DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/45

Pumping Power

Rock quality of chalk in the Stevns 1 drill core and possibilities of finding higher strength chalk at depth here and at other locations in Denmark

Christian Knudsen, Niels Schovsbo
& Anders Mathiesen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

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1 Summary

Chalk is the only near-surface rock type in Denmark apart from granite on Bornholm, which may qualify for accommodating large caverns. Areas with shallow overburden over the chalk are located in an area from Hanstholm over Aalborg and Grenå to North Sjælland, Stevns to Lolland. In these areas the least tectonic disturbance is expected on eastern Sjælland, Falster and eastern Fyn together with the area between Grenå and Aalborg. The area with shallow chalk in north-western Jylland is influenced by tectonics and less well suited.

Rock-mechanical testing of the drill-core from Stevns-1 shows that there is a general increase in Unconfined Compression Strength (UCS) with depth and that the UCS is above 10 MPa for the chalk below 300 m and generally above 20 MPa in the depth interval between 300 and 500 m. The rock quality (Q-value) also increases with depth. The Q-values are above 10 at levels deeper than 210 m. It is considered possible to construct caverns in the chalk.

The increase in rock strength with depth is tied to a decrease in porosity, and is mainly tied to dissolution and reprecipitation of calcite in pore-space caused by the weight of the overburden. The increase in rock strength is also seen as an increase in sonic velocity and the interval with UCS above 10 MPa has sonic velocity in the interval 90 to 110 µsec/feet equivalent to 2,8 to 3,4 km/sec.

A similar increase in sonic velocity with depth can be observed in wells penetrating the upper part of the chalk in other parts of Denmark, but the intervals which from the Stevns-1 well are known to have UCS > 10 MPa occur at slightly deeper levels e.g. at Hobro at a depth of ca. 400 m and in Stenlille at ca. 450 m. However, at these locations the sonic velocity continues to increase, which suggests that more compact chalk with lower porosity and higher strength is likely to be found at deeper levels.

When the findings in Hobro-1 and Stenlille-6 are projected to Stevns, it is foreseen that the strength will increase down to at least 600 m depth. Based on analogues to limestone at other localities, an UCS in the interval 25 to 60 MPa is likely to occur at a depth of ca. 600m.

In Stevns-1 there are frequent 1 to 5 cm thick marly layers in the chalk in the depth interval 300-450 m. These are weaker than the chalk and have a negative effect on the overall rock quality. Fewer marly layers and accordingly chalk with higher Q-value is likely to occur in the depth interval 6-700 m at Stevns at according to the γ-log in comparable stratigraphic levels in Stenlille-6 and Hobro-1wells.

It is likely that the rock quality in the chalk is good at ca. 600 to 700 m depth at Stevns and Grenå, and it is recommended to drill two ca. 700 m deep, cored holes to test the rock quality at these two localities.

2 Introduction

Objectives

The overall aim with the project is to locate potential sites for establishing “pumping power” in Denmark and deliver parameters for initial design considerations.

The objective with the work reported here is to evaluate the best areas in Denmark for building “pumping power” caverns in chalk.

The work is conducted by GEUS for DONG Energy Power.

Background

Naturally fluctuating energy sources such as wind- and other (wave- tidal- and sun-energy) is projected to contribute with an increasing fraction of the Danish energy production, and their integration into the electrical power system/grid will become more and more important.

The planned increase in wind energy production in Denmark may lead to a situation where there is not enough capacity to cover the demand for electricity in periods with little or no wind. There may also occur situations where there will be overproduction/-flow in the electricity system.

When the contribution from wind energy increases, the main challenges for the electricity system will be:

- Generation of power when there is no wind
- Handling of fluctuations in power demand and use
- Full use of the electricity production in periods with high wind power production.
- Prediction of when electrical power is available

Due to the nature of the fluctuating energy sources there is a strong need for efficient electricity storage facilities/technologies. An efficient electricity power storage facility can store the power when there is overproduction of e.g. wind energy and deliver the electricity when the wind does not blow sufficiently relative to the electricity consumption.

There are many different electricity storage technologies among which the most widespread is “pumping power” with more than 70 GW installed worldwide. The principle is that there are two reservoirs – an upper and a lower and in times of excess energy water is pumped from the lower to the upper reservoir. When the power is needed the water is then let through a turbine from the upper to the lower reservoir.

Initial investigations indicate that pumping power is the most efficient way to store large quantities of power with high energy conversion efficiency (ca 80%).

In Denmark there is a lack of natural topography to make the above described model possible on the surface. Accordingly, the present investigation is part of an evaluation of the viability of using an underground caverns as lower reservoir. As an upper reservoir either an artificial lake or the sea can be used. The target depth for the cavern was 300 to 500 m and the target volume is ca. 1 mill m^3.

To be able to make a cavern with the sufficient volume at a depth of 300 to 500 m, the rock must have certain strength (ca. > 10 MPa). Chalk with the sufficient strength has been identified at Stevns (Knudsen & Jakobsen 2008).

Chalk occurs near the surface over wide areas of Denmark (Fig. 1), and it forms very thick (> 1000 m) deposits in the Danish subsurface.

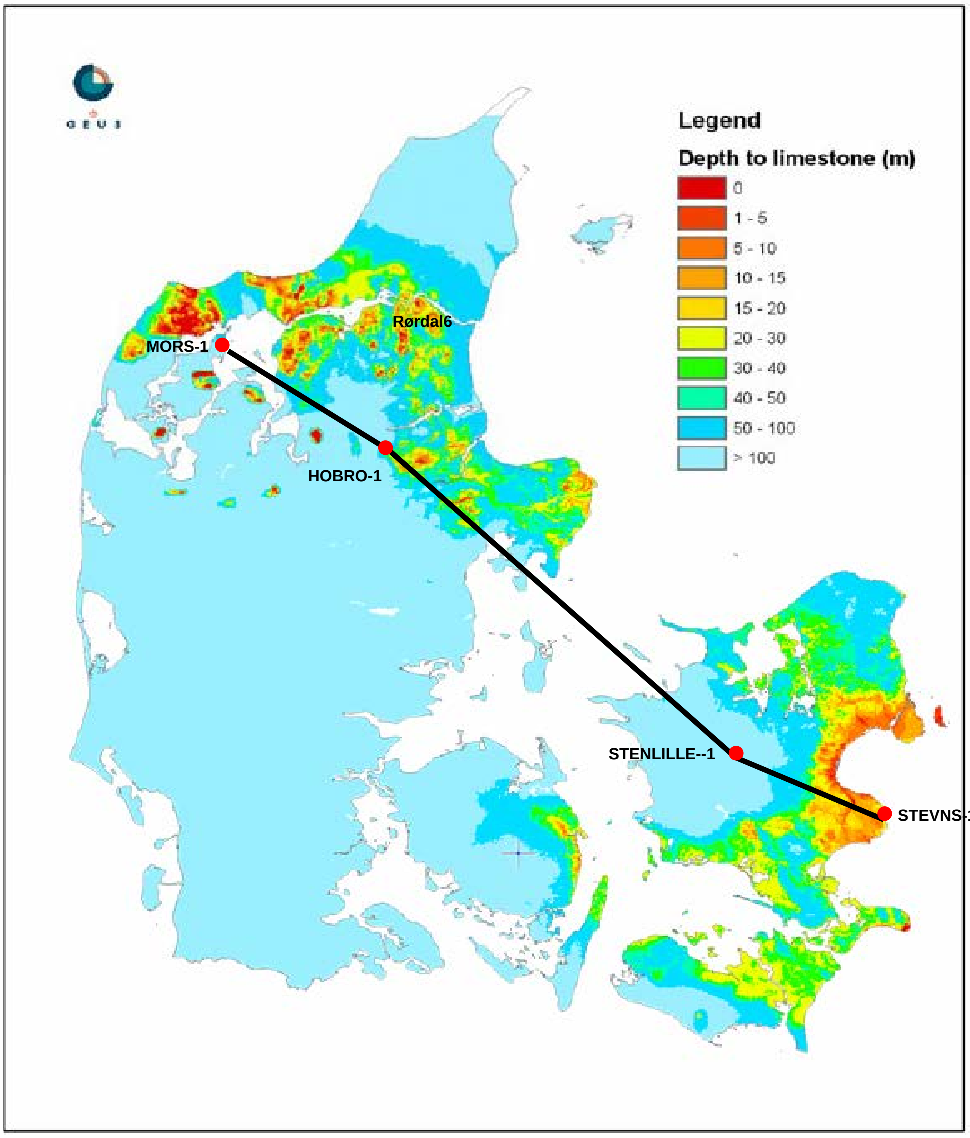

Figure 1 Map showing depth to the chalk. The line connects the 4 wells shown in the well correlation panel (Fig. 9).

3 Porosity, permeability, rock strength and sonic velocity in chalk

There is a substantial variation in the porosity of the chalk due to variable degree of cementation of the pore space (Fig. 2). The Unconfined Compression Strength (UCS) of the rock (Fig. 3) increase with increasing cementation of the rock and with depth (Fig. 4).

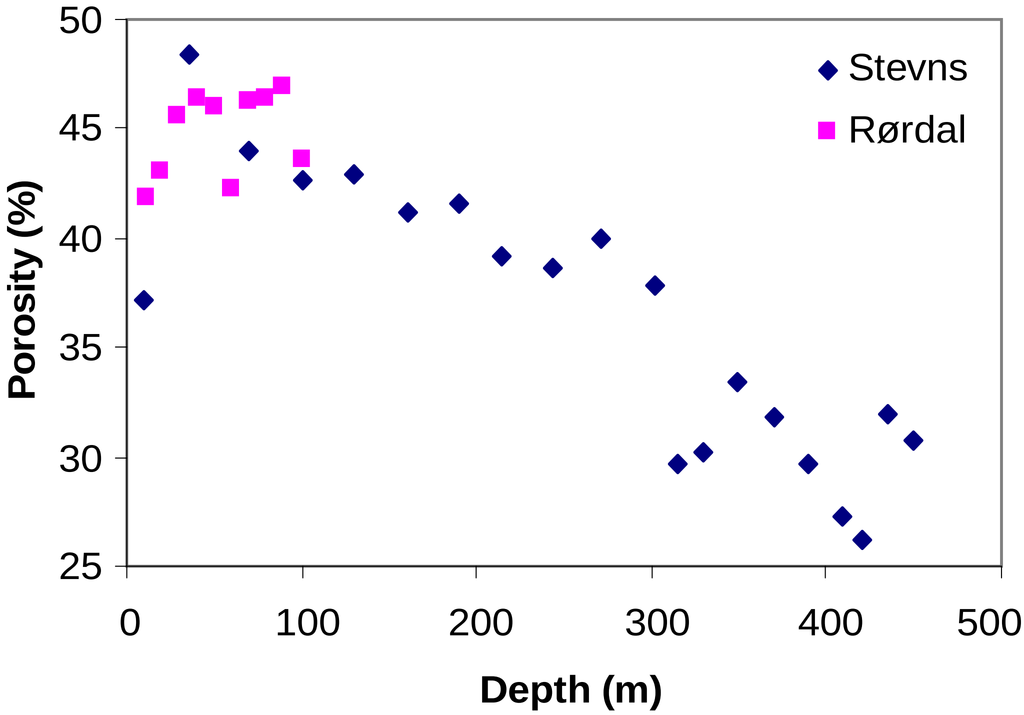

Figure 2 Plot of chalk porosity versus depth for core samples from Stevns-1 and Rørdal wells. Data from Knudsen & Jacobsen (2008). Note the decreasing porosity with increasing depth.

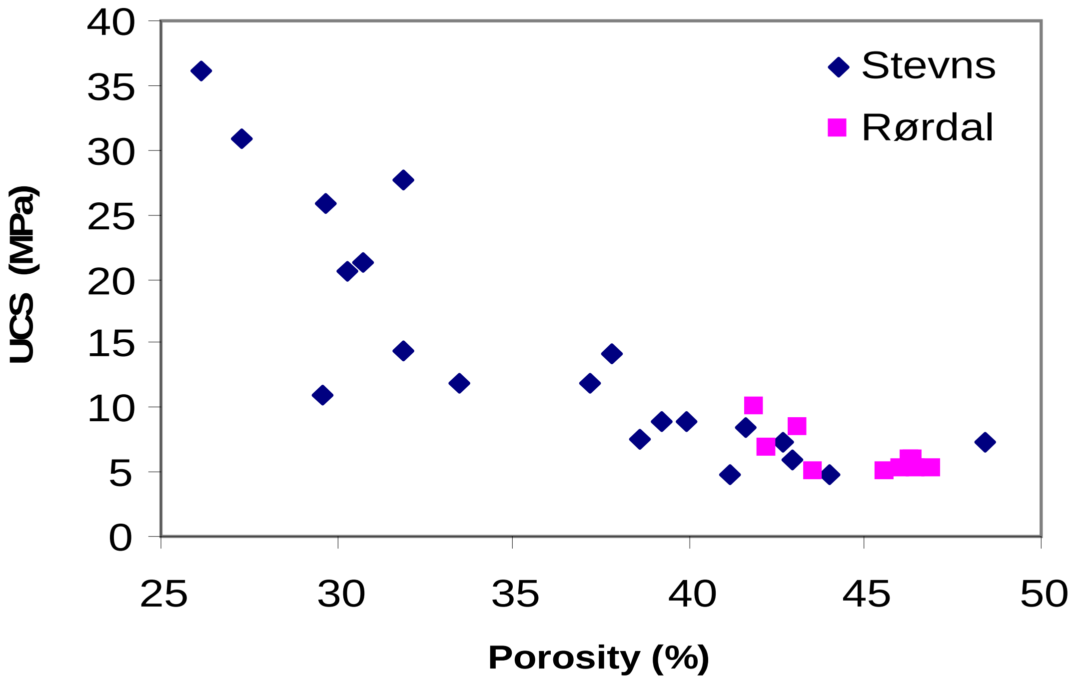

Figure 3 Unconfined Compression Strength (UCS) versus porosity. Note the increase in UCS with decreasing porosity.

The reason for the higher strength is that the grains are “glued” together with the calcite cement precipitated in the porespace. The high strength rocks have porosity below ca. 33 %.

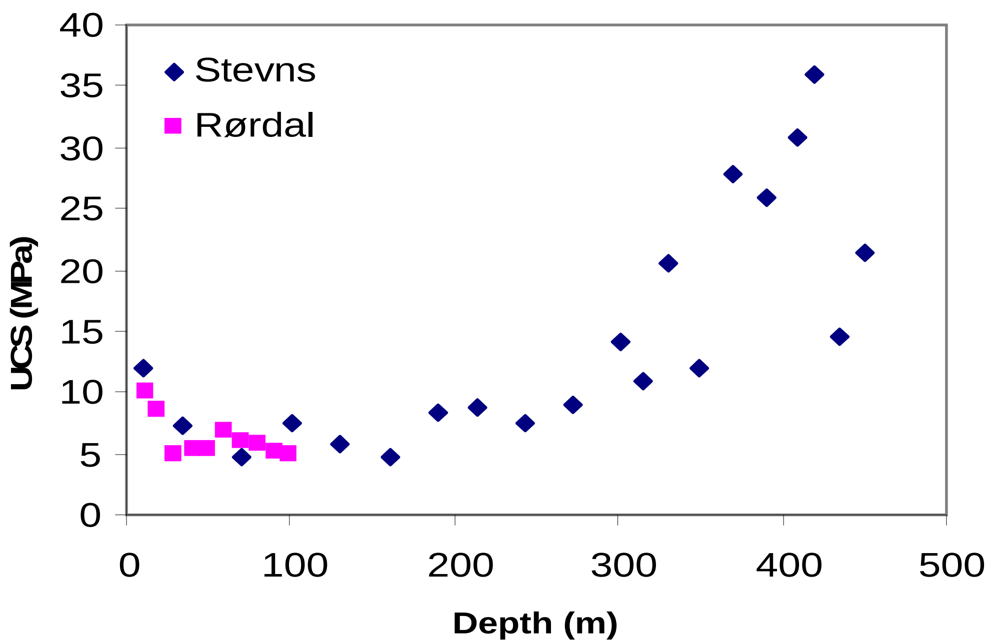

Figure 4 Unconfined Compression Strength versus depth.

There is a general increase in the strength with depth (Fig. 4). The reason for the decrease in porosity is that the calcite starts to dissolve at grain contacts because of the weight of the overburden (pressure solution). This is estimated to begin when the burial depth exceeds ca. 1100 m (Fabricius et al., 2008). The assumed amount of sediments removed by erosion at Stevns is ca. 600 – 700 m (Fig. 5) indicating that pressure solution should be found at a depth of ca. 400 m at Stevns. The data in Fig. 4 support this model.

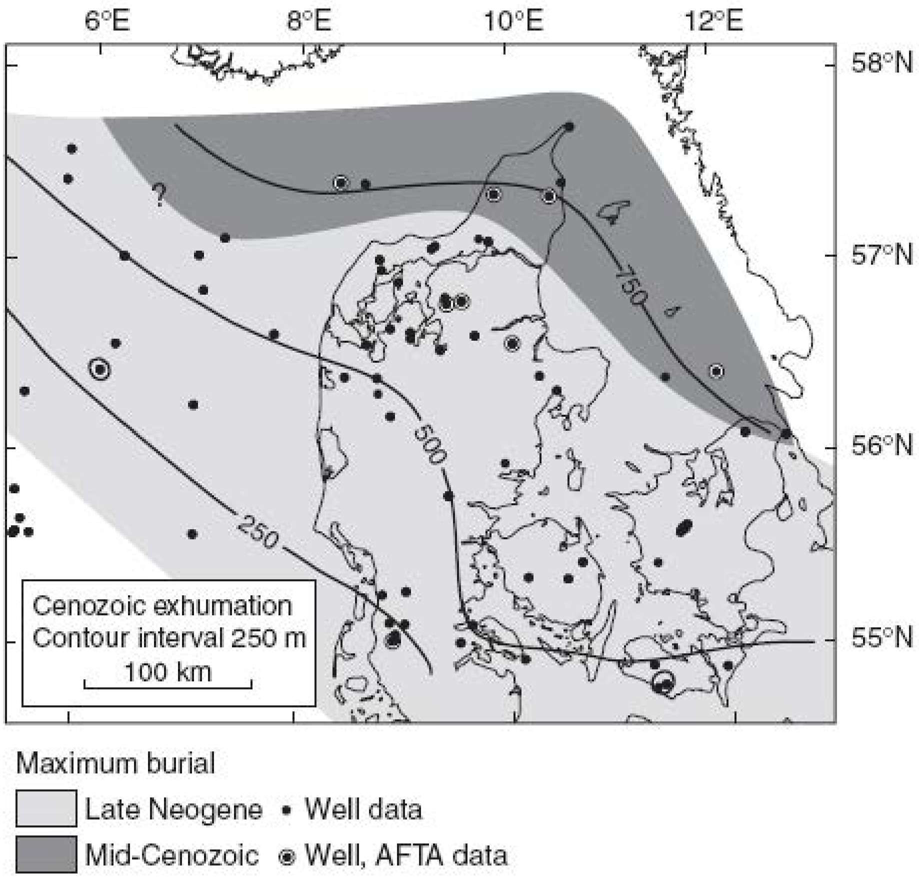

Figure 5 Map showing the expected thickness of rocks that once was deposited over the present day surface and later removed by erosion and deposited e.g. in the North Sea. From Japsen et al. (2007).

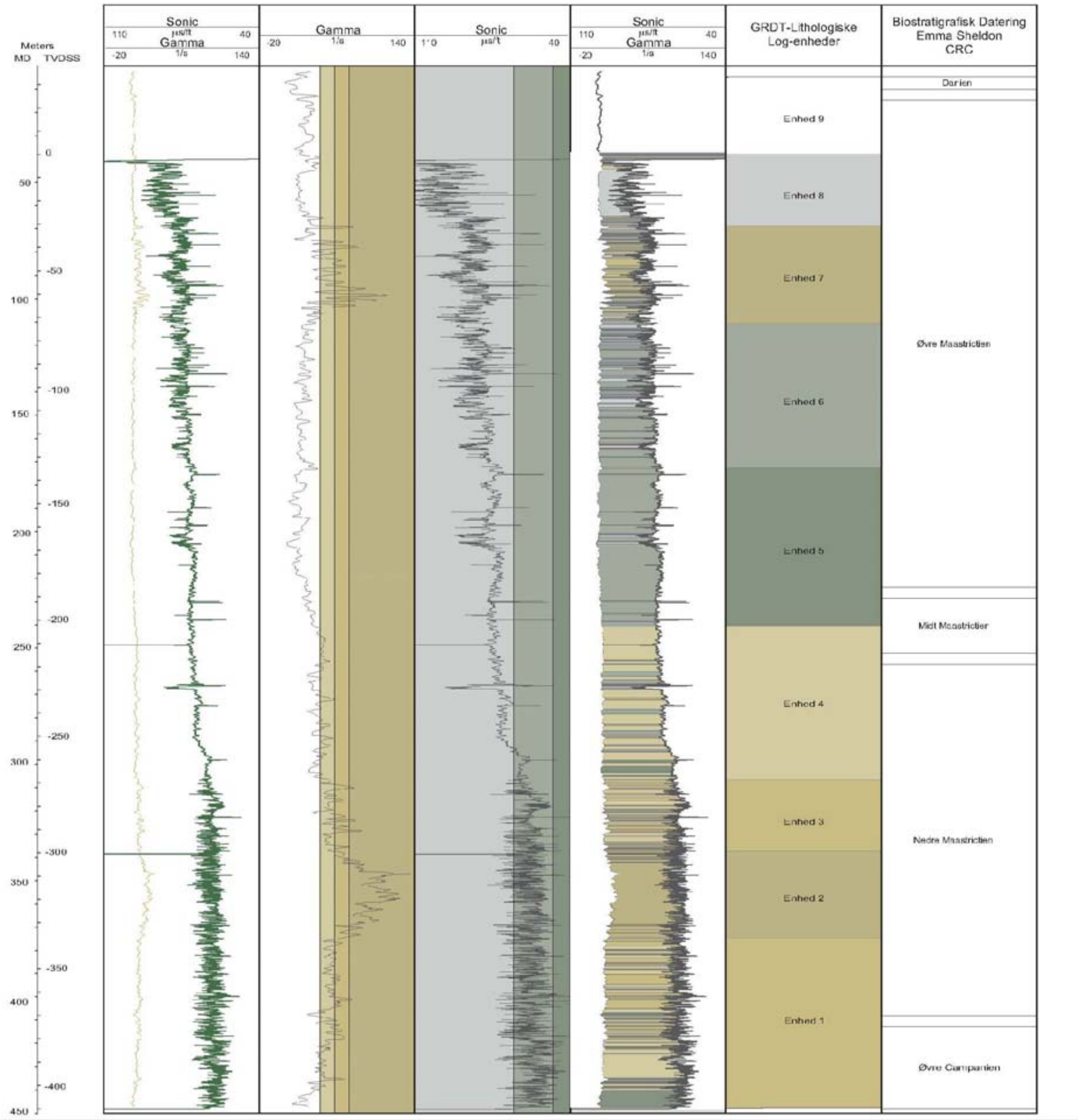

Figure 6: Gamma and sonic log in Stevns-1 (Jensen, 2007).

On Fig. 6 an increase in the gamma-log can be seen between 300 and 400 m in Stevns-1. This is caused by an increase in potassium in clay in the chalk.

In the logs from Stevns 1 (Fig. 6) it can be seen that the sonic velocity also increases with depth. The relationship between sonic velocity and porosity (Fig. 7) reflects a higher sonic velocity in the cemented limestone where the pore-space has been filled with calcite (below ca. 300 m depth.

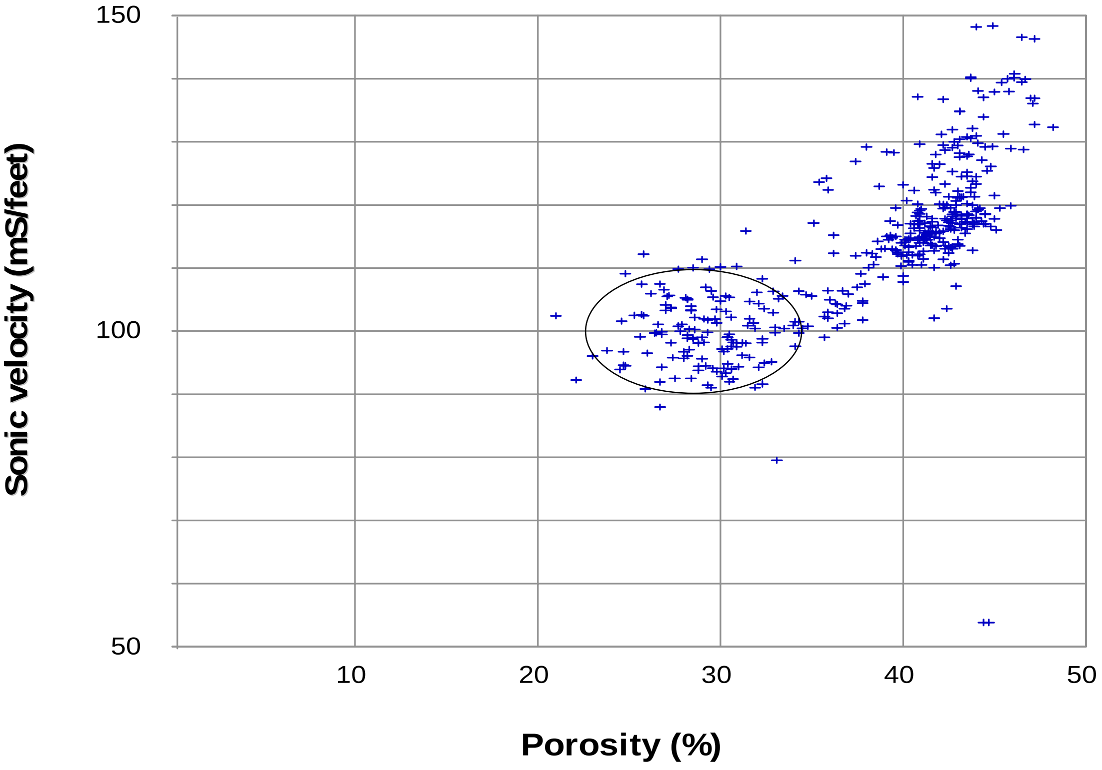

Figure 7 Sonic velocity (µsec/foot or "travel time") versus porosity in Stevns-1. The low porosity rocks (< 33 %) have sonic velocities in the range 90 to 110 µsec/feet equivalent to 3.4 to 2.8 km/sec.

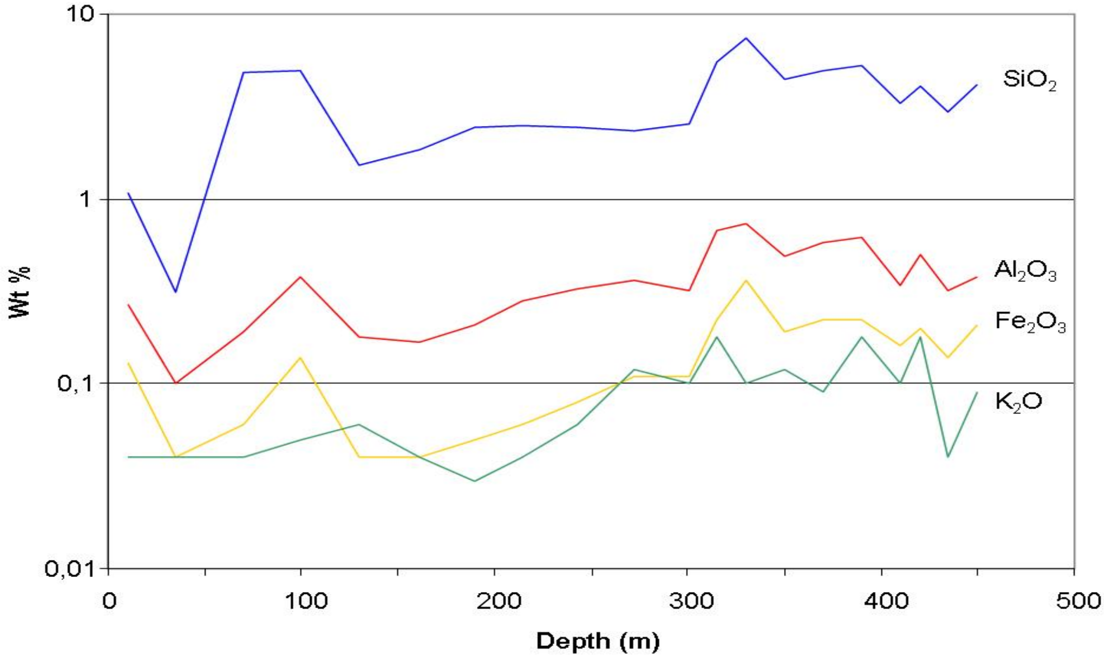

Figure 8 Plot of content of SiO_2, Al_2O_3, Fe_2O_3 and K_2O content in the chalk versus depth in Stevns-1.

In Fig. 8, it can be seen that below 300 m, there is an increase in the silica content. However, the silica content is too high (Al_2O_3:SiO_2 = 1/10) to be accounted for only by the clay as the ratio between Al_2O_3 and SiO_2 in clay usually is between 1:3 to 2:3. This indicates that there is disseminated silica in the chalk in this interval accounting for the anomalously high strength of the chalk in this section.

The increase in gamma signal on the gamma log is explained by the increase in potassium (K) content. The potassium is located in clay minerals.

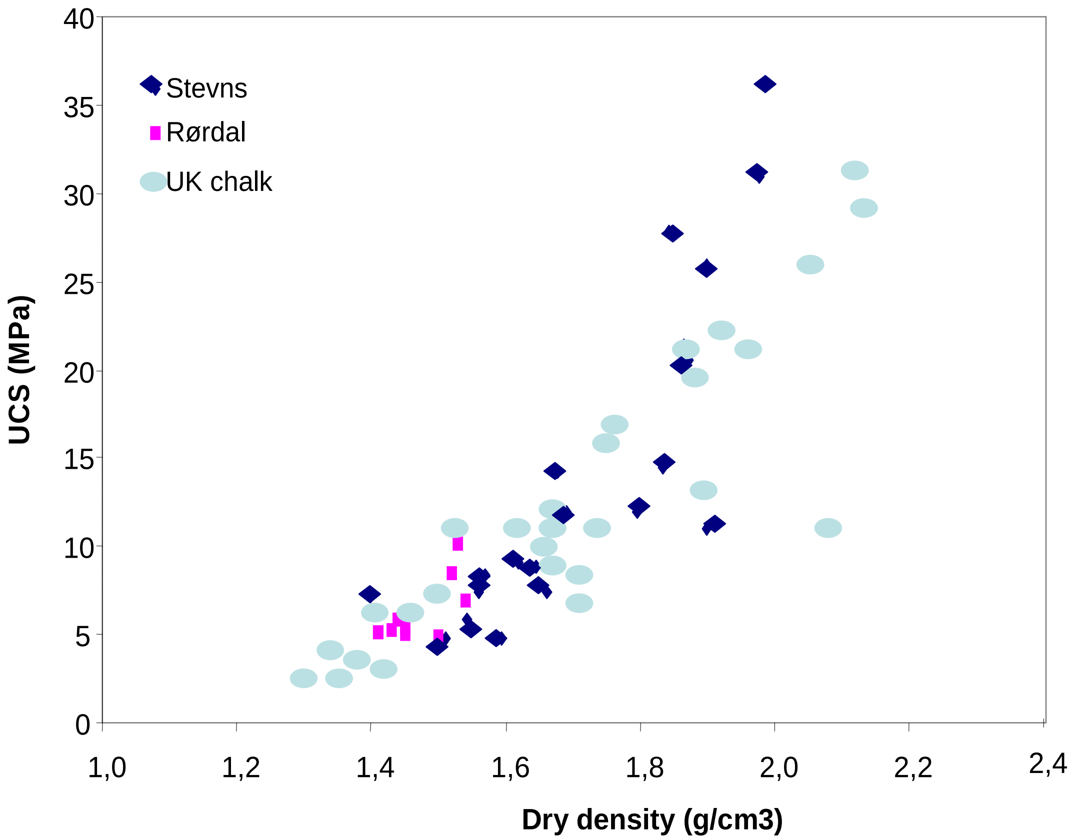

Figure 9 Unconfined Compression Strength (UCS) versus dry density. The UK chalk data are from Matthews and Clayton (1993).

On Fig. 9 it can be seen that the strength of the dense rocks at Stevns is higher compared to other chalk samples.

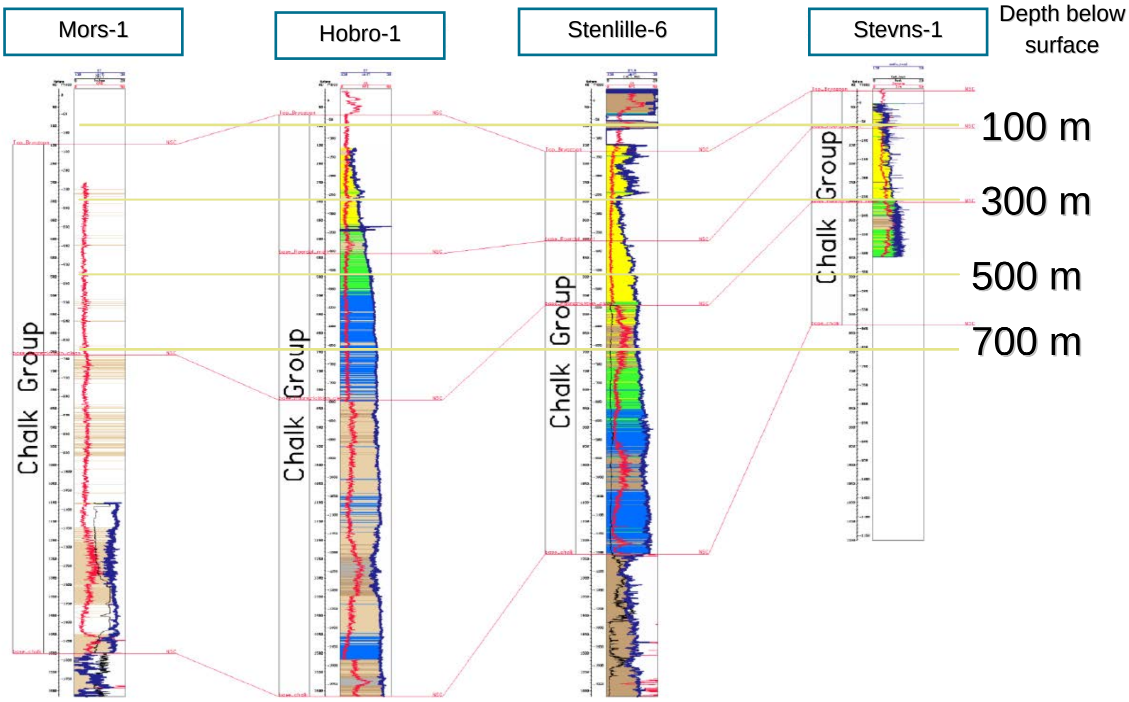

Figure 10 Log panel (line on Fig. 1): Sonic (blue) and gamma (red) logs from Mors-1, Hobro-1, Stenlille-6 and Stevns-1. Lithology legend: Light to dark brown colors reflects impure chalk with high to very high γ-values.

Color interval for clean chalk (low gamma-values) is based on sonic curve:
Yellow: >107 msec/feet, (slow sonic velocity - weak chalk).
Green 88 to 107 msec/feet (faster sonic velocity - stronger chalk).
Blue < 88 msec/feet. (fast sonic velocity - very strong chalk).

The log correlation of key wells in Denmark on Fig. 10 indicates a very consistent lithological variation in the Chalk. Based on cores and cuttings from Stenlille-6 and Stevns-1 we expect that the upper 100 – 200 m of the chalk group is flint rich. The 300 – 700 m depth of interest zone include in the key wells:

- **Stevns-1**: Pure chalk extending down to marly chalk below 300 m. The 300 to 450 m interval is characterized by occurrence of cyclic chalk-marls.
- **Stenlille-6:** Pure chalk. Chalk is colored yellow corresponding to velocities > 107 µsec/feet i.e. slight slower than similar depth zone in Stevns-1 and is thus inferred to be more porous. This may be an effect of lower maximum burial (Fig. 5). Between ca. 570 and 750 m the stratigraphic level rich in marly layers known from the deep part of Stevns-1 are seen on the gamma-log. Below this level, the chalk is pure again for the next ca. 300 m. Below ca. 850 m the sonic log indicate very strong rocks to be present.
- **Hobro-1:** Pure chalk with few marly intercalations. The transformation from yellow to green occur ca. 100 deeper than in Stevns-1. The blue color at a depth of ca. 600 m indicate that strong chalk may be present at this depth.
- **Mors-1:** Pure chalk. No sonic log available at depth below ca. 1000 m.

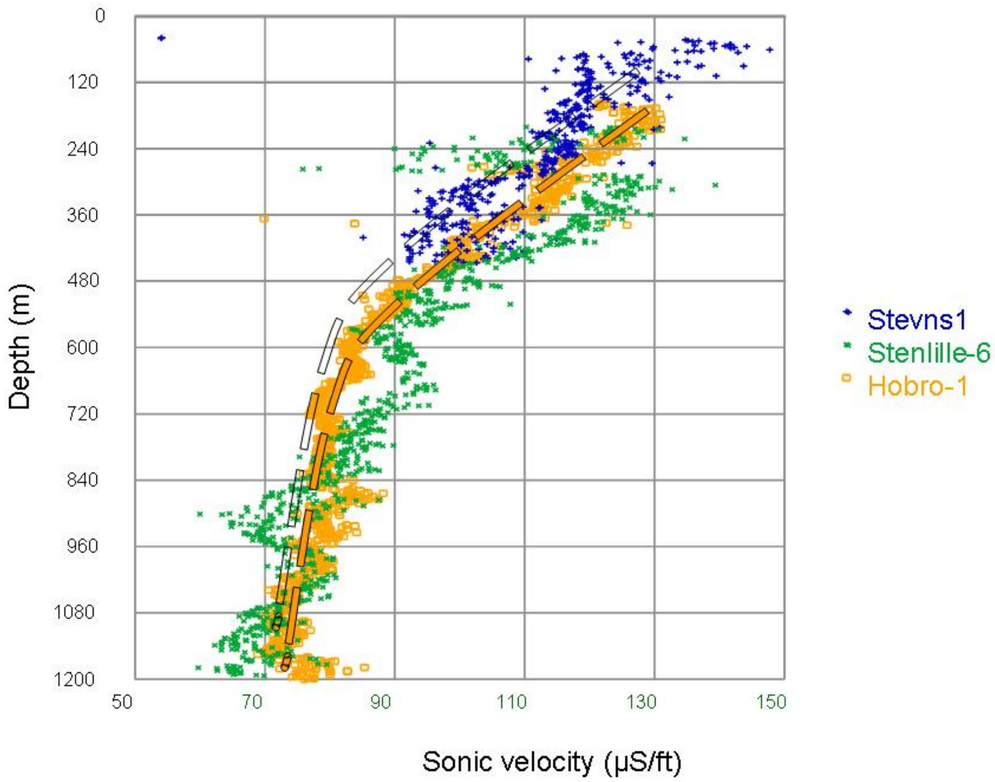

Figure 11 Depth versus sonic velocity for Hobro-1, Stenlille-6 and Stevns-1.

As can be seen on Fig. 11, a mean sonic velocity of 90 to 70 µsec/foot equivalent to 3,4 to 4,4 Km/sec. can be expected if we drill deeper at Stevns-1.

The different relationships between depth and sonic velocity among the three wells illustrate the slight difference in the amount of overburden that has been removed above the chalk (Japsen & Bidstrup, 1999, Japsen et al., 2007). The Stevns area has been buried approximately 150 m deeper than Stenlille-6 i.e. to depth of +750 m at maximum Neogene burial depth.

On Figs. 10 and 11 it can be seen that the sonic velocity in the chalk continue to increase below the stratigraphic level to which the Stevns-1 well has penetrated. This indicates that more indurated and strong rocks can be expected to occur at depth.

We do not have data concerning the strength of the chalk in the Stenlille-6 and Hobro-1 wells, but estimates of the strength that can be expected can be derived from

- the sonic velocities derived from analogies to the Stenlille-6 and Hobro-1 wells (Fig. 11) namely between 3.4 and 4.4 km/sec and
- the relationship between sonic velocities and UCS on Fig. 11.

This suggest that the strength that can be expected at a depth of 600 m at Stevns is between 25 and 60 MPa. The UCS values observed in the Stevns-1 well below 300 m are between 25 and 40 MPa except from the marly layers.

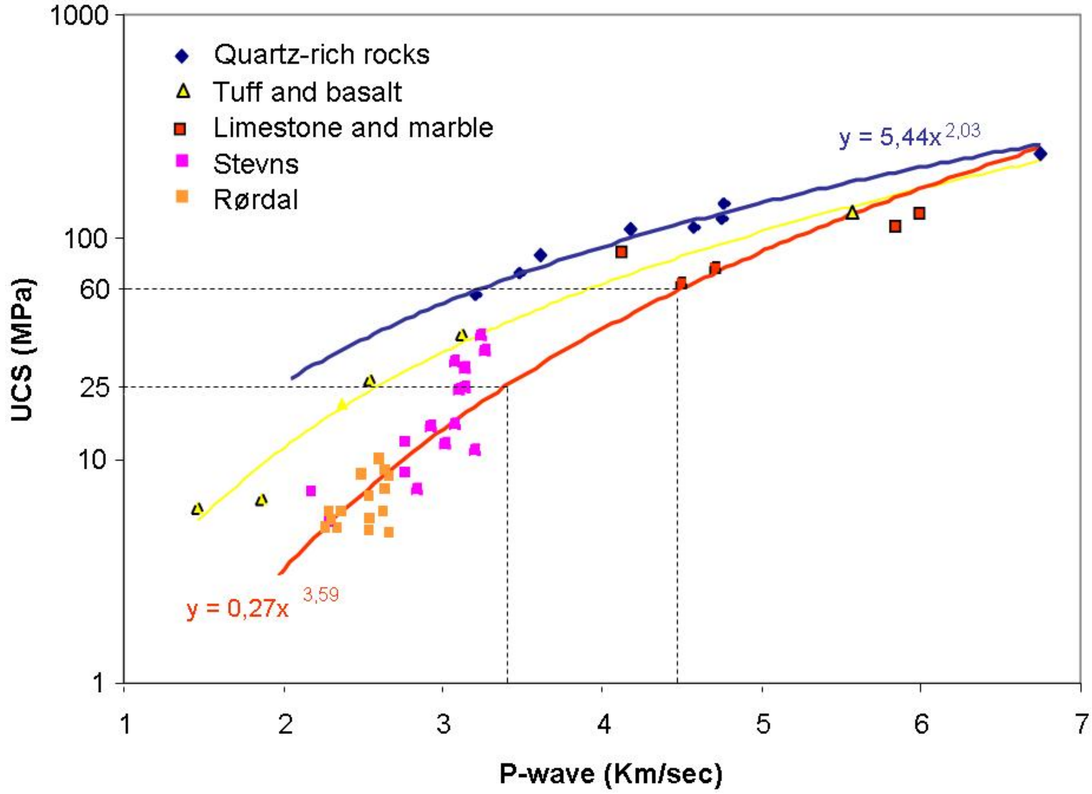

Figure 12 Unconfined Compression Strength (UCS) versus sonic velocity in different rock-types. Stevns-1 and Rørdal samples data are based on Knudsen & Jacobsen (2008) and the data concerning other rock-types are from Kılıc & Teymen (2008).

On Fig. 12 it can be seen that the strong rocks found in the interval 25 to 40 MPa from Stevns-1 are stronger than would be expected from the relationship between UCS and sonic velocity. This is parallel to the observation on Fig. 9 where they are stronger than similar chalk with the same density. The chalk in this interval contains elevated amounts of silica probably indurating the rock.

4 Tectonic considerations

The Stevns area is stabile with few faults and fractures, which can be seen in the well exposed coastal section of the chalk as well as in the chalk pit at Sigerslev. The structure in the chalk can be studied using shallow seismic methods (Fig. 12).

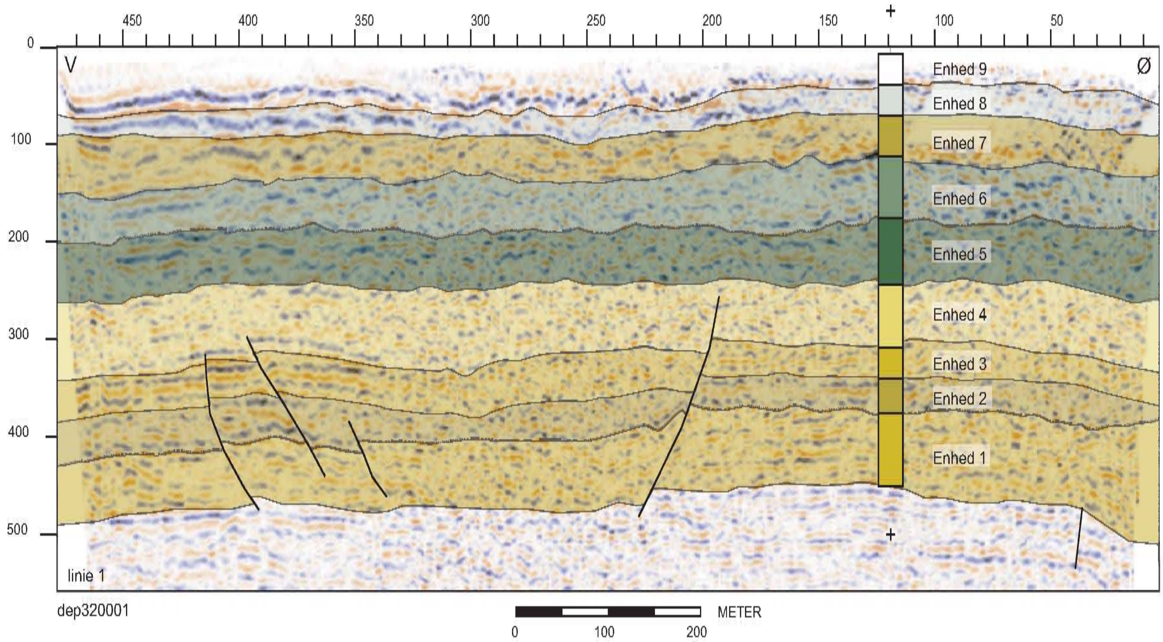

Figure 13 East – west oriented reflection seismic section of chalk at Stevns. The lithological variation in the chalk can be resolved in seismic investigations (Jensen, 1997). The main lithological change at 270 m from rather clean chalk (enhed 4 to 9) to cyclic chalk-marl (enhed 3-4) is seen as a relative marked change in the seismic facies.

The frequency of faults and fractures in the chalk depends mainly on:

- Fault zones tied to major structural/tectonic features such as the Fennoscandian Border zone and the Ringkøbing-Fyn High
- Occurrence of salt diapirs below the chalk
- Glacial disturbance (e.g. responsible for formation of Møns Klint)

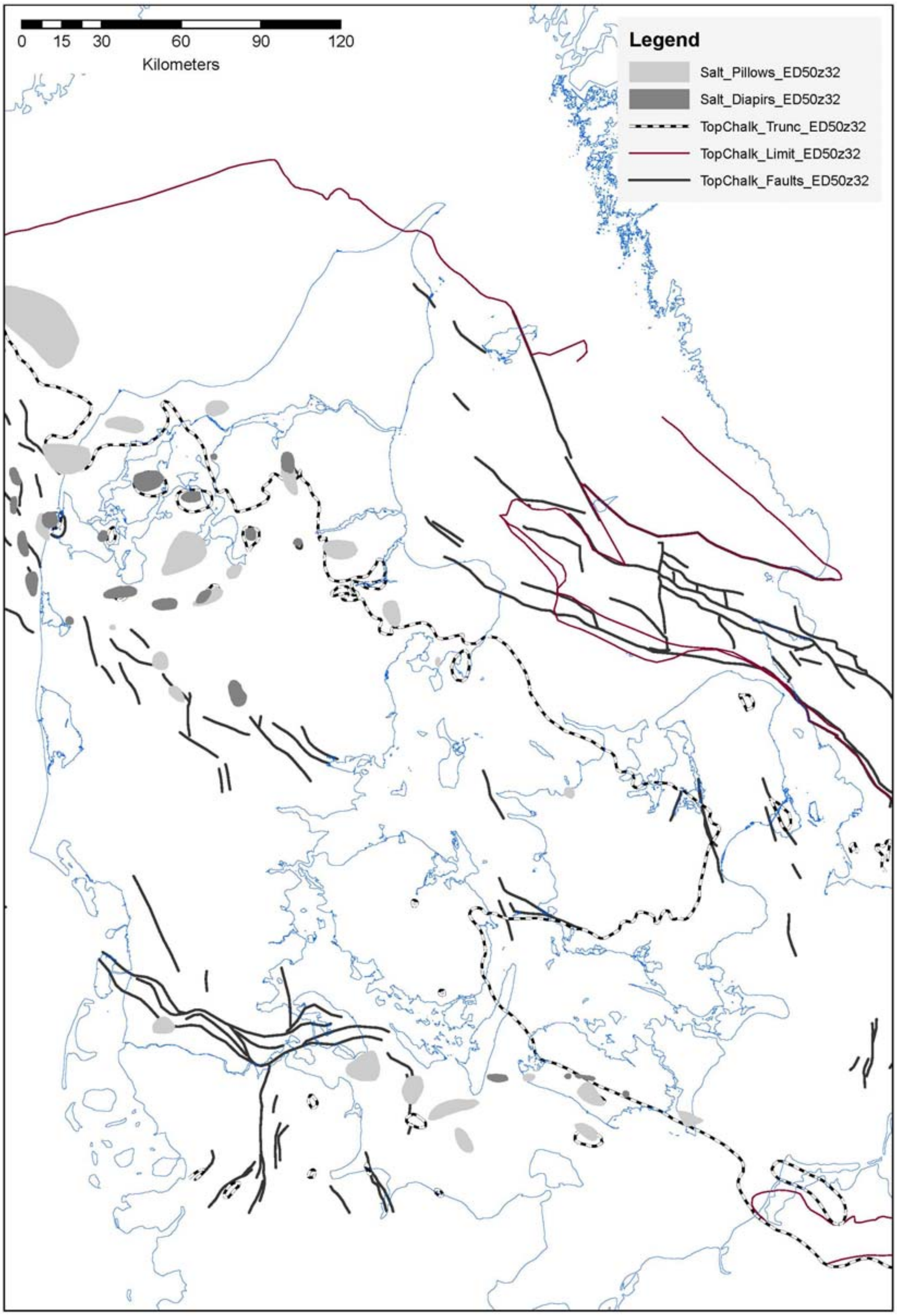

Figure 13 Map showing major fault-zones and areas where salt diapirs occur.

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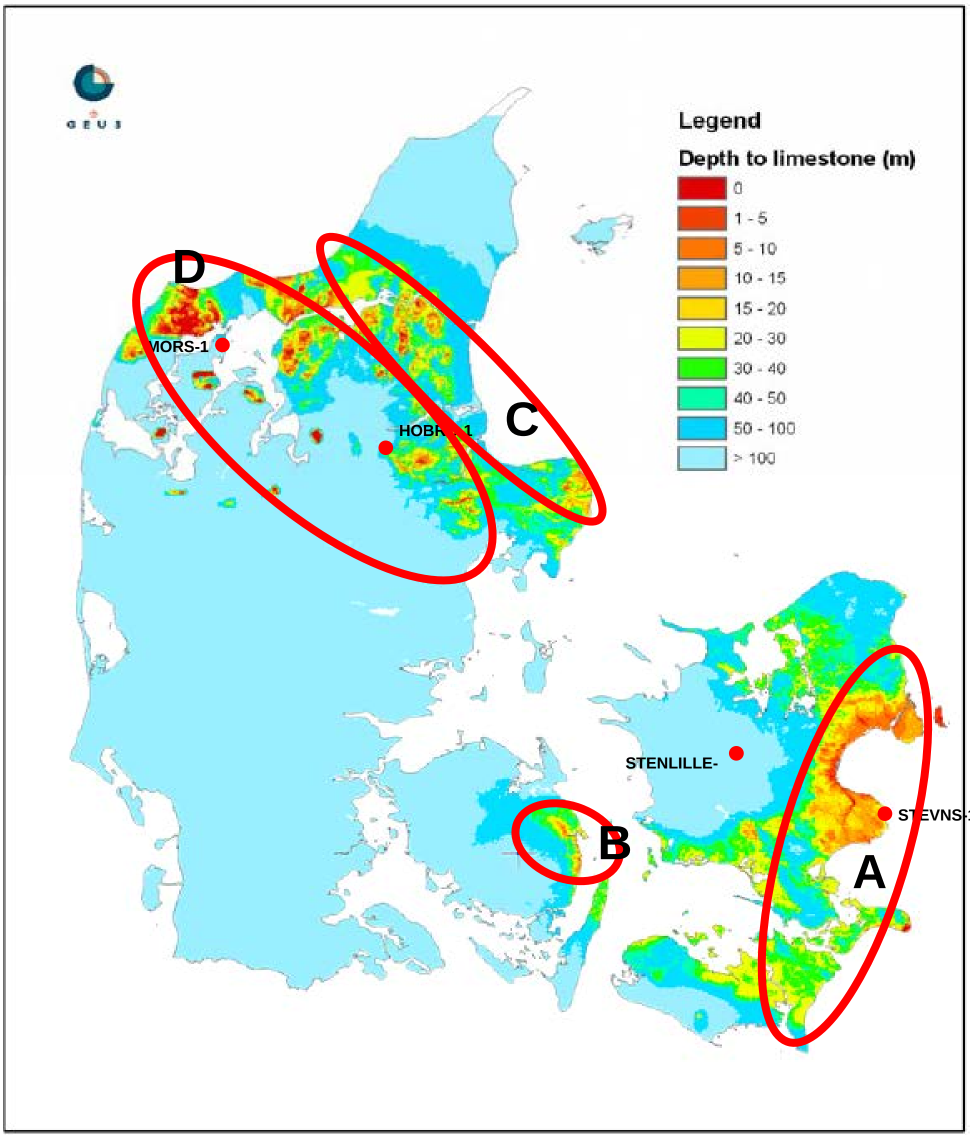

Figure 14 Map showing areas where the chalk is located not deeper than 100 m from the surface.

A: Eastern part of Sjælland extending South to Møn and Falster: Shallow lying chalk not affected by salt diapirs. Glacial disturbance of the southern part of the area.

B: Eastern part of Fyn (Nyborg Area). Shallow lying chalk with no salt diapirs.

C: Mols peninsula extending NW to Aalborg: Shallow lying chalk with moderate influence from salt diapirs.

D: Eastern Jutland extending to NW to Råbjerg Knude. Shallow lying chalk strongly affected by salt diapirs.

5 Conclusions and recommendations

Rock-mechanical testing of drill-core from Stevns-1 show that there is a general increase in Unconfined Compression Strength (UCS) with depth to > 10 MPa for the chalk below 300 m and generally above 20 MPa in the depth interval between 300 and 500 m. This increase in rock strength is also seen as an increase in sonic velocity. The interval with UCS above 10 MPa has sonic velocity in the interval 90 to 110 µS/feet.

A similar increase in sonic velocity can be observed in other wells penetrating the upper part of the chalk. The intervals with rock with UCS > 10 MPa occur at slightly deeper levels as compared with Stevns-1, e.g. at Hobro at a depth of ca. 400 m and in Stenlille at ca. 450 m.

Even higher sonic velocities than observed in Stevns-1 were found at greater depth in Hobro-1 and Stenlille-6 indicating that strong rocks can be located here. The implication of this is, that the rock stability is likely to be higher, which in turn may compensate for the increased weight of the rock pile on top of a cavern that may be constructed.

Among the areas with shallow chalk, least tectonic disturbance are expected on eastern Sjælland, Lolland, Falster and eastern Fyn. The area between Grenå and Aalborg is also favourable, whereas the area with shallow chalk in north-western Jylland is strongly influenced by tectonics induced by salt diapirs.

It is recommended that further investigations are initiated in the Stevns and Grenå areas. These investigations should primarily consist of cored wells to a depth of ca. 700 m. The cores should be described and logged for Q-values and the wells should be logged using γ-log, sonic log, porosity and density as well as optical televiewer log for orientation of fractures. The core should be tested for UCS. The purpose of this will be to generate data for estimating the cost of building a cavern for pumping power at larger depth and thereby increase the efficiency of the pumping power facility.

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