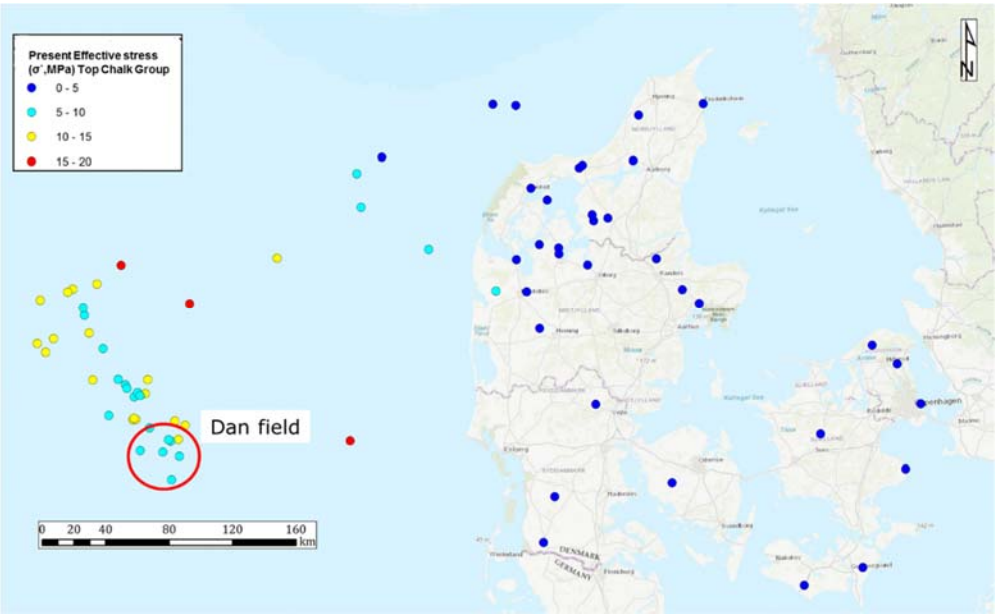

Figure 5 Present effective stress at the top of the Chalk Group.

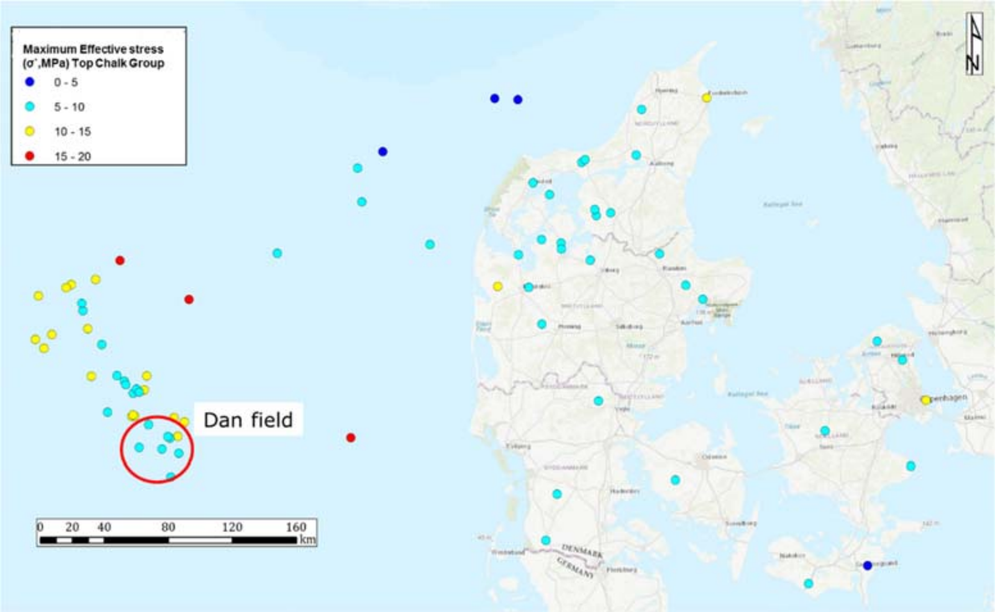

Figure 6 Maximum effective stress at the top of the Chalk Group.

The well logs used in this study originate from four wells: Margretheholm-1, Stenlille-1 and Stevns-1 located onshore Zealand and M-10X in the North Sea (Dan field). Based on elastic P-wave velocity and bulk density data the mechanical properties of the Chalk Group in Zealand are estimated and compared with those of the Dan field. The elastical properties (in casu Young´s modulus and Poisson´s ratio) are obtained by means of the iso-frame model proposed by Fabricius (2003). The model allows to estimate the Elastic moduli by comparing the elastic modulus obtained by P-wave measurements with the theoretical one obtained under the assumptions of either particles in suspension or cemented together in a frame [14]. Figure 7 shows the estimated mechanical and petrophysical properties of the Chalk Group at the two different geographical locations. In the top of the figure, Young's modulus (E, which is a measure of the stiffness of the rock) from well logs (right) and laboratory test (left) is compared. The elastic modulus of the Copenhagen Limestone (Danian) does not follow a clear trend and covers a wide range from hundreds of MPa up to 50GPa, while the elastic modulus based on deep well log data presents an overall increase with depth. The Poisson´s ratio describes the phenomenon in which a material tends to expand in directions perpendicular to the direction of compression (i.e. the ratio of transverse strain to axial strain). It ranges between 0.0 and 0.5, where an incompressible material deformed elastically at small strains would have a Poisson's ratio of exactly 0.5. In rock engineering application, the Poisson´s ratio of a rock formation estimates the stress around underground opening (e.g. boreholes) and reflects the stiffness of the rock [15]. The value of the Poisson´s ratio increases slowly with depth reflecting the increasing stiffness of the chalk.

The Upper Cretaceous limestones (depth interval: 700-1500mbsl) on average show low porosity between 10% and 20%, while the Danian limestones (depth interval: 30-400mbsl) have a higher average porosity, around 30-40% as seen in Figure 7. The Elastic P-wave velocity tends to increase slowly with the burial (i.e. higher contact cementation) and to decrease with increasing porosity. Both the mechanical and petrophysical properties plot of Stevns-1 are wildly scattered, reflecting a poor quality log. Figure 8 shows the cross-plot of Young’s modulus (E) and Porosity of the Chalk Group at the two locations. Dan field chalk has Porosity – E modulus relationship distinctly different from chalk of Stenlille-1, Margretheholm-1 and Stevns-1. Despite the fact that Dan field has comparable maximal effective stress, the rock physic modelling does not indicate a clear relationship between the two locations. The reason is probably that although the stress history is comparable, the temperature history is not because of the difference in actual maximal burial.

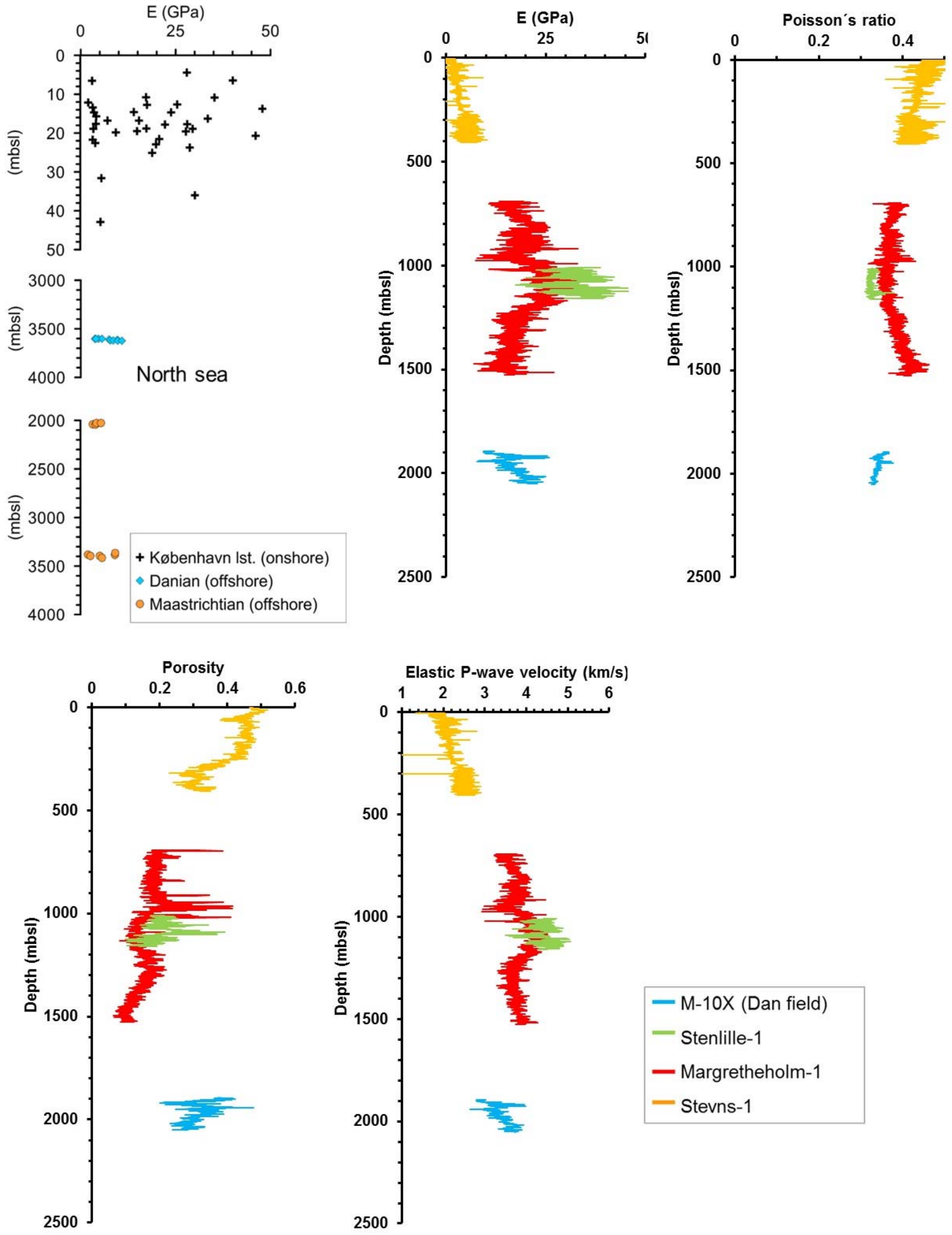

Figure 7 Elastic and petrophysical properties of the Chalk Group in Zealand and North Sea (Dan field).

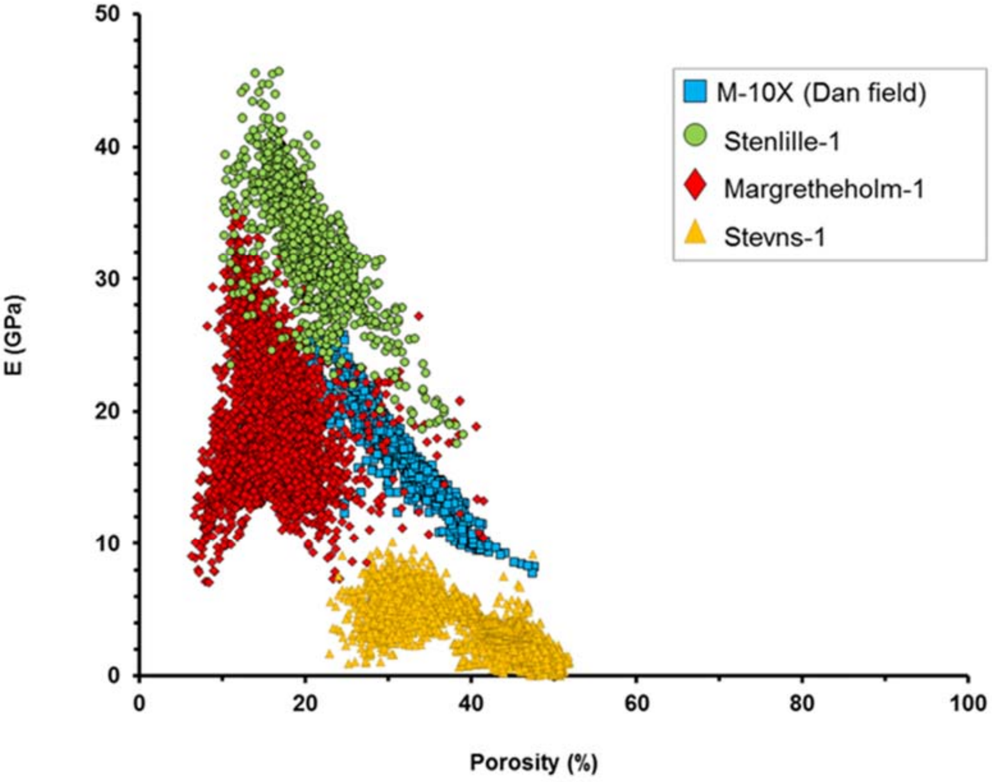

Figure 8 Cross-plot: Young’s modulus (E) versus Porosity.

4. Conclusion

This study underlines that the sparse geotechnical information and poor quality well log data are the main challenges when estimating the geotechnical and petrophysical properties of the Chalk Group in the greater Copenhagen area. There are no available geotechnical data for chalk of Copenhagen area in target depth interval. Dan field Chalk could not be used as an analogue for the Copenhagen chalk because, from effective burial modelling, Dan field has comparable maximal effective stress, but from rock physic modelling, Dan field chalk has Porosity – E modulus relationship distinctly different from the chalk of Stenllile-1, Margretheholm-1 and Stevns-1, caused by its different temperature history.

The DTU-Byg group underlines the necessity of retrieving deep chalk cores from Copenhagen area to provide material for pertinent geotechnical testing. Moreover, it is recommended that geophysical logs must be of high quality commercial standard in order to provide quantitative information. Finally, it is advised to study the effect of water injection on the geotechnical properties, because experience from the North Sea indicates potential enhanced pore collapse.

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